Wave Energy Scotland
Knowledge Capture Project
AWS Project No 15-007

Technology Description and Status
Self-drilled Pile System

Document Title:	Technology Description and Status – Self-drilled Pile System
Unique Document Reference:	15-010r4
Author:	A Hall, S Grey
Checked:	
Issue:	Revision 4
Date:	11 February 2016
Circulation:	WES

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Revision Details

Date	Revision	Comments	Issue by
04/09/2015	1	First issue	AWS
17/09/2015	2	Edited for general release	AWS
22/09/2015	3	Edit to incorporate WES comment	AWS
11/02/2016	4	Edit to incorporate WES comment	AWS

References

Doc Ref	Title	Author(s)	Issue / date
15-001r5	AWS Wave Power Development Experience	S. Grey et. al.	02/09/2015
15-012r2	Report on LCOE Sensitivity Modelling	S. Grey	11/02/2016
[R1]	WEC Technology Readiness and Performance Matrix – finding the best research technology development trajectory; International conference on Ocean Energy, 4th International Conference on Ocean Energy, Dublin	J. Weber et. al.	17/10/2012

Nomenclature & abbreviations

Name or acronym	Explanation
AWS	Archimedes Waveswing
AWS Ocean	AWS Ocean Energy Ltd
DNV	Det Norske Veritas
LCOE	Levelised cost of energy
M & E	Mechanical and electrical
MRCF	Marine Renewables Commercialisation Fund
PTO	Power take-off
R&D	Research & Development
ROV	Remotely Operated Vehicle
SDPS	Self-drilled Pile System
TPL	Technology performance level
TRL	Technology readiness level
WEC	Wave energy converter
WES	Wave Energy Scotland Limited

1 General

1.1 Background

This document has been produced in response to a brief by Wave Energy Scotland ("WES") to provide a report on the technology status of the Self-drilled Pile (SDPS) anchoring system.

This report is one of a suite of reports provided to WES and the reader is recommended to read AWS Ocean report 15-001 *AWS Wave Power Development Experience* to further understand the background to the development of the technology.

1.2 Purpose of the report

The purpose of this report is to provide a description of the current design for the SDPS and to provide a TRL assessment of the major sub-systems, together with an assessment of AWS Ocean Energy's confidence of achieving TRL 9 for that system. The report also provides an assessment of the overall TPL of the system.

This information is intended to provide WES with a snap-shot of the current state-of-the-art in relation to the SDPS technology.

1.3 Structure of this report

This report is structured as follows:

- Section 2 provides a general description of the technology and its operation;
- Section 3 provides a sub-system breakdown of the technology, a gap analysis and high-level TRL assessment;
- Section 4 provides a technology assessment in line with DNV RP-A203 and a subjective view on the development challenges for the system;
- Section 5 addresses the operational aspects of construction, deployment operation and maintenance of the device;
- Section 6 provides a TPL assessment of the system;
- Section 7 addresses the challenges to achieving a commercial system;
- Section 8 provides an outline technology development plan;

It is hoped that this structure will provide a progressive level of detail such that the reader can easily access the information required.

2 Device background – the Self-drilled Pile System

2.1 Description

The Self-drilled Pile System (SDPS) provides a means of installing a subsea piled anchor through the use of a drilling rig remote from its support vessel connected only by an umbilical. By removing the fixed vessel-drill link a wider weather window may be used along with a more readily available (and consequently cheaper) vessel. The concept was conceived to solve a mooring/anchoring problem which was identified during development of the WaveSwing Mk II device. Devices such as this which encounter uplift (vertically loading the anchor) were, with existing technology, forced to use either very large gravity anchors or a piled system requiring a large jack up vessel. Both these methods can involve large, expensive vessels with limited availability.

The SDPS comprises a number of sub systems, many of which are already in use in the offshore sector:

- Base frame
- Piles
- Drill mechanism
- Spoil removal system
- Hydraulic power unit
- Grouting system
- Vessel
- Control system

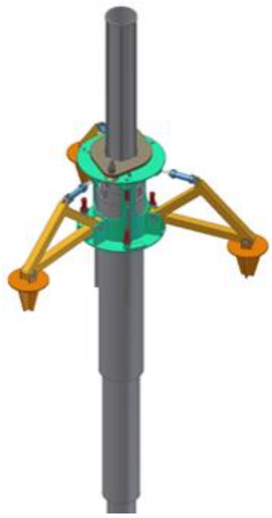

Figure 1: Self-drilled pile assembly

2.1.1 Base frame

The base frame (Figure 2) is a temporary seabed pile support with hydraulically adjustable legs used to level the device. The feet may be either spud cans or mud-mats depending on seabed conditions. In some conditions supplementary fixings such as pin piles may be required to secure the frame and resist drilling torques. The base is equipped with stabbing guides and guide-wires for locating further equipment and piles on to the base. Slots are provided into which radial fins on the pile locate to guide the pile and transfer drilling torque from the pile to the base. Once in position, the first pile can be tripped down the guide-wires and inserted into the base.

The base frame is the only truly bespoke sub-system and requires substantial capital investment. Significant design and development work will be required to ensure satisfactory operation.

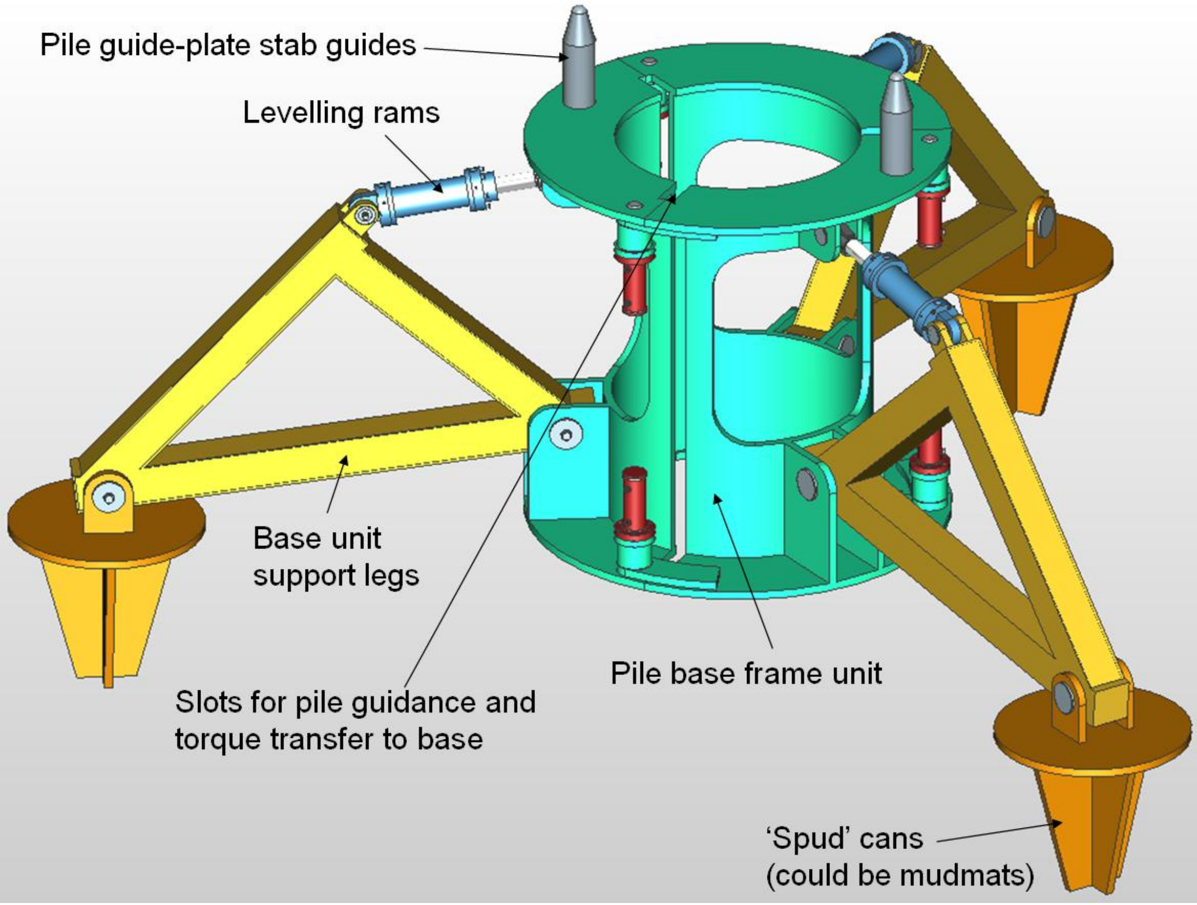

Figure 2: Base frame assembly

2.1.2 Piles

The piles (Figure 3) are simple tubular steel components with radial fins welded to the outside to provide guidance and torque transfer. The fins are on both the outside and inside of the pile so inner piles can transfer the torque to the outer piles. The required pile size is determined by the forces imparted by the device which is to be anchored. In the case of vertically loaded piles the resistance to uplift increases with increasing surface area in contact with the bedrock - to withstand high loads a pile of larger diameter or length is required. As diameter is limited by drills which are available, increasing the length is the easier solution however soon the pile becomes difficult to handle, for example:

If we consider a pile of diameter 0.8 m, and vertical load of 600 tonnes then the pile length required is around 18 m. Such a length of pile could not be ably supported by the base frame which is about 3 m tall. As such, the total anchor resistance is developed by sequentially drilling and placing longer piles inside the previous pile.

By using concentric piles of shorter length the SDPS system minimises the required size of the base frame. The resistance to vertical loading can be improved by welding on axial rings known as grout rings.

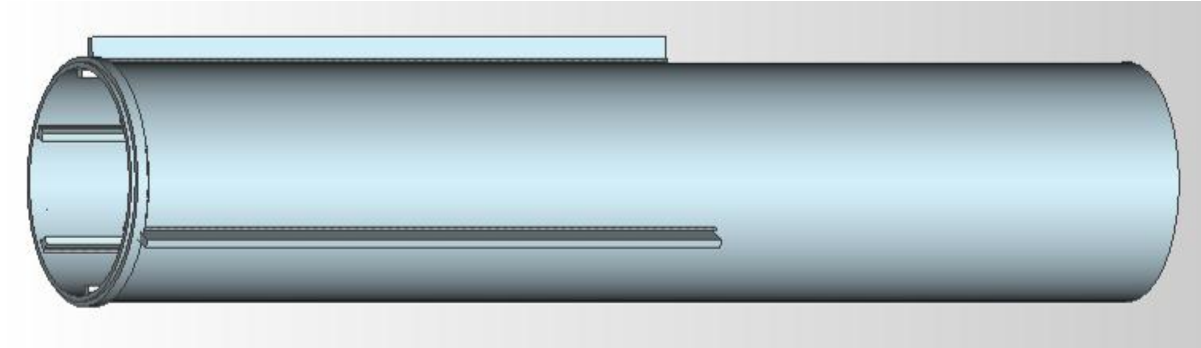

Figure 3: Pile with torque fins

2.1.3 Drill mechanism

The drill mechanism is located at the bottom of the pile being drilled. The drill motor is likely packaged into an enclosure incorporating hydraulic locks (either locking pins or an inflatable tyre like locking band) to fix the drill motor to the bottom of the pile. Figure 4 shows a schematic of the drill mechanism. The drilling torque reaction is transferred to the pile and in turn the base-frame into the seabed. As such, it is preferable to minimise the drilling torque. This can be achieved by either providing a counter-rotating drill bit (which is a complex solution) or alternatively by utilising impact drilling which is lower torque. This has the further advantage that less weight-on-bit is required for a given drill rate.

As the drilling package is to be withdrawn up the pile following completion of drilling, the drill bit must incorporate under-reaming cutters which can be retracted into the drill bit to allow passage up the pile. The greatest challenge is packaging a drill motor of sufficient power inside the pile and reacting the torque back to the frame successfully.

2.1.4 Spoil removal system

Drilling a socket for a 1 m x 30 m pile necessitates the removal of around 50 tonnes of spoil to ensure the drill bit head is kept clear of debris and that drilling progresses at a satisfactory rate. Reverse circulation requires high flow velocities to lift the spoil (the flow area is usually inside the drill string thus velocities are high for a given flow rate). Therefore, some restriction in area inside the pile may be required to promote spoil removal. Although there are challenges to be solved this is well understood and routinely applied technology.

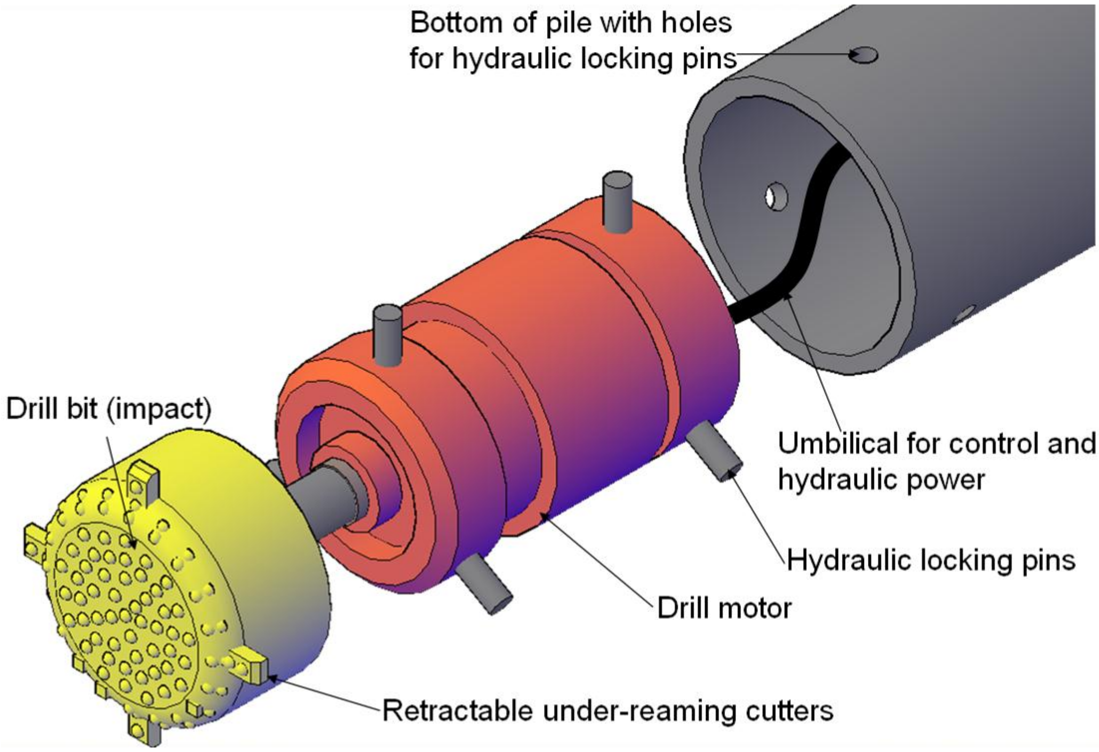

Figure 4: Drill unit schematic

2.1.5 Hydraulic power unit

The hydraulic drilling head may require around 200 kW of hydraulic power to operate. This is supplied by a hydraulic power unit on the vessel with power transmitted via umbilical hose. These are "off-the-shelf" components commonly available for hire.

2.1.6 Grout system

The annulus between pile and bedrock must be grouted to stabilise the pile and develop the vertical load resistance. Grouting piles and/or casings is a frequent and well understood exercise both off-shore and on-shore. It is possible that equipment could be hired. Grout plugs are required to seal off the bottom of the pile and ensure that the grout does not get mixed with contaminants or washed out by seawater.

2.1.7 Vessel

The piling system is to be deployed and controlled from a surface vessel. The intent is that the vessel should be low cost. In order to achieve this, the components of the SDPS must be as light as possible as vessel costs increase exponentially with lift capability. The vessel should be able to spread its own moorings and be able to hold station in moderately energetic wave and tidal conditions.

2.1.8 Control system

As with any subsea operation the control of processes underwater is challenging. Provisions must be made for interface and control of all actuators, transducers and mechanisms. ROVs, possibly with CCTV cameras, may provide useful observation capability and manipulator grips may be required to actuate controls or mechanisms subsea.

2.2 Advances from the state of the art

The most common anchoring solutions for marine energy devices are gravity anchors or piled anchors installed using a jack-up barge. When large uplift forces are encountered, gravity anchors can reach masses of 100 tonnes or higher. A gravity anchor of this magnitude is highly expensive for both raw materials and deployment and although plausible for a prototype device it cannot be justified for farm scale deployment. Jack up barges can be very expensive, often with limited availability and with operating restrictions relating to environmental conditions which give only limited weather windows at good marine energy locations.

2.3 Operating principles

As described previously, the SDPS is intended to reduce the cost of anchors requiring resistance to uplift by removing the requirement of a jack up barge or very large gravity anchor.

The pile installation sequence is shown in Figure 5 and is described as follows:

- The base frame is lowered to the sea bed and levelled using remote-controlled jacks;
- The first pile with drill head pre-mounted is lowered down guide wires and located into the base frame;
- The first pile is drilled to depth following which the under-reamer on the drill head is retracted and the drill head recovered;
- The second smaller diameter pile with drill unit pre-fitted (with smaller under-reaming head) is lowered down guide wires and located into the first pile;
- The second pile is drilled as per the first pile, following which the drill unit is removed again;
- Process is repeated for a third pile if required;
- With the pile sections installed, the pile is grouted into place and the base frame recovered to the surface.

The operation makes use of many standard sub-sea techniques but will require the development of specific equipment and methods of this application, particularly where tidal streams are high.

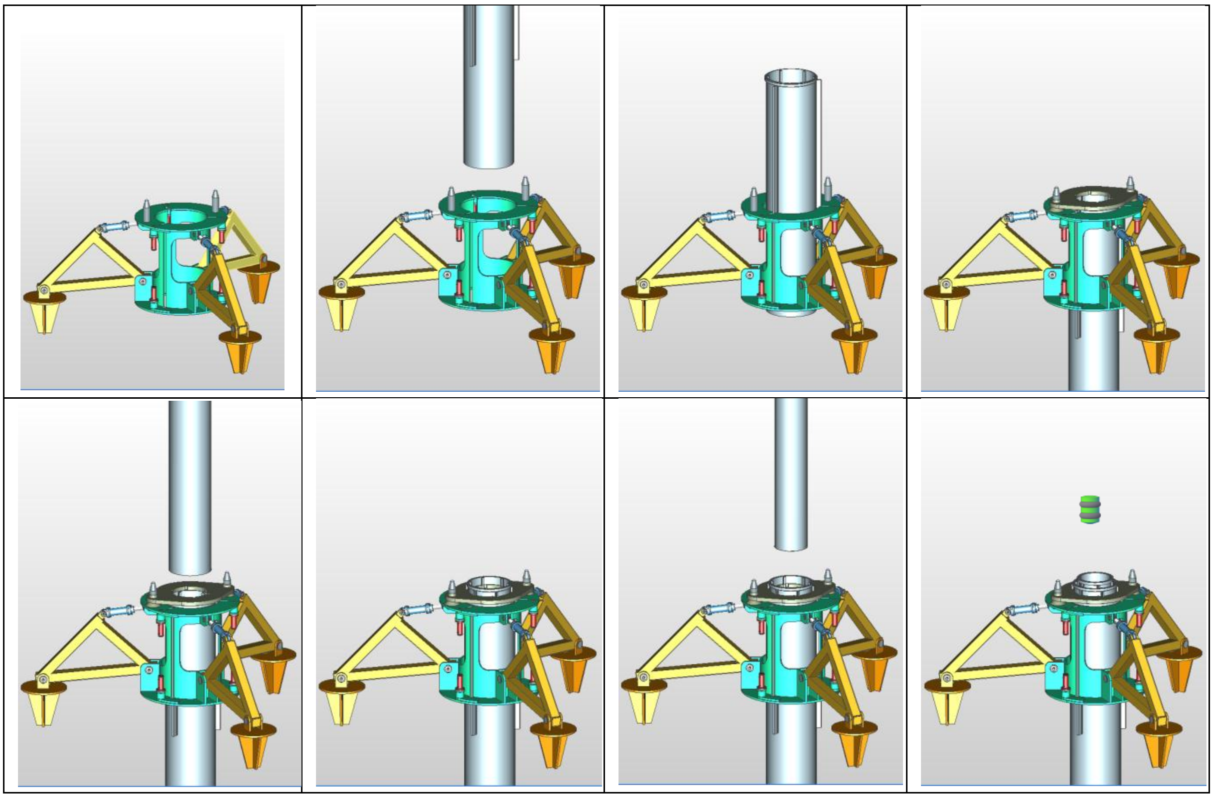

Figure 5: Pile installation sequence (left to right)

2.4 Unique features of the SDPS

In order for the SDPS to become a commercially viable process with patentable IP, it must contain a number of unique selling points. As it is currently embodied, SDPS has, or intends to have, the following USPs.

- Anchor uplift resistance
- Utilises light-lift, cost effective vessel
- Anchor solution attracts minimal wave and current loadings (unlike massive gravity anchor)
- Cost effective
- Can drill mooring in deep water without off-shore jack-up drill rig
- Can drill mooring in shallow water without civil jack-up (e.g. SeaCore)

The cost effectiveness results from the avoidance of the use of jack-ups. Even if a near-shore civil jack-up was commercially viable they can operate in a maximum of about 30 m water depth. Therefore, being able to operate in greater water depths, where the incident wave energy is higher, is a significant advantage of the SDPS.

In terms of unique patentable features a patent application has been filed covering the entire system. Other patents in the field have been granted and are described below

2.5 Overview of intellectual property

2.5.1 AWS Ocean Patents

WO2010015799: ***Pile system –*** *priority date 2008-08-06*
AWS Ocean hold a patent on the pile system described in WO2010015799 – a base frame which is self levelling and which can install a number of concentric piles using an under-reaming drill and torque transfer from pile to base frame. A schematic of the system is shown in Figure 6.

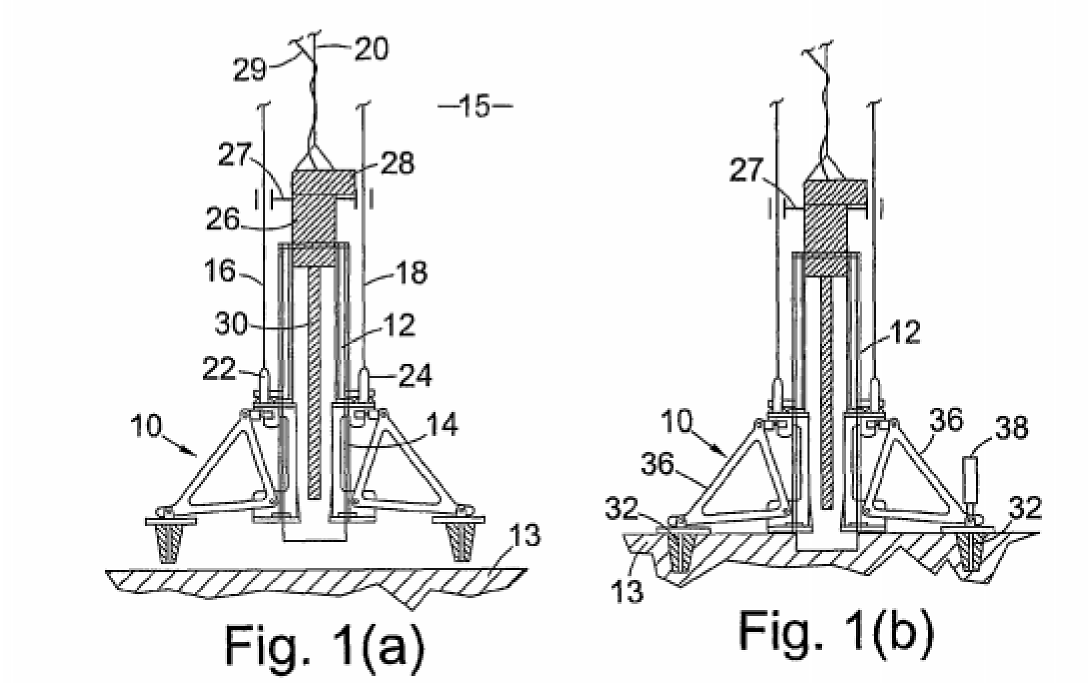

Figure 6 - Schematic of WO2010015799

2.5.2 Known competition

Anchoring and mooring of vessels is a well understood and developed field. Anchoring and mooring of marine energy convertors less so, and it could be argued, is a more challenging field. Some companies describe remotely drilled piled anchors, particularly:

Bauer Renewables:
Bauer developed the Bauer Seabed Drill (BSD3000) for the installation of a Voith Tidal turbine in the summer of 2011. A large DP3 vessel, North Sea Giant, was used for the installation work. A drill is lowered through the base frame then removed before a pile is placed and grouted. The base is recovered to the vessel.

Bauer Flydrill System:
A drill used to drill through the hollow centre of hammered piles which have become stuck due to rock. Undercuts the pile to allow it to be lowered. Requires a jack up.

Ballast Nedam:
List their capabilities as including a drill through pile system which uses a large pile handling tower on a barge. Limited detail is discussed.

Blade Offshore Remote Drilling:
A subsea drilled anchor pile, only removes an annulus of rock leaving the rock core behind. The bottom edge of the pile appears to have cutting teeth and the whole pile is rotated to cut through the rock.

McLaughlin & Harvey:
Claim to have carried out Scottish Government/Carbon Trust/MRCF funded work on remotely drilled piles. Suggested links to SeaRoc, Scot Renewables & RPS. Very little technical detail disclosed however patent application contains details on tension anchor.

2.5.3 Existing Patents

Many marine energy companies do not at present explicitly describe their proposed anchoring solutions for their devices. However, some published IP does exist in the field. The most relevant patents are (*note: all figures referred to in this section are shown in Appendix C*):

Number	GB2431189
Title	**Installation of underwater anchorages**
Holder	Tidal Generation Ltd
Overview	A cost effective means of securing a load bearing structure to the sea bed from a surface vessel using umbilicals only. The drilling operation uses the load bearing structure as a drilling template. The drilling assembly can be recovered to the surface in a single light-lift operation. Figure 9 shows a schematic of the proposed device in operation.
Comment	Again, a very similar premise to the SDPS and may result in IP conflict however uses the load bearing structure to support the piles rather than a separate base frame

Number	GB2448358
Title	**Installation of underwater ground anchorages**
Holder	Tidal Generation Ltd
Overview	A means of securing load bearing structures to the seabed in fast flowing water and a range of ground conditions. Two or more pile installation rigs are pre-installed on the load bearing structure to be affixed then deployed by vessel connected by umbilicals. Installation gear recovered to vessel later. Figure 10 shows an overview schematic of the patent.
Comment	Again, a very similar premise to the SDPS and may result in IP conflict however uses the load bearing structure to support the piles rather than a separate base frame.

Number	GB2488839
Title	**A system and method for the installations of underwater foundations**
Holder	McLaughlin & Harvey Ltd
Overview	Remote drilling apparatus for installation of tension anchor(s) which can be operated in deep water. Figure 11 shows an overview schematic of the patent.
Comment	The patent seems to refer to a tension anchor rather than a piled system. This may be different enough to avoid conflict

Number	GB2460172
Title	**Installation of a pile in the seabed using a guide structure**
Holder	Marine Current Turbines Ltd
Overview	Remote drilling apparatus for installation of tension anchor(s) which can be operated in deep water. Figure 12 shows an overview schematic of the patent
Comment	Very similar except all references include the surface piercing element to the guide frame/installation jig.

Number	EP2562310
Title	**Submarine drilling assembly and method for producing a borehole in a sea floor**
Holder	Bauer Maschinen GmBH
Overview	Remote drilling apparatus for installation of pile. Relates to equipment used for installation of Voith Tidal monopole. Figure 13 shows an overview schematic of the patent.
Comment	Similar looking rig however requires removal of drill before pile is inserted.

Number	EP2322724
Title	**Submarine drilling assembly and method for inserting a tubular foundation element into the sea floor**
Holder	Bauer Maschinen GmBH
Overview	Remote drilling apparatus for installation of pile or piles. Uses an installation frame to support pile(s) with drill fitted. Once pile is installed drill is retracted through pile and lifted away with installation frame. Figure 14 shows an overview schematic of the patent.
Comment	More similarities than the other Bauer patent, may result in IP conflict.

In summary, IP exists in the vague field of “self-installed anchors” with which there may be some conflict with SDPS. However, the patents described use a permanent anchoring structure as part of the installation process whereas SDPS leaves just a pile when the process is completed. As such, it could be argued that SDPS contains novel IP and a patent may well be grantable.

Additionally, “Blade Offshore Services Ltd” are the applicant in a number of self-drilling anchor patents which utilise an annular drill which does not remove the rock core.
WO2014198607 “Anchor device and drilling assembly incorporating such anchor member “,
EP2299006 “Method of attaching a submerged structure to a floor of a body of water” &
GB2485935 “Method, apparatus and system for attaching an anchor member to a floor of a body of water”

2.5.4 Withdrawn/out of date Patents

A number of patents are either time expired or had their application withdrawn before being issued. These do not provide obstacles to use of the IP but do form part of the prior art and may affect the ability to patent an idea. The most relevant patents are (*note: all figures referred to in this section are shown in Appendix C*):

Number	GB2436320
Title	**Deep water remote drilled anchoring system**
Holder	John Richard Carew Armstrong
Overview	A vessel or equipment (could be marine renewable device) anchor which is lowered to the sea bed and drills and fixes itself in place by remote instruction (surface or shore). A schematic of the system is shown in Figure 15. It compromises a hexagonal frame with drill bits in each foot. The drilling mechanism revolves to drill down each bit in turn. Thereafter, the bit is grouted into the seabed and forms a rock anchor to the frame.
Comment	The premise of this system is similar to that of the SDPS. ***There is no IP conflict between the two as this patent application was terminated before it was granted***

Number	GB1249548
Title	**Apparatus for providing an under-water anchorage system on a firm or rocky sea bottom**
Holder	IHC Holland NV
Overview	Remote casing drilling apparatus which can be operated in deep water. Drills two or three casings attached by cross-beams to which anchor chain is attached. Figure 16 shows an overview schematic of the patent.
Comment	This patent was filed in 1968 and has hence expired. It is unclear if this method ever made the step into production/operation. Seems quite complex.

3 System break-down and gap analysis

3.1 System breakdown

A system breakdown has been undertaken for the Self-drilled Pile System in order to allow subsequent analysis of technology maturity and potential gaps. This breakdown is presented below in Figure 7 and further explanation is as follows:

- The major systems have been grouped by physical function and/or major assembly;
- Operations have been included as non-system elements which are nonetheless important from the perspective of technology development
- Numerical modelling and technology qualification activities have also been included as non-system elements as these are also important to the overall development of the technology
- System and sub-system elements have been colour-coded to represent the level of maturity. Further explanation of the colours is as follows:

Solution available (green)	A solution has been identified using existing technology and what remains is to carry out the detailed engineering design;
Solution identified (blue)	A solution has been identified however technical feasibility has not yet been finally confirmed;
Options identified (orange)	Options for potential solutions have been identified but not yet down-selected to a preferred option;
New tech required (red)	Solution not yet identified. New technology may be required to enable solution;

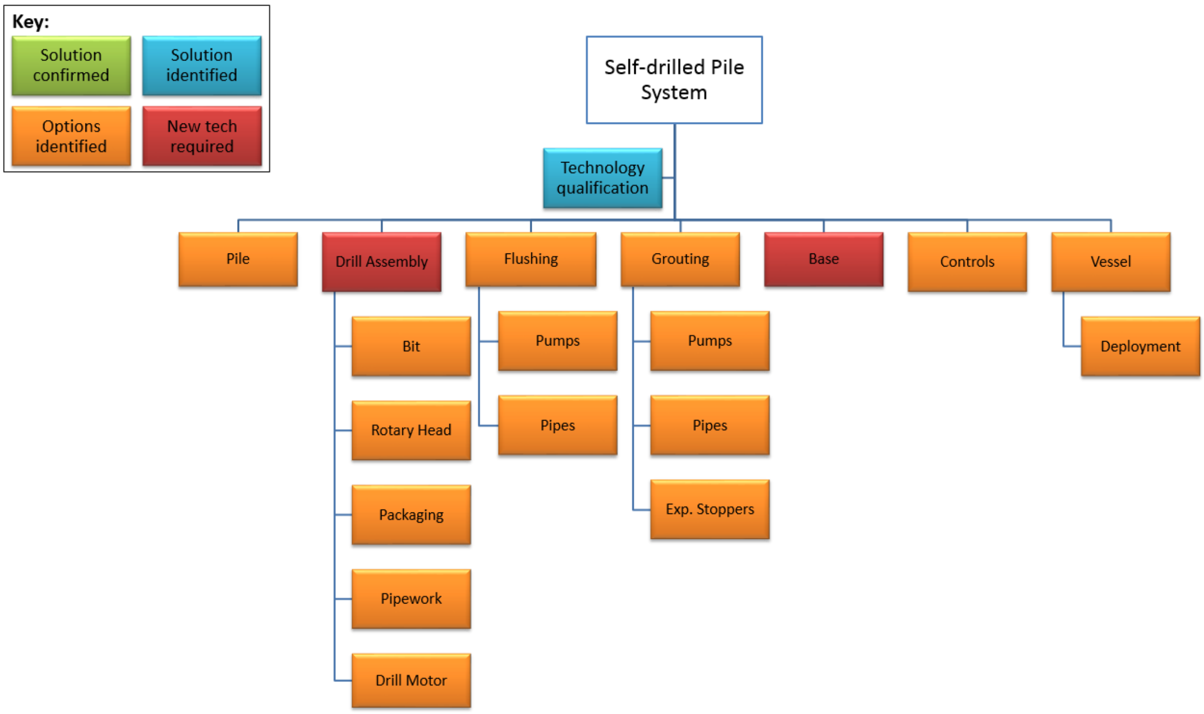

Figure 7 - System breakdown and gap analysis

3.2 Gap analysis summary

The Self-drilled Pile System includes a mixture of components which have operated successfully in subsea drilling environment and components/sub-systems which involve significant advancements to technologies. Whilst it promises an opportunity to reduce the cost of moorings and anchors, the limited development means potential cost savings are still unclear.

Further details regarding the development status of the various sub-systems is provided in Section 4.

3.3 TRL assessment

A TRL assessment has been conducted for each of the sub-systems, together with an assessment of the likely difficulty in reaching TRL 9. Some systems have been down-rated to TRL 4 due to the fact they have not yet been demonstrated as part of the SDPS system (e.g. drill motors & grouting pumps which are commonly in service but not tested in this application, hence TRL4).

The TRL scale used is set out in Appendix **B**.

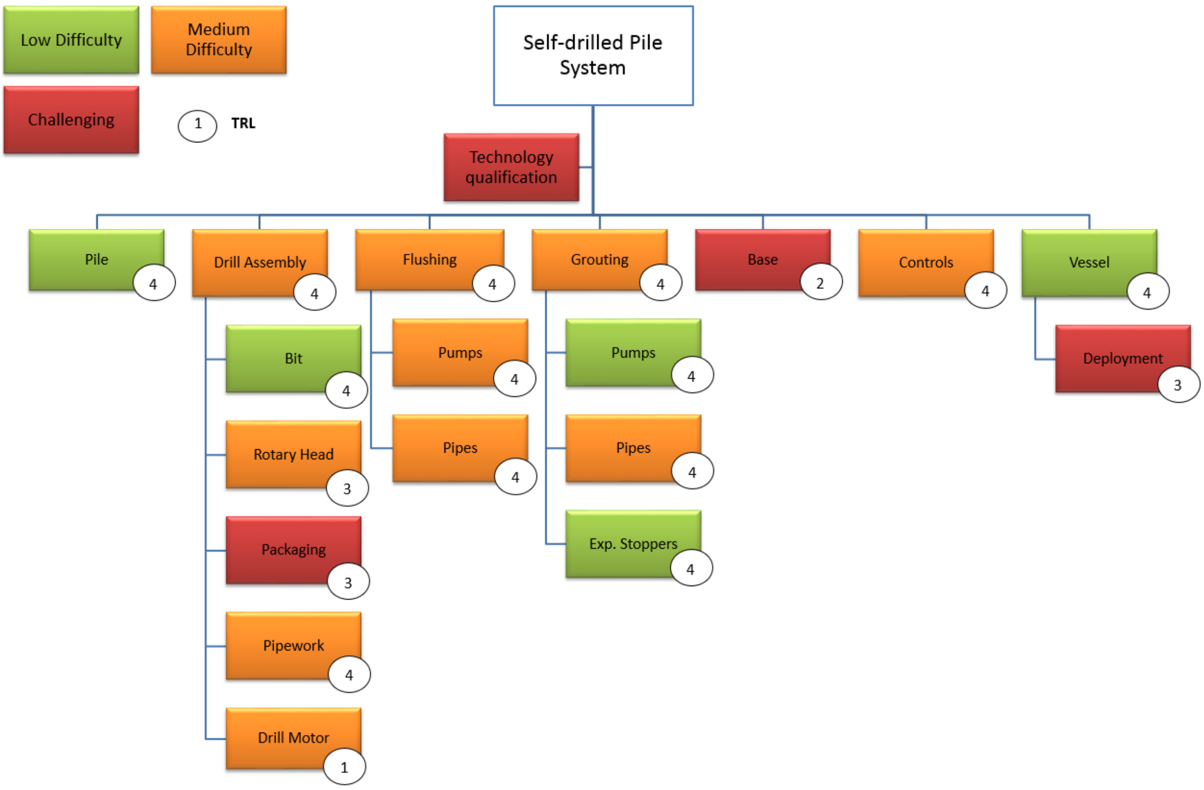

Figure 8 - Sub-system TRL assessment

4 Sub-system development status

The DNV recommended practice for Qualification of New Technology (DNV-RP-A203) is used to categorise the various sub-systems of the device and to help develop a technology qualification plan. The following table is used as an aid in the categorisation.

Application Area	**Degree of novelty of technology**		
	Proven	Limited Field History	New or Unproven
Known	1	2	3
Limited Knowledge	2	3	4
New	3	4	4

This categorisation indicates the following:

1) No new technical uncertainties (proven technology).
2) New technical uncertainties.
3) New technical challenges.
4) Demanding new technical challenges.

Many of the technologies and/or systems proposed for use in the SDPS have already been developed for use in other applications, but the use in a wave energy converter is novel. More details and justification for the category assigned to each of the sub-systems is given in the following sections.

4.1 Pile

4.1.1 Development status

Initial concept design has been created based on standard driven pile technology but now including the axial fins to interlock with other piles.

4.1.2 Technology categorisation

Category **2** – Piles are proven technology for subsea anchoring, new application is segmented design and torque transfer during installation.

4.1.3 Confidence levels

Piles are established technology for seabed anchoring. Accordingly, confidence is high that a viable solution can be engineered.

4.1.4 Development challenges

Unknowns within the design are:

- Torque transfer from pile to base & prevention of jamming
- Load transfer between pile sections

4.2 Drill Assembly

4.2.1 Development status

No detailed development work has been carried out on drill development. An initial review of commercially available drilling solutions has been carried out.

4.2.2 Technology categorisation

Category **2** – Subsea drills are in common use, including some which are available for drilling inside piles.

4.2.3 Confidence levels

Similar technology has been used commercially. Accordingly, confidence is high that a viable solution can be engineered.

4.2.4 Development challenges

Unknowns within the design are:

- Restraint of drill within pile (torque transfer/axial position)
- Packaging of drill with sufficient power within space restrictions
- Cost minimisation to keep cost of pile installation low.

4.3 Flushing (Spoil removal system)

4.3.1 Development status

No detailed development work has been a carried out. Potential solutions were identified in an initial review (air lift/Archimedes screw/recirculation).

4.3.2 Technology categorisation

Category **2** – Existing technology in new application which may have some constraints which require modification of the existing solution.

4.3.3 Confidence levels

Whilst there is a novel element to the application, spoil removal systems are in common use in the offshore industry. Accordingly, confidence is high that a viable solution can be engineered.

4.3.4 Development challenges

Unknowns within the design are:

- Constraints within the pile/drill layout which restricts flow path for spoil removal
- Required material flow rate and flow velocities for spoil removal
- Size of debris particles

4.4 Grout system

4.4.1 Development status

Grout systems are commonplace both in onshore construction and in sub-sea drilling. The specific components required for this application have not yet been developed however.

4.4.2 Technology categorisation

Category **1** – Commonly used technology (grouting of pile) in existing application (subsea).

4.4.3 Confidence levels

Grout systems are commonly used for subsea piles. It may be possible to hire a system. Accordingly, confidence is high that a viable solution can be engineered.

4.4.4 Development challenges

Unknowns within the design are:

- Design of grout plug to prevent leakage/contamination
- Integration of grout system with pile & base unit

4.5 Base

4.5.1 Development status

Initial concept design has been created.

4.5.2 Technology categorisation

Category **4** – New design with new features used in a challenging new application.

4.5.3 Confidence levels

Whilst the design and application are new, similar technology has been used successfully in offshore oil & gas developments. Accordingly, confidence is high that a viable solution can be engineered.

4.5.4 Development challenges

Unknowns within the design are:

- Keeping the cost low enough to provide a saving on proven methods;
- Preventing piles from jamming in base (torque transfer);
- Providing a stable base for drilling;

4.6 Control system

4.6.1 Development status

No work has been carried out on a control system.

4.6.2 Technology categorisation

Category **2** – Existing technology in novel (but similar to existing) application.

4.6.3 Confidence levels

Whilst the application is a new one, control systems for subsea operations and processes are common. Accordingly, confidence is high that a viable solution can be engineered.

4.6.4 Development challenges

Unknowns within the design are:

- Verification of successful grouting & pile deployment (limited potential for visual confirmation)

4.7 Vessel

4.7.1 Development status

No development work has been carried out.

4.7.2 Technology categorisation

Category **1** – Existing technology in known application.

4.7.3 Confidence levels

The SDPS will be designed for deployment from a typical commercially available vessel. Accordingly, it is highly likely that a viable solution can be engineered.

4.7.4 Development challenges

Unknowns within the design are:

- Minimising mass of system to minimise the lifting capability required;
- Suitable station keeping ability – dynamic positioning/spreading of own anchors;

5 Operation & maintenance

Maintenance of the SDPS had not been considered in detail, however as the device is used for short periods of time sub-sea and then recovered, it is expected that all maintenance will be carried out onshore or with the equipment recovered to the deck of a vessel.

6 TPL Assessment

A TPL assessment is not applicable for the SDPS as it forms only a portion of the mooring sub-system.

7 Challenges to achieving commercial solution

7.1 General comment

Little development work has been carried out on design and costing of the SDPS. An initial costing was carried out in 2008 and a review of AWS Ocean work by external consultants concluded that further work is necessary to confirm whether the SDPS installed pile will actually be operationally cheaper than a conventional jack-up. They predict that a market is likely as wave and tidal devices reach commercial deployment. Additionally, due to the few contractors who can currently install piles in rock at diameters greater than about 0.5 m (and most of these limited to shallow water) they see markets in off-shore wind and oil and gas as well, particularly as offshore wind turbines grow in size.

7.2 General technical & engineering challenges

The SDPS is still at a very early stage of development. Significant challenges specific to the device lie in the following key areas:

- Commercial – keeping the costs low of bespoke systems operating in a harsh environment
- Commercial – Possible IP restrictions from existing patents
- Commercial – Competitors who have successfully demonstrated their technology
- Technology – Finding a solution to the base frame
- Technology – Developing a drill package combing the power and space requirements

Cost reduction and customer confidence is likely to be at the heart of the development challenges. Bespoke sub-systems will be required (particularly the base frame) however the system will be competing with other, simpler technologies with a proven track record.

Developing a system with as many reusable parts as possible will allow for the cost of key components to be spread across many pile installations.

8 Technology development plan outline

The technology development plan has not yet been considered in sufficient detail to allow presentation at this stage.

9 Conclusions

The Self-drilled Pile System is a promising solution to reducing the cost of subsea anchors which are capable of resisting uplift forces. Since the initial project work and patent application a number of competing solutions have appeared on the market and new patents have been awarded. As a patent is held it is likely there is a place in the market for the SDPS however this would be reliant on a low cost, reliable system being developed. Whilst developed initially for marine renewables there is cross over potential to any sector requiring an anchor to resist uplift.

Appendix A: TRL scale

TRL	Basic definition	Description	Level of integration
9	System qualified through successful operations.	Technology proven in its final form and under operational conditions.	System fully integrated.
8	System development completed and qualified through test and demonstration.	Technology has been proven to production standards and under the full range of expected conditions at sea. This TRL represents the end of Demonstration. Test and evaluation of the system to demonstrate it meets the equipment specifications and requirements specifications.	Internal and external integration validated on final production design.
7	System prototype demonstrated in an operational environment.	Prototype of the operational system demonstrated in the operational environment. Full scale prototype tested in representative conditions at sea. Supporting evidence provided to show that full capability requirements can be met	All systems integrated and interfaces (internal and external) qualified in an operational environment. Full-scale system demonstration
6	System / sub-system model or prototype demonstrated in a relevant environment	Representative model or prototype system tested in a relevant environment / relatively benign sea conditions. Prototype tested in a “high fidelity” laboratory environment or in simulated operational environment.	Interfaces demonstrated at system level in a relevant environment. Sub-scale system or full-scale sub-system demonstration
5	Technology component or basic sub-system validated in relevant environment.	The basic technological components are integrated with realistic supporting elements and tested in a simulated environment. Integrated components tested in a “high fidelity” laboratory environment. Technology demonstrated in similar applications and analysis shows it is scalable to the specific application.	Interfaces demonstrated at subsystem level in a relevant environment. Impact on other systems is specified and quantified. Sub-scale demonstration
4	Technology component or sub-system validated in laboratory environment.	Basic technology components are shown to work, but at relatively “low fidelity” compared to the eventual system. Hardware demonstrated in a laboratory / small scale tank testing. Technology demonstrated in other applications (possibly at a different scale).	Interface constraints specified. The likely impact on interfaced systems is explored and can be traded.
3	Analytical or experimental critical function and characteristic proof of concept.	Technology has been shown to be viable for the application through validated analysis or experiment. Components that are not yet integrated are representative	Analytical assessment conducted to establish interface constraints.
2	Technology concept and application formulated.	Practical applications for the technology are postulated, but there is no proof or detailed analysis to support the assumptions. Patent application possible	
1	Basic principles observed and reported	Research and paper studies identify basic properties of the technology.	

Appendix B: Images from patents

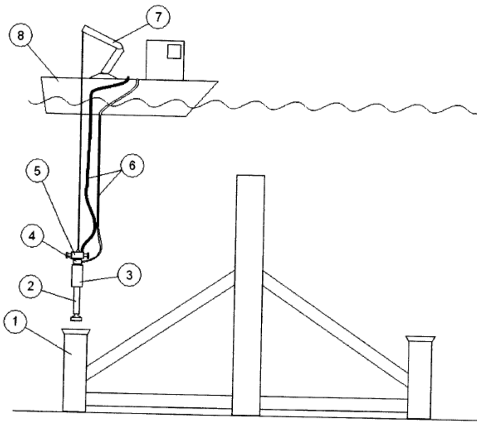

Figure 9 - Schematic of GB2431189

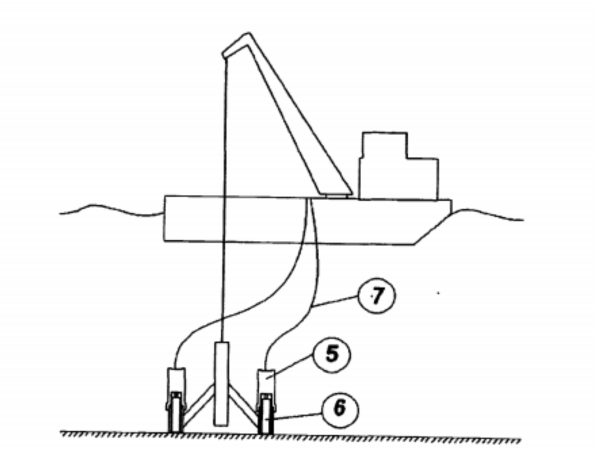

Figure 10 - Schematic of GB2448358

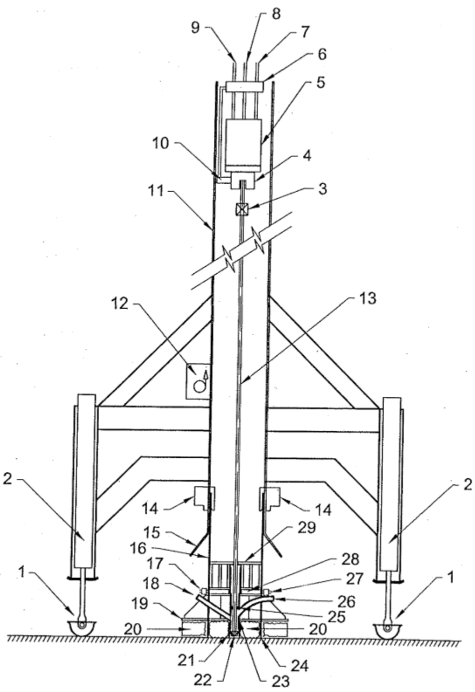

Figure 11 - Schematic of GB2488839

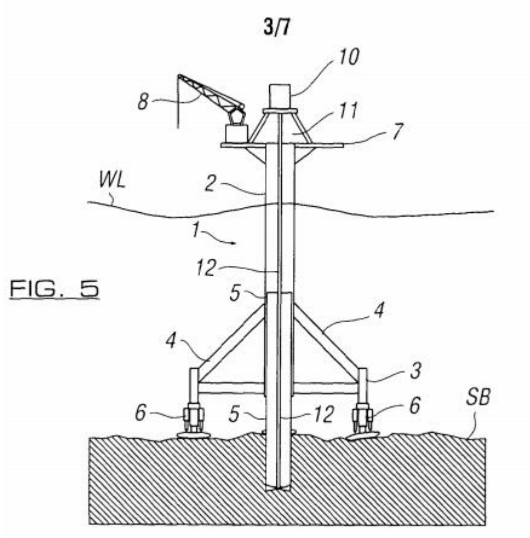

Figure 12 - Schematic of GB2460172

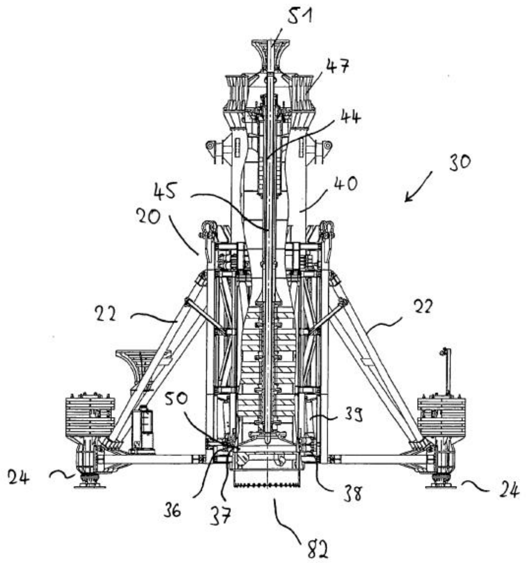

Figure 13 - Schematic of EP2562310

Fig. 7

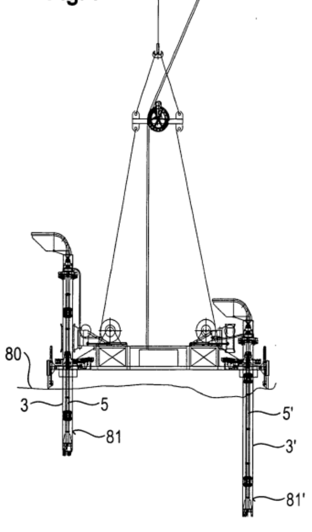

Figure 14 - Schematic of EP2322724

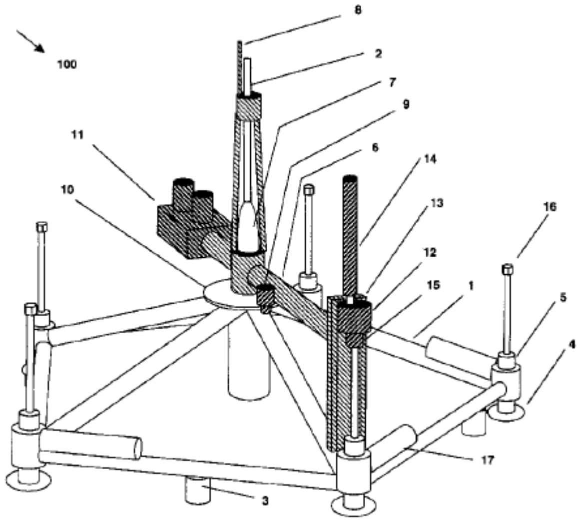

Figure 15 - Schematic of GB2436320

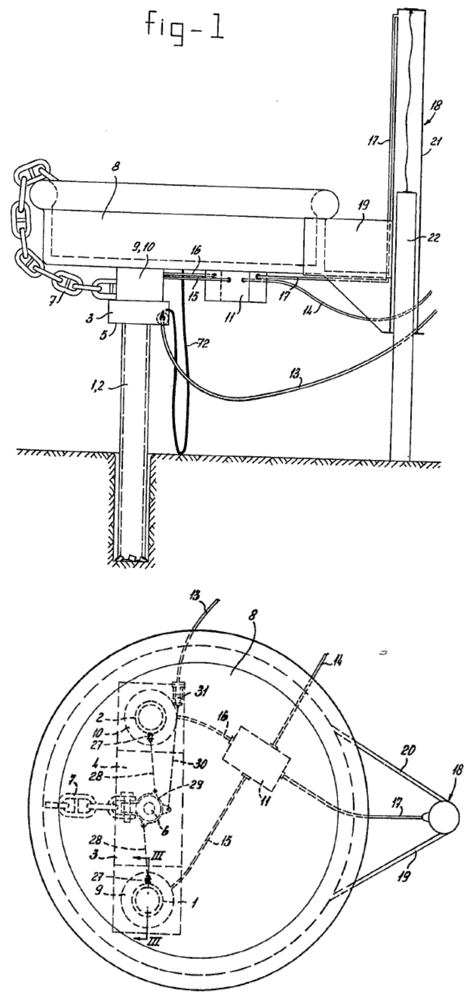

Figure 16 - Schematics of GB1249548