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Geo-engineering for floating wind turbines

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ABSTRACT: Floating wind is a potential method of generating significant renewable electrical energy. Geotechnical engineering is an important part of the design and installation process. This paper explains the seabed surveys required to determine the design parameters for mooring systems. The advantages and disadvantages of the anchor types such as drag anchors, suction piles, gravity anchors, driven piles and drilled piles will be described. The seabed survey methods described include met-ocean, bathymetry, geophysical and geotechnical. Seabed surveys are required for the fit-out port, wet storage location, export cable route, the anchor locations of the floating offshore wind turbine and the possible substation. Design of mooring systems for installation and maintenance activities are seen as priority areas for the cost reduction of floating offshore wind projects. The floating nature of the substructures permits turbine placement in previously unattainable (or prohibitively costly) sites. The installation procedure assumes a critical role in the reduction of the lifetime cost of energy production for floating offshore wind turbines.

1 INTRODUCTION

Going farther offshore means stronger and more consistent winds and little or no visual impact for coastal communities, [Crowle, 2022]. However the issue is that deeper water presents technical and economic hurdles for carrying out surveys, mooring installation and mooring hook up [Jiang, 2021]. The geotechnical conditions are an essential part of installation design for floating offshore wind turbines [Ziang 2021]. Surveys are also required for the expected weather at construction and offshore locations. This paper sets out the geophysical and geotechnical survey requirements, section 2. Mooring design requirements are described in section 3. Whilst section 4 sets out mooring line options. Types of floating wind are also briefly discussed in section 4. Mooring line components are described in section 5. Section 6 discuses anchor types. Installation of anchor types is discussed in section 7 (drag anchors). The paper will compare mooring types in section 11 (results). Managing survey site data, relied upon information and unforeseeable ground condition risk in marine renewable energy projects is an important consideration. Options for transport and installation of the anchor types have been compared.

2 DETAILED SURVEY

2.1 General

In order to determine the seabed conditions at the offshore wind locations both geotechnical and geophysical surveys are required. As part of the acquisition of seafloor data and interpretative report is required. With the structure of the seabed known the detailed engineering design can progress. Taking account of possible geo-hazards is part of the design process.

Prior to carrying out the geotechnical surveys an environmental assessment survey is required, such as benthic surveys to identify any potentially sensitive habitats or species that may be impacted by marine development.

In addition an unexploded ordnance, [Fugro, 2023], survey is carried out. In parallel with the geophysical and geotechnical surveys long term met-ocean measurements are made of wind, waves, tides and current at the offshore wind farm, export cable route and in the fit out shipyard.

2.2 Geotechnical assessment

The measurement of geotechnical features is through the drilling of boreholes into the seabed. Geophysical information is data is collected over a wide area including:

- Inshore construction site
- Tow route for the completed structure
- Offshore wind farm
- Export cable route
- Substation location

The seabed information is used to develop a geological model so as to better understand:
- Anchoring methods
- Depth of cable burial

The geophysical data and the geotechnical boreholes, define seabed soils across a site, In addition they help to provide guidance on the best location of the proposed floating wind farm. Natural hazards such as underwater hills and valleys are also identified through these seabed surveys. The geophysical investigations identify man-made obstacles, such as pipelines, UXO, wrecks and cables.

A safe and economical design of the floating offshore wind farm requires information on the soil and weather conditions at the nearshore fabrication location and the final positions of the mooring system anchors. Prior to the offshore site surveys a paper study is carried to ascertain what information already exists. The analysis of previous geo-hazard can enable the design, construction and offshore installation of new floating structures to be used to minimise the new geotechnical surveys, [BS, 2023].

Thus the initial step for a geotechnical survey is a review of available previous soil investigation data. The purpose of this review is to identify potential problem areas and to concentrate on locations where the least amount of data is available.

Geophysical surveys should be performed first to identify potential any geo-hazards before the geotechnical investigation. There have been several accidents using jack up vessels to drill boreholes where one of its legs has punched through the seabed causing it to capsize.

The soil surveys are used to produce a geological model of the offshore wind farm an export cable route so the resultant design can be optimised. The on-site boreholes need to extend to a depth of soil to the maximum penetration expected of anchors or piles.

2.3 Shallow geophysical investigation

A geophysical investigation can provide information about:
- Soil stratigraphy
- Evidence of geological features,
- Any slumps or scarps,
- Possible irregular or rough topography
- Mud volcanoes and lumps
- Collapse features
- Sand waves
- Seabed faults
- Erosional surfaces
- Gas bubbles in the sediments
- Buried channels
- Variations in stratum thicknesses.

The equipment for geophysical surveys includes:
- Echo sounders define water depths
- Swathe systems define variable topography
- Mini-sparkers for seismic source analysis
- Sub-bottom profilers
- Side-scan sonar

The results of the equipment fitted to a mobile marine vessel are used to define the water depths and seabed qualities. The geophysical report developed from measurements is input to positioning the boreholes and cone penetration test (CPTs) and finally as input into the design analysis of the moorings system.

3. MOORING DESIGN

Floating turbines are attached to the seabed with multiple mooring lines and anchors. Input is
- Dimensions of the floating wind structure
- Displacement of the structure
- Seabed data from geophysical surveys
- Borehole data from geotechnical survey
- Cone penetration test data
- Available anchor handling tugs
- Offshore weather data
- Available crane vessels for piling

Design engineers are involved from conceptual engineering through to detailed system design and installation, including:
- desktop studies;
- conceptual design
- front-end engineering design (FEED)
- detailed engineering

- mooring system design
- procurement
- fabrication
- transport to marshalling port
- installation
- tension drag anchors
- connect moorings
- final tensioning

The best anchoring methods and their installation methods require integrated use of soil data, past experience, aerodynamic loads and hydrodynamic loads.

4 MOORING SYSTEMS

4.1 Catenary mooring

The most common mooring line configuration in shallow water is the catenary consisting of chain or wire rope (figure 1). In deep to ultra-deep water, the weight of the mooring line starts to become a limiting factor in the design. To overcome this problem, new solutions need to be developed e.g.

- Synthetic ropes (less weight)
- Taut leg mooring system.

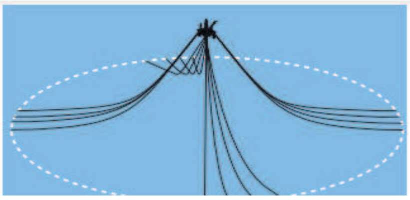

Figure 1 Catenary mooring (credit Acteon)

The catenary mooring system remains popular because it is relatively simple to deploy. A catenary mooring arrives at the seabed horizontally. For a catenary mooring the anchor point is only subjected to horizontal forces. In a catenary mooring, most of the restoring forces are generated by the weight of the mooring line.

4.2 Taut leg mooring

The taut leg mooring arrives at the seabed at an angle (figure 2). This means that in a taut leg mooring that the anchor point has to be capable of resisting both vertical and horizontal forces. In a taut leg mooring, the restoring forces are generated by the elasticity of the mooring line. An advantage of a taut leg mooring is that it has a small footprint. This reduces the material quantity, cost and weight of the total mooring system.

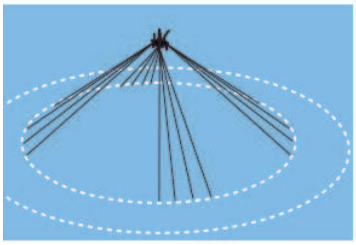

Figure 2 Taut mooring (credit Acteon)

A taut mooring can be complicated to install.

4.3 Tendon- Tether tension mooring

The tension leg mooring system (TLP), minimizes the space required on the seabed for the mooring system, (figure 3).

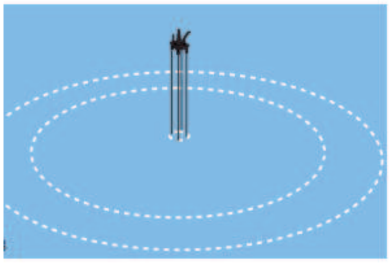

Figure 3 Tension leg platform (credit Acteon)

The tension mooring system is very time consuming to install. The installation process can only be carried out in good weather.

In addition TLPs have small water plane area in service, which that during tow to the offshore wind farm that they have low intact stability, limiting the weather for this operation.

4.4 Turret mooring

A turret mooring system, or pivot buoy, figure 4, [X1wind, 2023) features

- Mooring legs attached to a turret,
- Bearings allow whole structure to rotate
- Can be mounted externally or internally
- Swivel transmits electrical power

Figure 4 Turret Pivot Buoy (credit X1)

The pivot is easier to install than a TLP. It has the advantage of good intact stability during tow out.

4.5 Floating wind types

The principal floating wind types are shown in figure 5, [Equinor, 2023]. Semi submersibles and Spars usually have catenary moorings. Tension leg platforms (TLPs) use wire or chain tethers.

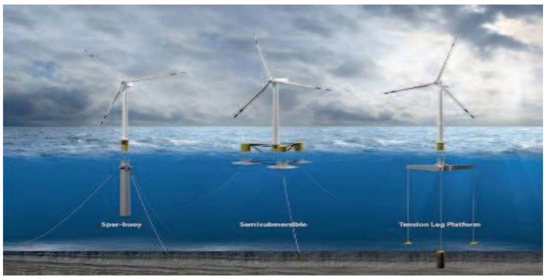

Figure 5 Floating wind type (credit DnV)

5 MOORING LINE COMPONENTS

5.1 Chain

The most common product used for mooring lines is chain, [Xu, 2020], which is available in:

- Different diameters
- Various steel grades
- Stud-link and stud-less chain.

For catenary moorings any part of the mooring line which might touch the seabed is main of stud-less chain

5.2 Wire rope

When compared to chain, wire rope has a lower weight for the same breaking load and a higher elasticity. The wire rope is terminated with a socket. Generally, wire rope is more prone to abrasion damage and corrosion than chain.

5.3 Synthetic fibre rope

The use of synthetic fibre ropes in the mooring line is being developed for deep water mooring. Typical materials that can be used are polyester and high modulus polyethylene. The major advantages of synthetic fibre ropes are the light weight and elasticity of the material. However synthetic ropes are subject to abrasion damage and so are not used near or on the seabed.

6 ANCHORING TYPE

6.1 Anchor options

The basic choice of the type, [Acteon, 2023], of anchoring point is determined by a combination of:

- Water depth in which it is to be applied
- Condition of the soil
- Load on the anchor point
- Remoteness of the mooring location
- Practicality of an anchor point
- Cost transportation and installation

Mooring anchor types are shown in figure 6, [ABS, 2013]. .

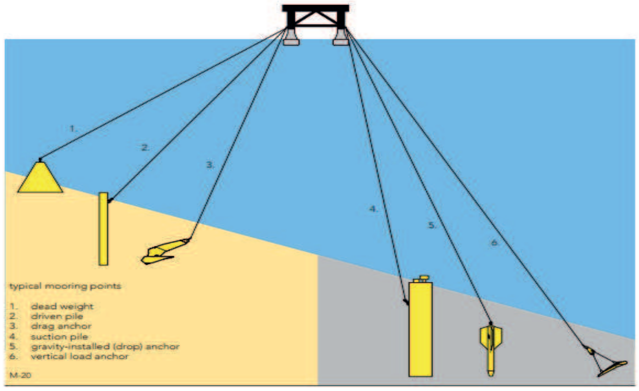

Figure 6 Anchor types (credit Acteon)

6.2 Dead weight

The dead weight, or gravity anchor, holding capacity is generated by the weight of the material used and partly by the friction between the dead weight and the seabed.

Common materials in use today for dead weights are steel and concrete (figure 7).

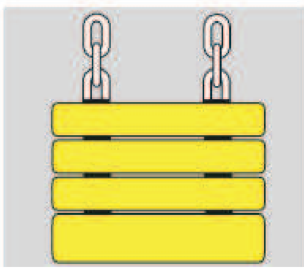

Figure 7 Gravity dead weight(credit Acteon)

Gravity base anchors need large floaing crane vessels for installations and are not normally favoured for permanent anchor systems.

6.3 Pile

The pile is a hollow steel pipe that is installed into the seabed by means of either:

- Drilled by underwater equipment
- Driven with under water hydraulic hammer

The holding capacity of the pile is generated by a combination of the friction of the soil along the pile and lateral soil resistance. Generally, the pile has to be installed at a great depth below the seabed to obtain the required holding capacity, [Manceau, 2021]. The pile, whether drilling or driven, is capable of resisting both horizontal and vertical loads (figure 8).

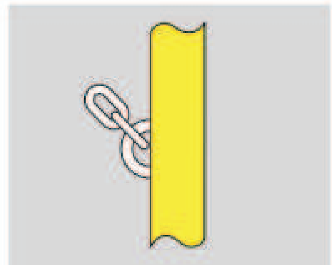

Figure 8 Pile,mdriven or drilled(credit Acteon)

The driven pile installation requires, figure 9:

- Underwater guide frame
- Underwater hydraulic hammer
- Observer ROV required

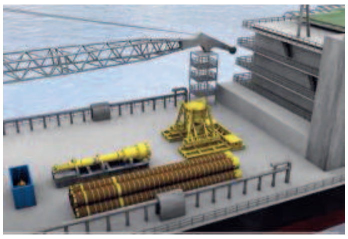

Figure 9 Driven pile installation(credit Acteon)

Drilled foundations are employed in regions with stiff soil conditions where traditional installation methods, such as impact driving, vibration, or gravity-based foundations, are no longer feasible, [Löhning, 2021]. A typical underwater pile drill is shown in figure 10, [Bord, 2023].

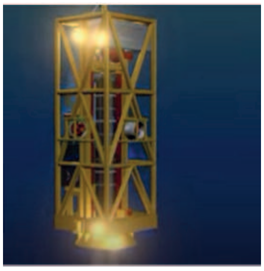

Figure 10 Underwater pile drill(credit Acteon)

The driven or drilled pile requires a large floating crane vessel for it's installation, assisted by work class ROVs.

6.4 Drag embedment anchor

This is the most popular type of anchor. The drag embedment anchor has been designed to penetrate into the seabed, either partly or fully. The holding capacity of the drag embedment anchor is generated by the resistance of the soil in front of the anchor. The drag embedment anchor is very well suited for resisting large horizontal loads, but not for large vertical loads, (figure 11). Drag anchor high holding power anchor capacity is given in Table 1, [API, 2015] and [Bruce, 2023].

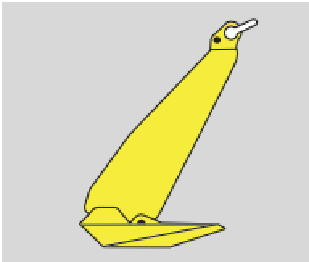

Figure 11 Drag anchor(credit Acteon)

It is assumed that there is chain in the area where the mooring line is touching the seabed.

Table 1 High holding power capacity (modified API data)

Drag anchor weight t	Very soft clay t	Medium clay t	Sand and hard clay t
10	120	170	280
20	250	400	550
30	400	580	800
40	500	700	1000

Drag anchors are installed by conventional anchor handling tugs.

6.5 Suction pile

The suction pile is a hollow steel pipe, [SPT, 2023]. The suction pile is closed at the top and is of large diameter. The suction anchor is forced into the seabed by means of a pump connected to the top of the pile. When the water is pumped out of the suction pile, it creates a pressure difference between the outside of the pile and the inside, forcing the pile into the seabed. After installation is complete, the pump is removed. The holding capacity of the suction pile is generated by a combination of the friction of the soil along the suction pile and lateral soil resistance. The suction pile is capable of withstanding both horizontal and vertical loads (figure 12).

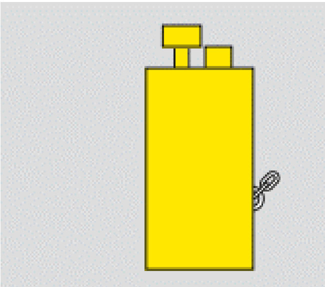

Figure 12 Suction pile(credit Acteon)

The suction pile requires a large floating crane vessel for it's installation, aided by work class ROVs to operate the pump. Anchor handling tugs are required to pre lay the mooring on the seabed, prior to the atrrival of the floating offshore wind turbine.

Characteristics of suction pile installation, figure 13, are as follows:

- No limit on suction pile capacity
- Suction pump on top
- Work ROV required

Figure 13 Suction pile installation(credit Acteon)

6.6 *Drop-installed anchor*

This drop anchor type combines t vertical and horizontal load capacity. It installs itself due to its drop weight and requires no external energy or mechanical handling. It is therefore ultimately suited for ultra deep water moorings (figure 14).

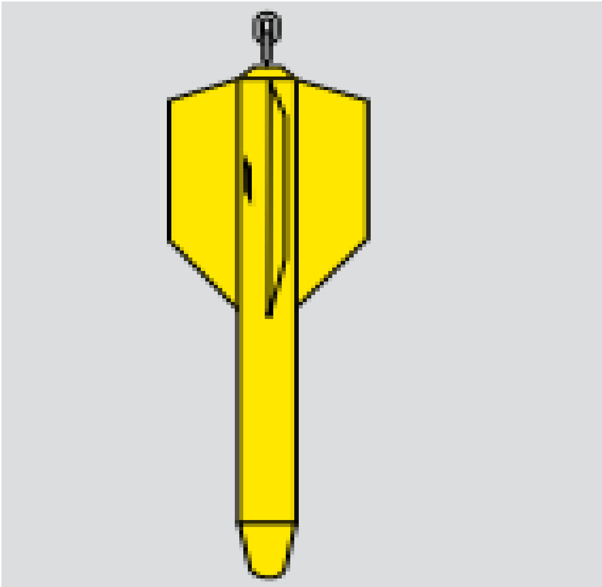

Figure 14 Drop installed anchor(credit Acteon)

The drop installed anchor requires a large floating crane vessel for it's installation, aided by observation class ROVs.

6.7 *Vertical load anchor*

The vertical load anchor, (figure 15):

- Can withstand horizontal loads
- Takes vertical loads
- Good for deep water applications
- Useful in vicinity of pipeline and cables

Figure 15 Vertical load anchor(credit Acteon)

The vertical load anchor is installed by a high capacity anchor handling tug.

7 DRAG ANCHOR DEPLOYMENT

7.1 Deployment for permanent moorings

The simplest deployment procedure is to use an Anchor Handling Vessel (AHV) (figure 16).

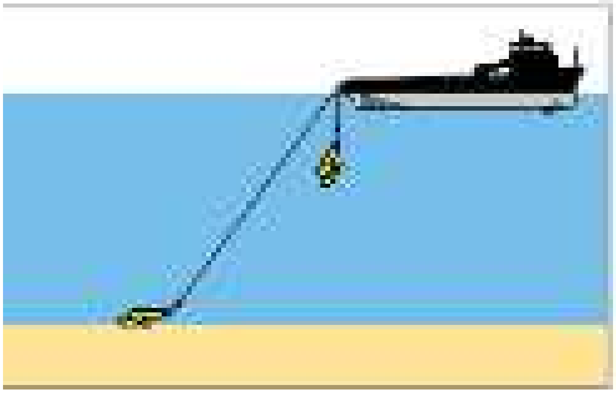

Figure 16 Drag anchor deployment(credit Acteon)

7.2 Drag anchor tensioning

Drag anchors need to be cross tensioned. A vertical load causes high horizontal loads. The anchor line tension is measured by a measuring pin located inside the tensioning device (figure 17).

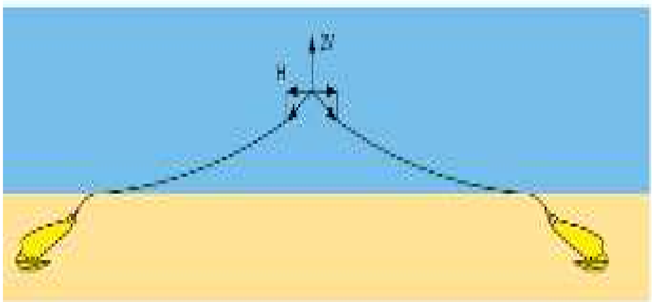

Figure 17 Tensioners(credit Acteon)

Drag anchors are tensioned using Anchor Handling Vessel and a tensioner device between the anchor lines. The benefits of drag anchors is that they are relatively easy to deploy.

8 RESULTS

Based on past experience, from the oil and gas industry, Table 2 compares anchor types for floating offshore wind turbines. The options which require crane vessel also need anchor handling tugs for laying mooring lines on the seabed. The limitation on anchor size depends on the installation vessel being used.

Table 2 Installation anchor types

Anchor Type	Vessel for anchor laydown	Advantages	Dis - advantages
Gravity-base anchor	crane vessel with DP2 and ROVS	OK for temporary moorings	Very heavy, not for soft seabed
Driven pile anchor	crane vessel with DP2 with ROVs	All types	Underwater vibrations
Drag-anchor	Large Tug	Very Experienced	Not for TLP
Suction pile	crane vessel with DP2 and ROVs	Some experience	Needs soft/medium soil
Gravity drop anchor	Large Tug	Lightweight	Limited experience
Vertical loaded anchor	Large Tug	Lightweight	Limited experience

The benefits of suction piles anchors for moorings are:

- Holding capacity at all load angles
- No external load tests required.
- High weight to holding capacity.
- Short installation time

9 DISCUSSION

The paper recommends the following key research to reduce the cost the mooring system:

- Reducing chain content with synthetic rope
- Maximising use of buoyancy and ballast

Simplification of mooring system by:

- Adopting load reduction devices
- Adopting shorter and lighter taut moorings
- Exploring different anchor solutions,
- Manufacture components with clean energy
- Reducing transport distance of components

To deploy the number of anchors and mooring lines expected for turbine arrays, large tugs with low availability and expensive day rates may not be feasible for the installation of commercial floating wind, [Ore, 2023].

The cost of mooring systems depends on:

- Material availability
- Manufacturing close to installation site
- Storage area for mooring components
- Installation vessels and equipment

There are only about 25 floating offshore wind turbines in the world. Only drag anchors and suction piles have been used for moorings, but at the time of writing there is no feedback on how successful these moorings have been.

Floating offshore wind turbines are anticipated to increase in capacity and water depth, and so it is predicted that mooring components will also need to be increased in size too.

10 CONCLUSION

Accurate and timely geotechnical and geophysical surveys are necessary for the design of floating wind mooring systems. Design of mooring systems for installation and maintenance activities are seen as priority areas for the cost reduction of floating offshore wind projects.

Studies and future developments need to focus on the following aspects:

- Expanding the weather window for surveys
- Mooring connection weather tolerant
- Simplification of pile installation
- Reduce risks to personnel working offshore
- Easy mooring connection

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