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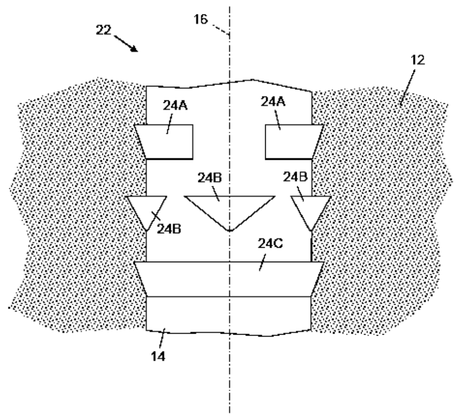
(54) Title **Embedded subsea foundations**

(57) Abstract

An embeddable subsea foundation such as a suction pile comprises: an elongate penetrating body having a soil-engaging surface configured for engagement with seabed soil; and a directional profile extending across the soil-engaging surface, that profile being configured to aid penetration of the foundation into the seabed soil in a distal direction and then to resist movement of the foundation relative to the seabed soil in an opposed proximal direction. The profile comprises barb elements such as plates or filaments that protrude from, and converge in the distal direction with, the penetrating body. At least part of each barb element may be movable relative to the penetrating body between retracted and deployed states.



Embedded subsea foundations

This invention relates to subsea foundations that are designed to be embedded into the seabed. Such foundations are exemplified in this specification by suction piles.

The invention aims to simplify and accelerate the installation of embedded subsea foundations. The invention also aims to improve the resistance to movement of embedded subsea foundations once they are installed.

In principle, the invention may allow the size and hence the cost of embedded subsea foundations to be reduced without sacrificing their capacity to resist break-out loads. The invention may also shorten the post-installation period that is required for the surrounding soil to regain sufficient strength, hence allowing such foundations to be ready for use more quickly than was previously possible. This enables overall project timescales to be shortened substantially.

Suction piles are commonly used in the subsea oil and gas industry for anchoring large offshore installations to the seabed in deep water. To do so, they are designed to engage soft seabed soil that typically comprises marine sediments or soft clays.

Suction piles engage the seabed soil by friction and/or by cohesion attributed to van der Waal forces. The engagement mechanism depends upon the composition of the soil. Engagement of a suction pile with a sandy seabed is based more on friction whereas engagement with a clay seabed is based more on cohesion.

Suction piles are also known in the art as suction anchors, suction cans, suction caissons or suction buckets. The design of such foundations may be determined with reference to standards such as DNV-RP-E303, entitled *Geotechnical Design and Installation of Suction Anchors in 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 engages the seabed soil by friction or cohesion upon being embedded axially into the soil.

The top of the skirt is closed by a steel top plate. This defines a suction chamber between the top plate, the skirt and the seabed soil trapped within the embedded skirt.

Underpressure in the suction chamber also promotes engagement of the suction pile with the seabed.

The top plate may comprise openable hatches or may be attached to the skirt only after the skirt has been lowered to the seabed. This reduces drag and improves stability while lowering the suction pile, or the skirt, through the water.

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. 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 as disclosed in GB 1451537, the resulting underpressure in the chamber draws the top plate toward the seabed. This causes the skirt to sink further into the soil as the suction chamber contracts under external hydrostatic pressure, hence effecting fuller engagement of the suction pile with the seabed.

Consequently, a suction pile engages with the seabed by virtue of a combination of friction or cohesion and suction. The installation method reflects these factors, firstly by allowing the pile to self-penetrate under its own weight into the seabed and secondly, after a short period of settlement, by pumping water out of the resulting suction chamber to apply suction.

Self-penetration of the pile ends when resistance to relative sliding movement between the skirt and the seabed soil balances the weight of the pile. Suction overcomes that resistance 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 and then left for a period for the surrounding soil to regain its strength, 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 for mooring or tethering a floating platform, a surface vessel such as an FPSO or a subsea riser-supporting buoy.

The top plate serves as a convenient interface with the equipment that the suction pile is intended to anchor or otherwise to support. For example, the top plate may provide an attachment point for a mooring line or a tether. However, it is also common for a mooring line to be attached to the skirt of a suction pile.

Mooring lines and tethers act in tension and so apply upward traction forces to a suction pile, with a major component of those forces being in a vertical direction. In that case, it is necessary for the pile to resist being pulled up out of engagement with the seabed.

In deep water, suction is generally applied by using a remotely-operated vehicle or ROV to pump water from the suction chamber. The use of an ROV requires the presence of a surface support vessel for an extended period, noting that pumping may need to continue for, typically, eight to twelve hours. This increases the cost of installation and requires a correspondingly long weather window during which the support vessel can remain safely on station above the installation site.

The installation method described above not only takes a long time but is also subject to uncertainties arising from the variable nature and consistency of the seabed soil under the pile. This presents a risk of being unable to embed the pile effectively into the seabed, for example because of greater-than-expected resistance to relative movement between the skirt and the seabed soil.

In theory, a low-resistance coating or finish on the skirt of a suction pile could address these problems by allowing the skirt to slide past the surrounding seabed soil more easily. This would help self-weight and suction to overcome resistance to movement of the skirt through the soil and so would enable the skirt to become embedded to a desired depth more quickly and more reliably.

In practice, however, it is not acceptable to reduce resistance to movement of the skirt through seabed soil in a system that relies substantially upon such resistance to work. For example, those skilled in the art know that the skirt of a suction pile must not be painted. This is because although a suction pile will sink relatively quickly and easily into seabed soil if it has a low-resistance coating such as paint on its skirt, such a pile will have correspondingly reduced resistance to upward traction. Thus, at least a lower major portion of the skirt is left with a substantially bare steel surface to increase resistance to relative movement between the skirt and the surrounding seabed soil in use.

There remains a need to find an appropriate balance between ease of penetration of an subsea foundation into seabed soil and resistance of the thus-embedded foundation to upward traction or pulling forces when in use.

CN 108423123 discloses a subsea pile that comprises a pull anchor system. After penetration in the manner of a guide pile or suction pile, a bottom anchor is deployed and a surrounding skirt is removed. This teaches away from using the skirt to engage the seabed soil as a permanent part of the foundation.

In GB 2277547, the skirt of a suction pile is widened or thickened by being splayed downwardly near its bottom edge to increase the reaction force of the pile to an upward pull load. However, such formations tend to make downwards penetration more difficult.

US 4064703 discloses pins or spikes that are extended from a pile into engagement with the surrounding seabed soil after penetration of the pile. While being extended, the spikes firstly deform the wall of the pile outwardly to form bumps in the wall before penetrating those bumps to protrude from the pile. The need to form the bumps implies that the spikes are insufficient, in isolation, to anchor the pile. Also, the wall of the pile has to be weak enough to be deformed and penetrated by the spikes, and a complex system is required to drive the outward movement of the spikes with sufficient travel and force.

US 2012/285362 discloses a suction pile comprising mud fins that are arranged to limit the depth of penetration. Such fins do little to resist an upward pull load and will also tend to make downward penetration more difficult.

WO 2017/157766 discloses the use of a low-resistance coating such as an aerogel, an aero-clay or a polymeric film on a bearing surface of a subsea foundation such as a suction pile. When the foundation is installed, the bearing surface is embedded in the seabed soil using the low-resistance coating to reduce resistance to movement of the bearing surface relative to the seabed soil. The low-resistance coating may then dissolve or fragment away from the bearing surface or transform into a higher-resistance state while remaining on the bearing surface. These mechanisms degrade a resistance-reducing property of the coating to increase resistance to movement of the embedded bearing surface relative to the seabed soil.

It is against this background that the present invention has been devised. In one sense, the invention resides in an embeddable subsea foundation that comprises: an elongate penetrating body having a soil-engaging surface configured for engagement with seabed soil; and a directional profile extending across the soil-engaging surface, that profile being configured to aid penetration of the foundation into the seabed soil in a distal direction and then to resist movement of the foundation relative to the seabed soil in an opposed proximal direction.

The directional profile suitably comprises a plurality of barb elements that protrude from, and converge in the distal direction with, the penetrating body. At least part of each barb element may be movable relative to the penetrating body, for example by pivoting or bending relative to the penetrating body.

At least part of each barb element may be movable toward the penetrating body in response to distal movement of the penetrating body relative to the seabed soil. Conversely, at least part of each barb element may be movable away from the penetrating body in response to proximal movement of the penetrating body relative to the seabed soil.

In some embodiments of the invention, a distal end of each barb element is attached to the penetrating body and a proximal end of each barb element is movable relative to the penetrating body. For example, the distal end of each barb element may be attached to the penetrating body by a hinge.

The foundation of the invention may further comprise a latch that is arranged to hold the proximal end of each barb element against movement away from the penetrating body. In that case, the foundation may further comprise a latch release that is operable to enable movement of each barb element away from the penetrating body by releasing the latch.

A bias element such as a spring or an expandable mass suitably acts outwardly between the penetrating body and the at least part of each barb element.

Each barb element may comprise a plate with self-supporting rigidity. Alternatively, the barb elements could be flexible filaments. In that latter case, the directional profile may comprise a nap of such filaments.

Barb elements of the plurality spaced longitudinally along the penetrating body may overlap with each other. At least a proximal portion of each barb element may be spaced laterally from the penetrating body.

Each barb element may be expandable away from the penetrating body, for example by resilient expansion. Each barb element may comprises an expandable mass whose expansion can be triggered by the application of a stimulus. In that case, the foundation of the invention may further comprise a triggering system that is arranged to initiate expansion of the mass by applying said stimulus.

Conveniently, the directional profile may comprise a base web that is moulded onto or attached to the penetrating body.

The inventive concept also embraces a method of installing a subsea foundation. That method comprises: advancing a penetrating body of the foundation in a distal direction to penetrate seabed soil; and by interaction between the seabed soil and a directional profile on the penetrating body, applying substantially greater resistance to movement of the penetrating body in a proximal direction than in the distal direction.

The seabed soil may be engaged with barb elements of the directional profile that protrude from, and converge in the distal direction with, the penetrating body. At least part of each barb element may be moved relative to the penetrating body, either inwardly in response to distal movement of the penetrating body relative to the seabed soil or outwardly in response to proximal movement of the penetrating body relative to the seabed soil.

At least part of each barb element may be driven or biased away from the penetrating body after penetrating the seabed soil, for example by expanding each barb element away from the penetrating body and optionally also by applying a stimulus to trigger that expansion.

At least part of each barb element may be latched against movement relative to the penetrating body and may then be unlatched to be free to move relative to the penetrating body.

At least part of each barb element may be extended through seabed soil that was relatively disturbed by the distal advance of the penetrating body and into contact with seabed soil that was relatively undisturbed by the distal advance of the penetrating body.

In summary, the invention provides an opportunity to install subsea foundations such as suction anchors that can be fully loaded sooner after installation than was previously possible. Achieving higher break-out capacity soon after installation could save an entire season waiting for the disturbed seabed soil around the foundation to regain strength. In this respect, the normal setup time to achieve full foundation strength could be as much as a full year.

The invention also provides an opportunity to reduce the size of a subsea foundation such as a suction anchor. If a desired break-out capacity is required quickly, the conventional approach has been to install a larger foundation to achieve the capacity that a normal suction anchor would attain after a season. The invention therefore enables a foundation of normal size, or less, to be installed and to be ready for use sooner after installation. This reduces cost in various ways by avoiding a prolonged installation project, by reducing fabrication operations and material usage, and by allowing a smaller construction vessel to be used.

Examples of the invention apply a shroud, sleeve or coating of a material, such as a fabric, to a subsea foundation. That material has directional resistance or frictional qualities akin to snakeskin, for example as used in synthetic tracks of summer ski-jumping ramps.

The seabed soil in very close proximity to the foundation will be remoulded after installation. Depending on the geometry, structure or texture of the snakeskin-like material, it will be possible to activate more soil volume further from the foundation and hence to gain resistance from undisturbed soil.

Embodiments of the invention provide a shroud, sleeve or coating for the skirt of a foundation pile such as a suction pile. The coating comprises skin elements that have a first friction coefficient when the pile is penetrating downwardly into seabed soil, and a second friction coefficient when the pile is subsequently pulled up, the second friction coefficient being higher than the first friction coefficient.

The skin elements may comprise at least one pliant blade that makes an acute angle downwards in the vertical direction. The blades may be of a synthetic material. The blades may have substantial stiffness and elasticity in order to be aligned with the vertical direction when driven down and tilted relative to the vertical direction when pulled up. The blades may be articulated, and may be spring-loaded or otherwise biased into a deployed or retracted position.

The skin elements may comprise a thixotropic material or may comprise compressible wedges, for example of a polymer that may be injection-moulded on the skirt of the pile.

The skin elements may comprise plates or scales. For example, a polymer coating may be applied to make a pattern of downwardly-facing scales. The skin elements may instead comprise soft plastic lamellae.

Skin elements may be applied to the pile as a coating, strapped to or otherwise attached to the pile, or injection moulded onto the metal of the pile. The skin elements may be partially coated with a low-friction material such as PTFE or paint.

Embodiments of the invention also provide a suction pile or anchor for an underwater foundation, a skirt of the pile comprising at least one panel that can be open at an angle with the penetration direction, during or after penetration of the pile into the seabed.

The opening may face upwards when the panel is open. The panel may be biased, for example with a spring, toward an open position. Such a spring may be preloaded behind a panel on the skirt of the suction pile. The spring may be released after installation of the suction pile, for example using a pin latch system that is operable from the top of the suction pile.

The spring will initially plastically deform the soil with an initial expansion. Over time the spring will push the panel further away from the suction anchor as the spring will lead to a consolidation of the soil. The expanded panel will increase the capacity of the suction anchor against break-out forces.

Chemicals that react with seawater may be enclosed behind the closed panel. For example, a material that inflates or otherwise expands when in prolonged contact with seawater may be enclosed behind the closed panel. Such a chemical or material could be a smart gel that has the ability to expand when exposed to contact with salt water.

A smart gel is a material that expands or contracts in response to external stimuli. A smart gel may, for example, comprise a fluid such as water that exists in a matrix of one or more large, complex polymers. The polymer is responsive to an external stimulus that can include: light; magnetism; acidity or alkalinity; temperature; or an electrical or mechanical stimulus. Such a stimulus will alter the polymer matrix to make the matrix more or less hydrophilic, which can precipitate swift and forceful expansion of the gel in reaction.

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:

Figure 1 is a schematic side view of a subsea suction pile embedded in seabed soil, as known in the prior art;

Figure 2 is a schematic partial side view of a suction pile of the invention, showing three variants of barb formations in accordance with the invention;

Figures 3a, 3b and 3c are a sequence of enlarged schematic detail views of a suction pile of the invention in longitudinal section, showing the operation of resiliently-deformable barb formations in accordance with the invention;

Figure 4 is a schematic partial side view of a suction pile of the invention, employing passively-movable barb elements in accordance with the invention;

Figures 5a and 5b are enlarged schematic detail views of a suction pile of the invention, showing two actively-movable variants of movable barb elements in, respectively, retracted and deployed states and two variants of bias or drive means arranged to move the barb elements from the retracted state to the deployed state; and

Figure 6 is a schematic partial side view of a suction pile of the invention, employing barb elements in accordance with the invention in the form of unidirectional fibres or filaments.

The suction pile 10 shown embedded in seabed soil 12 in Figure 1 comprises a cylindrical skirt 14 that defines an open-bottomed hollow straight tube. The skirt 14 is rotationally symmetrical around an upright central longitudinal axis 16.

The top of the skirt 14 is closed by a top plate 18 to define a suction chamber between the top plate 18, the skirt 14 and the seabed soil 12 that is trapped within the open bottom of the skirt 14. Seawater is pumped out of that suction chamber via a pump 20 or fluid coupling shown on the top plate 18. Activating the pump 20 or drawing seawater out through a corresponding fluid coupling advances the suction pile 10 downwardly in a forward or distal direction to complete engagement of the pile 10 with the seabed soil 12 by further penetration.

The suction pile 10 of the prior art as shown in Figure 1 suffers from the problem that, initially, its resistance to distal penetration movement substantially equates to its resistance to opposite proximal break-out movement under the upward load of a mooring or the like. Thus, expressed another way, a suction pile 10 that is easy to force down into engagement with the seabed soil 12 is approximately as easy to pull up out of engagement with the seabed soil 12, at least while the adjacent seabed soil 12 remains disturbed.

Resistance to break-out forces will improve as the disturbed seabed soil 12 surrounding the suction pile 10 settles, compacts and regains strength over a long period of time, for example several months. Until then, however, the suction pile 10 will not be ready for use.

Time is precious in the art of subsea engineering. The invention therefore proposes various ways in which an embedded subsea foundation such as a suction pile can be installed quickly and easily and can attain a required break-out capacity quickly. In particular, the solutions proposed by the invention maximise the ultimate break-out capacity of the foundation without causing a corresponding increase in its size and cost. Those solutions proposed also enable a subsea foundation to be modified to improve its resistance to break-out loads without suffering a corresponding increase in its resistance to penetration.

First examples of the solutions of the invention are shown on the suction pile 22 in Figure 2. Here, the seabed soil 12 surrounding the embedded suction pile 22 is engaged by barb elements in the form of barb formations 24 that protrude radially from the outer soil-engaging surface of the skirt 14. The barb formations 24 are exemplified here by three types denoted 24A, 24B and 24C. The barb formations 24 have a ramp or wedge shape in longitudinal section that tapers downwardly toward the outer surface of the skirt 14 and, conversely, widens upwardly away from the outer surface of the skirt 14. This arrow-head section of the protruding barb formations 24 facilitates downward penetration of the suction pile 22 into the seabed soil 12 while more strongly resisting upward break-out forces.

The barb formations 24 may be of various types, including those illustrated in Figure 2. The suction pile 22 may have a mix of different types of barb formations 24A, 24B and/or 24C; alternatively, all of the barb formations 24 of the suction pile 22 could be of the same type.

Specifically, the barb formations 24A and 24B comprise discrete protrusions that are interrupted or distributed circumferentially around the skirt 14 of the suction pile 22. Conversely, the barb formation 24C extends continuously in a circumferential direction around the skirt 14 of the suction pile 22.

The barb formations 24A and 24C each have a frusto-conical outer contour whose axis of curvature coincides with the central longitudinal axis 16 of the skirt 14. Conversely, the barb formations 24B taper downwardly when viewed in a radial direction with respect to the skirt 14. This further eases penetration of the suction pile 22 into the seabed soil 12.

Barb formations 24 like those shown in Figure 2 could be substantially rigid but are preferably resiliently deformable to collapse temporarily into a retracted state on penetration of the skirt 14 into seabed soil 12 as shown in Figures 3a to 3c. Again, the barb formation 24 shown in Figures 3a to 3c could be of any of various types, including those illustrated as 24A, 24B and 24C in Figure 2.

The barb formation 24 shown in Figures 3a to 3c is of a resiliently crushable or compressible material such as a flexible foam. This enables the barb formation 24 to flatten from an initially expanded or extended state shown in Figure 3a when above the seabed soil 12 to a collapsed state on encountering the seabed soil 12 as shown in Figure 3b. In doing so, the outer surface of the barb formation 24 adopts a smaller, more acute angle with respect to the underlying outer surface of the skirt 14.

When collapsed as shown in Figure 3b, the barb formation 24 presents minimum resistance to further penetration of the suction pile 22 into the seabed soil 12. However, after the suction pile 22 has been embedded in the seabed soil 12, the barb formation 24 relaxes back and expands to return or deploy to the extended state as shown in Figure 3c. This engages relatively-undisturbed seabed soil 12 spaced radially from the skirt 14 and increases resistance to upward break-out forces acting on the pile 22.

Thus, Figures 3a to 3c show how the outer surface of a subsea foundation defined by one or more barb formations 24 transforms from a low-resistance profile during installation to a high-resistance profile after installation. The profile of the outer surface transforms in terms of its shape or texture.

Figures 4 to 6 show that the function of the collapsible or extensible barb formations 24 shown in Figures 3a to 3c may instead be performed by other discrete unidirectional barb elements that are each movable relative to the underlying outer surface of the skirt 14, for example by hinging and/or flexing. In Figures 4, 5a and 5b, the barb elements are thin rigid or flexible plates 26, whereas in Figure 6 the barb elements are flexible fibres or filaments 28. In each case, the outer surface of a subsea foundation defined by the barb elements transforms from a low-resistance profile as the foundation moves longitudinally in one direction to a high-resistance profile if the foundation is moved in the opposite longitudinal direction. Specifically, at least part of each barb element may be movable relative to the skirt 14 between retracted and deployed states.

The plates 26 shown on the suction pile 30 in Figure 4 are in longitudinally-overlapping rows like scales or tiles. Here, the plates 26 are staggered circumferentially between longitudinally-alternating rows. However, these features of overlap and stagger are optional; it would be possible for the plates 26 to be arranged or grouped differently. For example, isolated plates 26 could be distributed longitudinally and/or circumferentially over the outer surface of the skirt 14. In this respect, it will be noted that Figures 5a and 5b show plates 26A, 26B that do not overlap longitudinally.

In Figure 4, each plate 26 is hingably attached at its lower end to the outer surface of the skirt 14. The opposed upper free edge of each plate 26 is pivotable about that hinge attachment away from the skirt 14 to an acute angle with respect to the skirt 14. To illustrate this, the plates 26 on the right of the central longitudinal axis 16 in Figure 4 are shown pivoted to a greater angle relative to the underlying skirt 14 than the plates 26 to the left of the central longitudinal axis 16.

Thus, when the suction pile 30 is driven downwardly relative to the surrounding seabed soil 12 as shown on the left in Figure 4, the plates 26 pivot toward the skirt 14 to lie relatively flat or flush and so present a relatively smooth low-resistance outer surface to the seabed soil 12. Conversely, if the suction pile 28 is pulled up relative to the surrounding seabed soil 12 as shown on the right in Figure 4, the free edges of the plates 26 engage the seabed soil 12 and cause the plates 26 to pivot away the skirt 14. This leaves an upwardly-facing gap or opening between the skirt 14 and the upper free edge of each plate 26. The protruding, upwardly- and outwardly-facing free edges of the plates 26 thereby present a relatively rough high-resistance outer surface to the seabed soil 12.

Figures 5a and 5b show variant examples of the plates 26 and their interaction with the underlying skirt 14 of the suction pile 30. Figures 5a and 5b also show how barb elements such as plates 26 need not only move passively in response to upward movement of the suction pile 30, as described in relation to Figure 4, but can be driven actively in an outward direction relative to the suction pile 30 after its penetration into the seabed soil 12. In this respect, the outward movement of the plates 26 shown in Figure 5b is analogous to resilient recovery of the original shape of the barb formations 24A, 24B, 24C shown in Figure 3c.

In Figures 5a and 5b, one of the plates 26A shown uppermost in these drawings is a rigid or semi-rigid hinged flap or panel. The plate 26A has a hinge 32 along its bottom edge via which the plate 26A is attached to the skirt 14 of the suction pile 30. A bias element 34 acts between the plate 26A and the skirt 14 to urge the upper free edge of the plate 26A away from the skirt 14. The bias element 34 is exemplified here by a spring 34A, more specifically a leaf spring. However, other spring configurations or other resilient or expandable elements could be used instead.

Initially, as shown in Figure 5a, the upper free edge of the plate 26A is held against movement away from the skirt 14 by a latch 36 that acts between the plate 26A and the skirt 14. This minimises resistance to penetration of the pile 30 into the seabed soil 12. The latch 36 is selectively disengageable from the plate 26A to allow the plate 26A to pivot outwardly about the hinge 32 under the bias of the spring 34A as shown in Figure 5b and hence to deploy after the pile 30 has sufficiently penetrated the seabed soil 12.

A deployment system shown schematically in Figures 5a and 5b comprises a controller 38 that acts on a latch release 40. The deployment system could operate mechanically, electrically and/or hydraulically. Deployment of the plates 26A is suitably initiated remotely via a mechanical, electrical or hydraulic link, for example from the top of the suction pile 30. In this respect, the controller 38 could be responsive to a triggering signal from a human operator or other external control system, from a timer and/or from a sensor that senses parameters such as hydrostatic pressure or prolonged contact with the seabed soil 12.

The latch release 40 may release the latch 36 in various ways, for example mechanically or hydraulically by moving the latch 36 into a release position or by detaching or ejecting the latch 36 from the skirt 14. The latch release 40 may also release the latch 36 electrically, for example by heating the latch 36 to cause the latch 36 to weaken or disintegrate as shown. Alternatively, the latch 36 could dissolve or weaken with prolonged immersion in seawater or with exposure to or abrasion of the seabed soil 12, until the plate 26A is free to deploy under the bias of the spring 34A.

The other plate 26B shown lowermost in Figures 5a and 5b is a flexible or semi-rigid flap or panel that can be bent to hinge or pivot relative to the skirt 14 of the suction pile 30. A minor bottom portion of the plate 26B is fixed to the skirt 14 and a major top portion of the plate 26B can bend or pivot relative to that fixed bottom portion. A bias element 34 acting between the skirt 14 and the top portion of the plate 26B urges the upper free edge of the plate 26B away from the skirt 14 as shown in Figure 5b.

The bias element 34 is exemplified here by an expandable mass 34B, for example of a smart gel material, that is interposed between the skirt 14 and the top portion of the plate 26B. The expandable mass 34B adheres to the plate 26B and, when in a compact contracted state, holds the top portion of the plate 26B close to the skirt 14. On expansion, the expandable mass 34B forces the top portion of the plate 26B outwardly into the deployed position shown in Figure 5b.

The controller 38 of the deployment system shown schematically in Figures 5a and 5b acts on a triggering system 42 that is arranged to initiate expansion of the mass 34B by applying an appropriate stimulus. Expansion of the mass 34B may, for example, be triggered by heat, light or vibration emitted by the triggering system 42.

The expandable mass 34B shown in Figures 5a and 5b could be used in conjunction with the hinged plate 26A instead of the spring 34A. Conversely, a different bias element such as a spring 34A could be used in conjunction with the bendable plate 26B instead of the expandable mass 34B. Other bias elements are possible, such as elements made of shape memory materials. It may also be possible for the expandable mass 34B to be used without an outer plate 26 if, on expansion, the mass 34B assumes an appropriately tapered barb-like shape like the barb formations 24 shown in Figure 3c.

Turning finally to Figure 6, this shows a suction pile 44 of the invention in which substantially unidirectional flexible fibres or filaments 28 serve as barb elements. Whilst flexible, the filaments 28 have resilience and sufficient stiffness to maintain an upwardly acute orientation with respect to the skirt 14 of the pile 44. The filaments 28 may have enough stiffness to be self-supporting in that upwardly acute orientation or may rely on the support of adjacent filaments in a mass of such filaments.

Here, the filaments 28 are carried by a base web 46 that is exemplified by a sleeve wrapped around the pile 44. The filaments 28 could instead be fixed directly to the suction pile 44 or the base web 46 could be in one or more discrete patches that are applied to the suction pile 44.

Each filament 28 extends upwardly from a fixed root end to a free upper end. Thus, the upper free end portion of each filament 28 can bend or pivot away from the skirt 14 to an acute angle with respect to the skirt 14. To illustrate this, the filaments 28 on the right of the central longitudinal axis 16 in Figure 6 are shown lying at a greater angle relative to the underlying skirt 14 than the filaments 28 to the left of the central longitudinal axis 16.

Thus, when the suction pile 44 is driven downwardly relative to the surrounding seabed soil 12 as shown on the left in Figure 6, the filaments 28 bend toward the skirt 14 to lie relatively flat or flush and so present a relatively smooth low-resistance outer surface to the seabed soil 12. Conversely, if the suction pile 44 is pulled up relative to the surrounding seabed soil 12 as shown on the right in Figure 6, the free end portions of the filaments 28 protrude and engage the seabed soil 12 to bend away the skirt 14. The protruding, upwardly- and outwardly-facing free ends of the filaments 28 thereby present a relatively rough high-resistance outer surface to the seabed soil 12.

In function, the base web 46 carrying the filaments 28 is akin to a ski skin that is attachable to a ski to provide traction when travelling uphill. A ski skin comprises a directional fabric that allows the ski to glide forward but stops the ski from slipping backwards. Thus, the filaments 28 may be arranged like a directional pile or nap of a furry or velvety fabric. The filaments 28 will therefore be much more numerous than is shown schematically in Figure 6. The filaments 28 will also be closer to each other than is shown in Figure 6. Indeed, individual filaments 28 may be in contact with and supported by neighbouring filaments 28.

Many variations are possible within the inventive concept. For example, a base web need not only carry a mass of filaments but could instead carry a plurality of other barb elements such as plates. This allows multiple barb elements to be affixed to the foundation in a single convenient operation, which may involve overmoulding onto the foundation or attachment to the foundation.

Claims

1. An embeddable subsea foundation, comprising:

an elongate penetrating body having a soil-engaging surface configured for engagement with seabed soil; and

a directional profile extending across the soil-engaging surface, that profile being configured to aid penetration of the foundation into the seabed soil in a distal direction and then to resist movement of the foundation relative to the seabed soil in an opposed proximal direction.

2. The foundation of Claim 1, wherein the directional profile comprises a plurality of barb elements that protrude from, and converge in the distal direction with, the penetrating body.

3. The foundation of Claim 2, wherein at least part of each barb element is movable relative to the penetrating body.

4. The foundation of Claim 3, wherein the at least part of each barb element is movable toward the penetrating body in response to distal movement of the penetrating body relative to the seabed soil.

5. The foundation of Claim 3 or Claim 4, wherein the at least part of each barb element is movable away from the penetrating body in response to proximal movement of the penetrating body relative to the seabed soil.

6. The foundation of any of Claims 3 to 5, wherein each barb element is pivotable or bendable relative to the penetrating body.

7. The foundation of Claim 6, wherein a distal end of each barb element is attached to the penetrating body and a proximal end of each barb element is movable relative to the penetrating body.

8. The foundation of Claim 7, wherein the distal end of each barb element is attached to the penetrating body by a hinge.

9. The foundation of Claim 7 or Claim 8, further comprising a latch that is arranged to hold the proximal end of each barb element against movement away from the penetrating body.

10. The foundation of Claim 10, further comprising a latch release that is operable to enable movement of each barb element away from the penetrating body by releasing the latch.

11. The foundation of any of Claims 3 to 10, further comprising a bias element acting outwardly between the penetrating body and the at least part of each barb element.

12. The foundation of any of Claims 3 to 11, wherein each barb element comprises a plate with self-supporting rigidity.

13. The foundation of any of Claims 2 to 12, wherein barb elements of the plurality are spaced longitudinally along the penetrating body and overlap with each other.

14. The foundation of any of Claims 2 to 13, wherein a proximal portion of each barb element is spaced laterally from the penetrating body.

15. The foundation of any of Claims 3 to 14, wherein the barb elements are flexible filaments.

16. The foundation of Claim 14, wherein the directional profile comprises a nap of said filaments.

17. The foundation of any of Claims 3 to 14, wherein each barb element is expandable away from the penetrating body.

18. The foundation of Claim 17, wherein each barb element is resiliently expandable away from the penetrating body.

19. The foundation of Claim 17, wherein each barb element comprises an expandable mass whose expansion can be triggered by the application of a stimulus.

20. The foundation of Claim 19, further comprising a triggering system that is arranged to initiate expansion of the mass by applying said stimulus.

21. The foundation of any preceding claim, wherein the directional profile comprises a base web that is moulded onto or attached to the penetrating body.

22. A method of installing a subsea foundation, the method comprising:

advancing a penetrating body of the foundation in a distal direction to penetrate seabed soil; and

by interaction between the seabed soil and a directional profile on the penetrating body, applying substantially greater resistance to movement of the penetrating body in a proximal direction than in the distal direction.

23. The method of Claim 22, comprising engaging the seabed soil with barb elements that protrude from, and converge in the distal direction with, the penetrating body.

24. The method of Claim 23, comprising moving at least part of each barb element relative to the penetrating body.

25. The method of Claim 24, comprising moving the at least part of each barb element toward the penetrating body in response to movement of the penetrating body relative to the seabed soil in the distal direction.

26. The method of Claim 24 or Claim 25, comprising moving the at least part of each barb element away from the penetrating body in response to movement of the penetrating body relative to the seabed soil in the proximal direction.

27. The method of Claim 24 or Claim 25, comprising driving movement of the at least part of each barb element away from the penetrating body after penetrating the seabed soil.

28. The method of any of Claims 24 to 27, comprising expanding each barb element away from the penetrating body.

29. The method of Claim 28, comprising applying a stimulus to trigger the expansion of each barb element.

30. The method of any of Claims 24 to 29, comprising:

latching the at least part of each barb element against movement relative to the penetrating body; and

unlatching to free the at least part of each barb element for movement relative to the penetrating body.

31. The method of any of Claims 24 to 30, comprising extending the at least part of each barb element through seabed soil that was relatively disturbed by the distal advance of the penetrating body and into contact with seabed soil that was relatively undisturbed by the distal advance of the penetrating body.

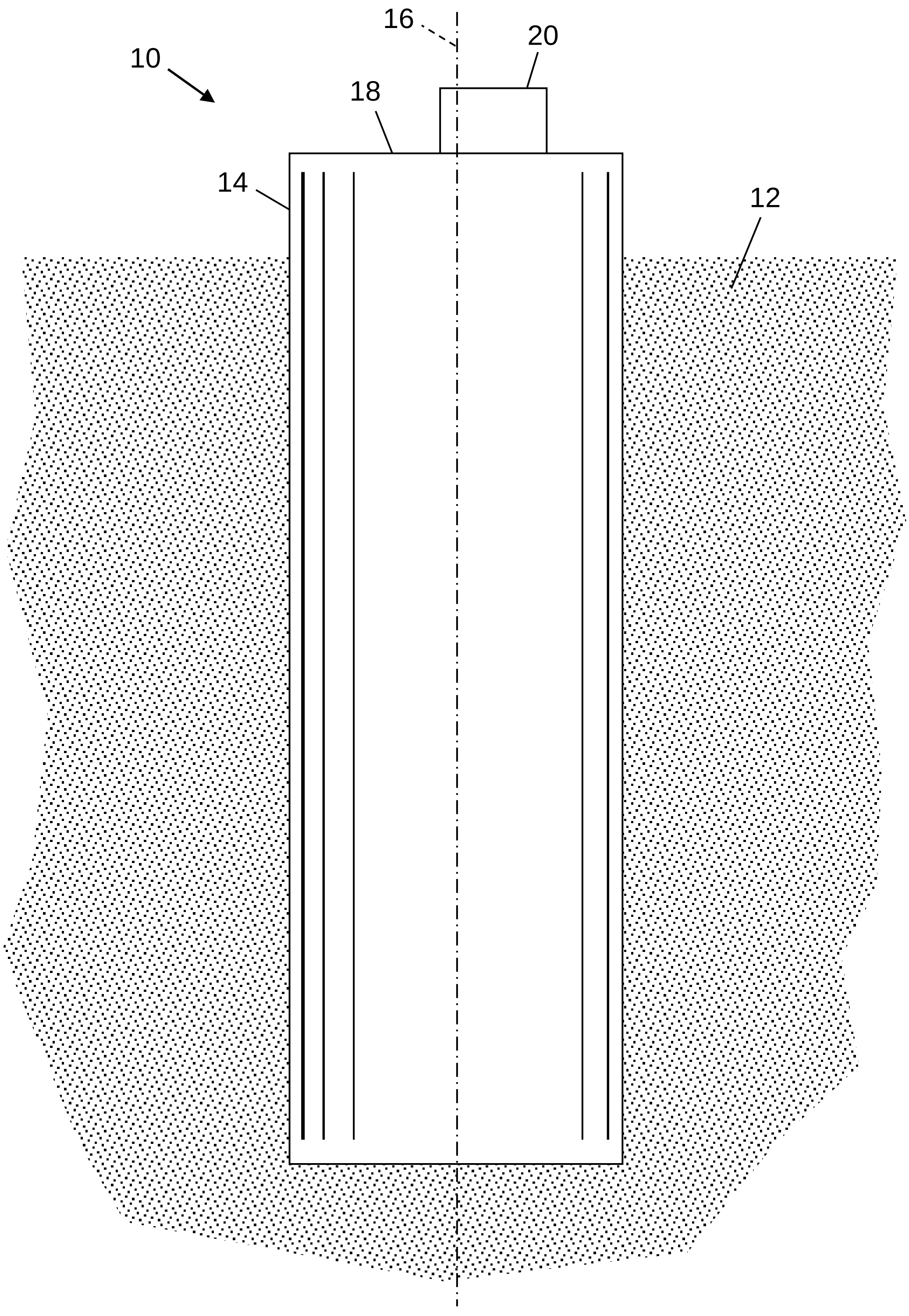


Figure 1

PRIOR ART

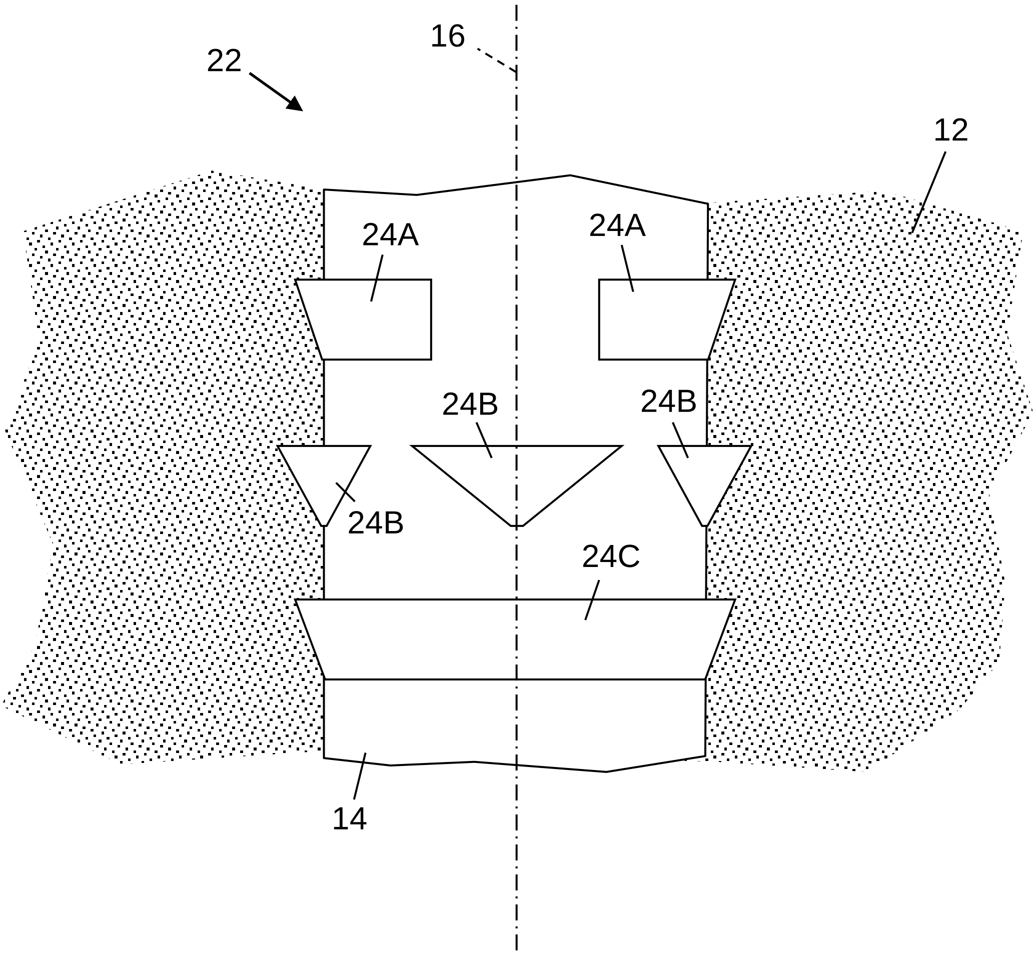


Figure 2

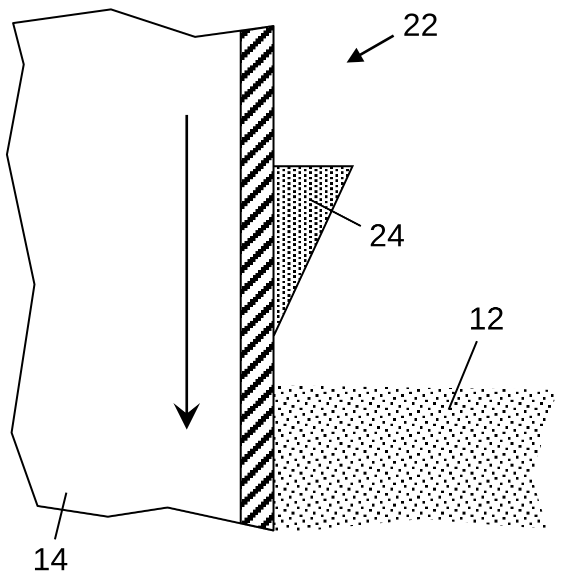


Figure 3a

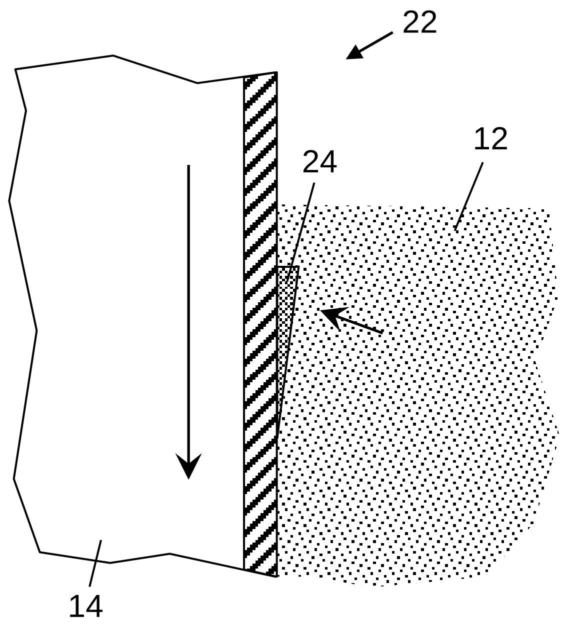


Figure 3b

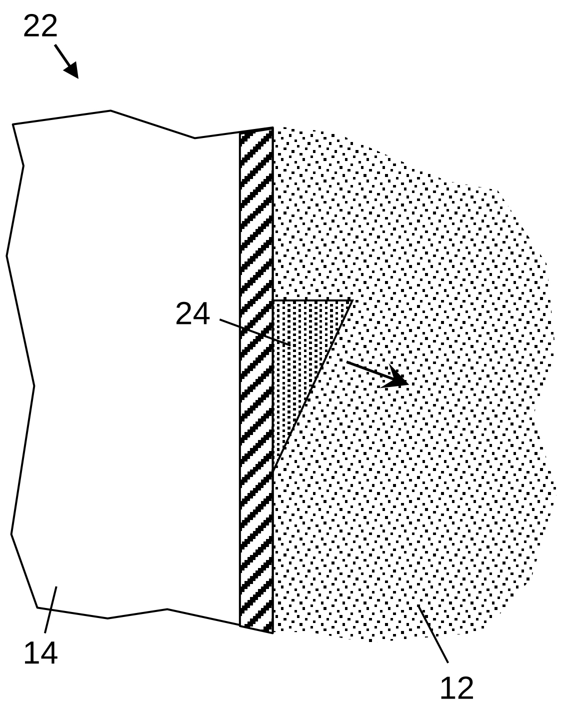


Figure 3c

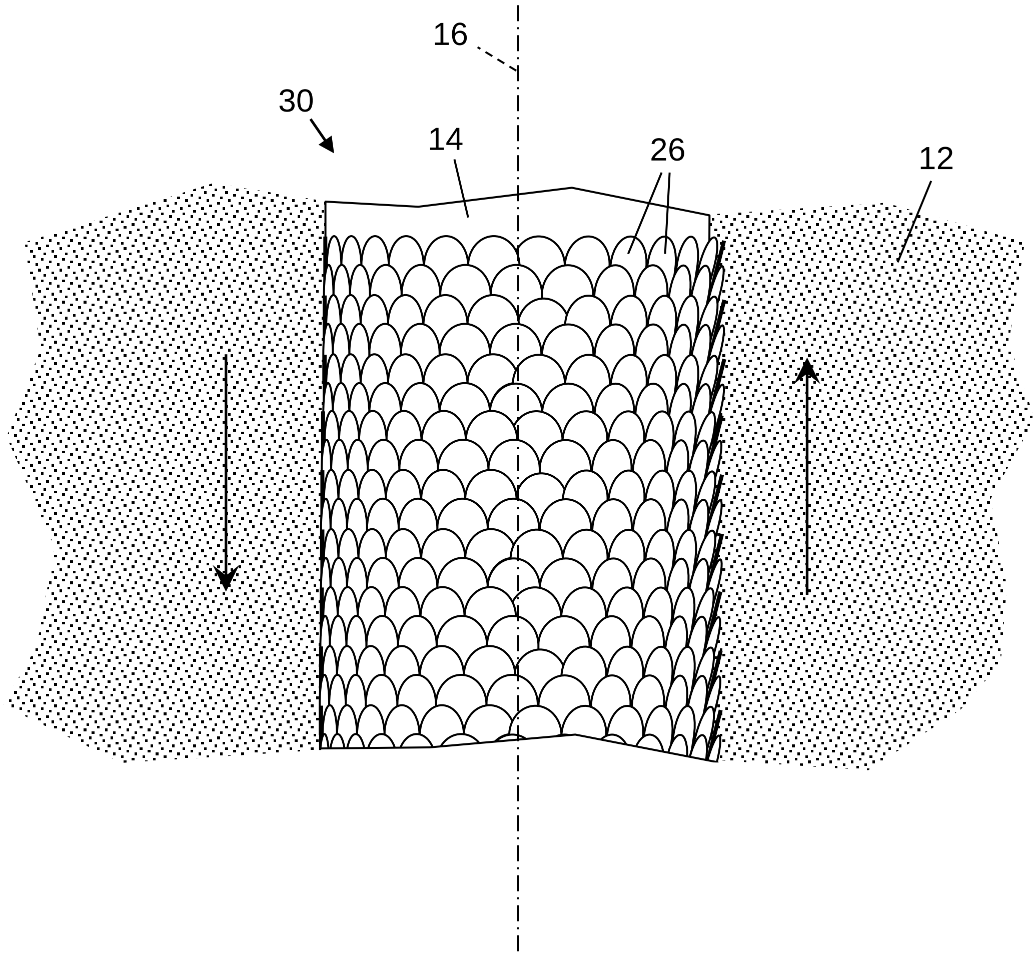


Figure 4

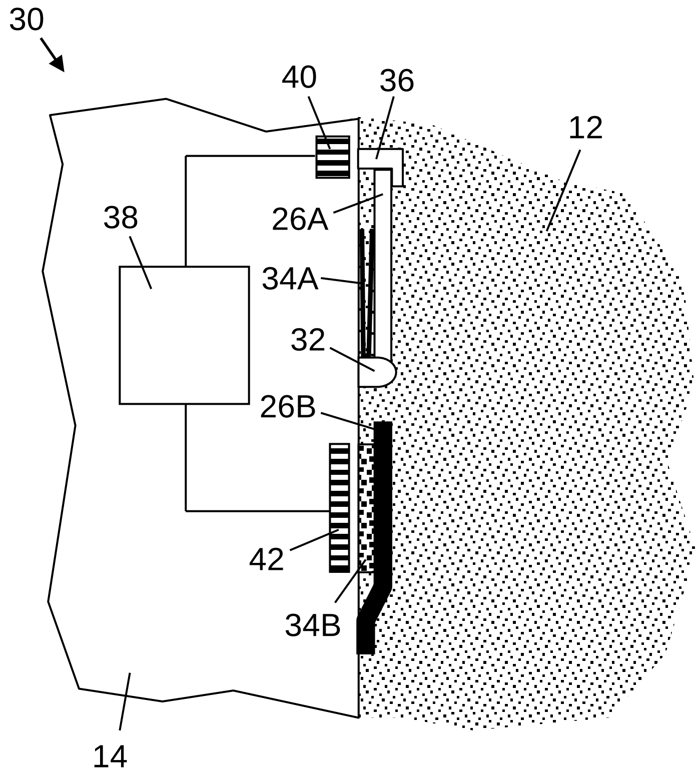


Figure 5a

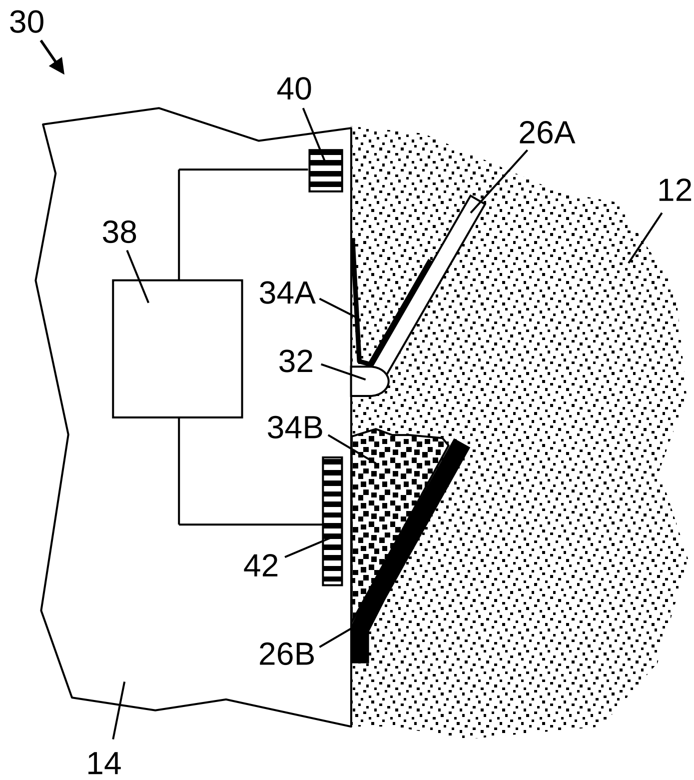


Figure 5b

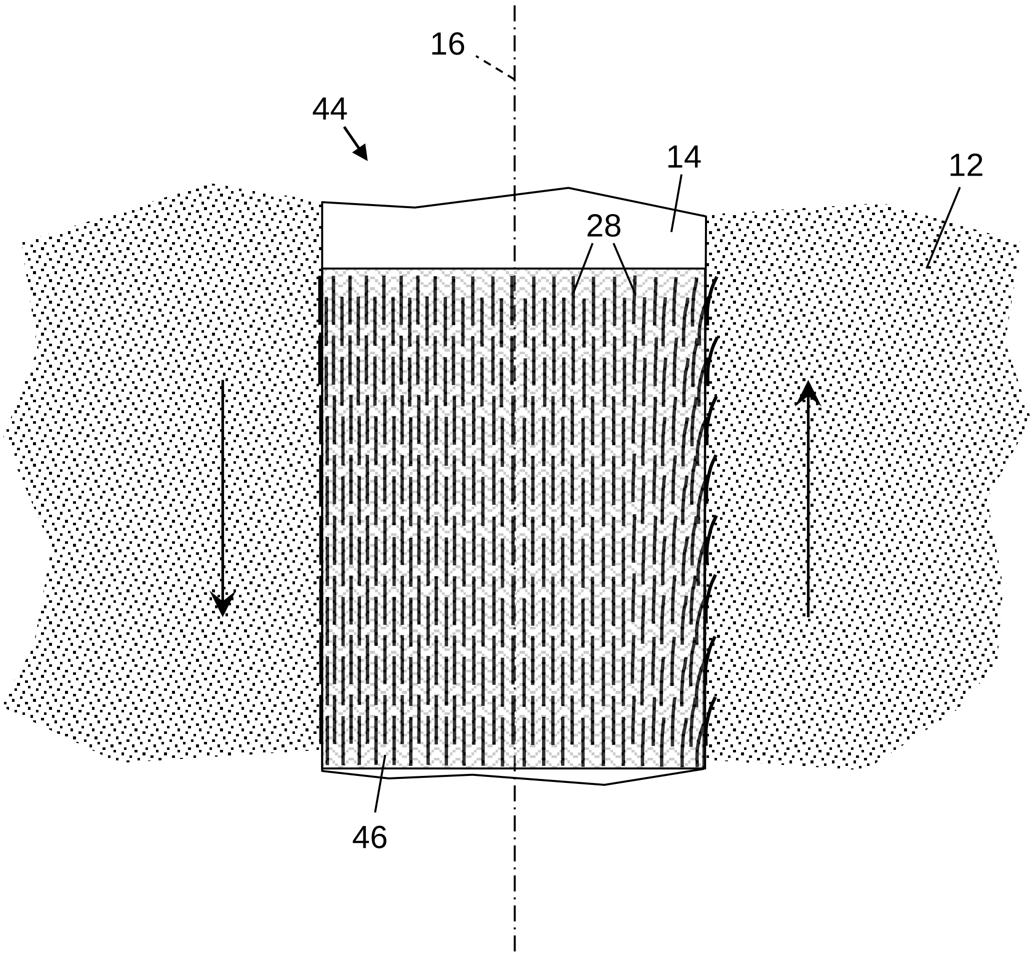


Figure 6