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Feasibility of anchor types for floating wind: Geotechnical drivers

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ABSTRACT: A successful floating wind project relies on anchors that meet the project geo-performance criteria while maximizing project benefit, such as optimizing cost and reducing project risk. Achieving this requires selection of an anchor technology that aligns the geotechnical drivers for anchor performance with the specific conditions and constraints of a project. This paper explores the factors influencing the geotechnical performance of commonly used anchor types to help inform optimal anchor selection. Firstly, this paper identifies geo-performance criteria for anchors, which commonly relate to anchor installation and in-place performance/capacity. An examination of geotechnical drivers that can influence an anchor's ability to meet these criteria is presented. These geotechnical drivers include ground conditions, mooring line loading conditions and other project factors relevant to the anchor selection and geotechnical design. The performance of commonly used anchor types is compared over the different geotechnical drivers. The comparison illustrates that significant differences in performance can occur between different anchor types. Finally, site characterization requirements to provide the inputs necessary to support anchor selection are discussed.

Keywords: Floating offshore wind, anchors

1 INTRODUCTION

The seabed area available in deeper waters suitable for floating wind projects far exceeds that in shallow water where fixed bottom projects are developed. This gives floating wind projects the advantage of more flexibility in site selection, providing the opportunity to target areas with higher wind speed while avoiding less favourable ground conditions. An optimal anchoring system for a floating wind project relies on selecting an anchor type that best aligns the geotechnical drivers for anchor performance with the specific conditions and constraints of a project.

There has been increasing attention on examining anchoring for floating wind (e.g. Shui et al., 2024; Ma et al., 2024; ORE Catapult, 2024; Cerfontaine et al., 2023). This paper adds to previous studies by focusing on the key drivers influencing the geotechnical performance of anchors to help inform optimal anchor selection. Guidance is provided for assessing anchor type feasibility by drawing upon anchoring project experience. This is provided for commonly used anchor types of gravity anchors, pile anchors and embedded anchors (Figure 1). Site characterization requirements to provide inputs necessary to support anchor selection are also discussed. The aim of this paper is to aid anchor feasibilty assessment to meet project geo-performance criteria and maximize project benefit.

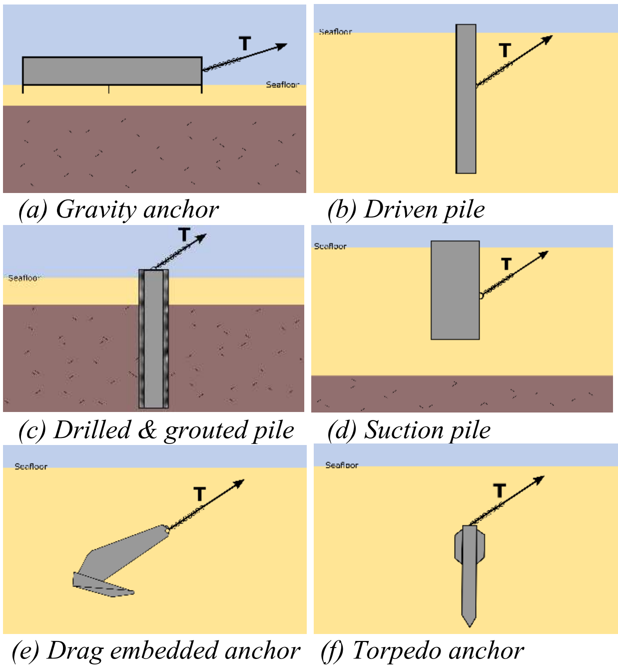

Figure 1. Examples of anchor types

2 ANCHORING FOR FLOATING WIND

There are many substructure concepts for floating wind turbines. They can generally be categorized into four types: spar, semi-submersible, barge and tension-leg platform (TLP). Common to all concepts is that they require a mooring system, comprising mooring lines to transfer the loads from the substructure to anchors at seabed level. Mooring configurations are typically either catenary, taut (or semi-taut), or tension-leg (Figure 2). Anchors are required to withstand the mooring line tension loads by mobilising sufficient soil resistance.

2.1 Anchor geo-performance criteria

The anchoring system selected for a floating wind project should be capable of i) satisfying the geo-performance criteria defined for the project, and ii) optimise project benefit. A set of geo-performance criteria may be:

- **Installation** – safe installation to tolerance. Tolerances may relate to minimum embedment depth, anchor verticality, anchor orientation (misorientation of the padeye from the mooring line heading introduces torsion to the anchor), or achieving the required proof load.
- **In-place performance** – effective and safe operation, surviving design events. This requires providing sufficient capacity to events such as storm or seismic loading. Displacement or rotation limits may also apply over the anchor design life.
- **Removal** – safe decommissioning and retrieval. The anchor should meet any end-of-life project requirements that may apply.

Project benefit can include improved performance, material, installation, or operational cost saving and reduced project risk.

2.2 Anchor geotechnical design components

To undertake the geotechnical design of an anchor system, the components to be considered include the i) anchor type, ii) padeye location and iii) mooring line embedment.

2.2.1 Anchor type

There is a range anchor types that can be used for floating structures. They can generally be split into three general categories, namely gravity, pile, and embedded anchors (Table 1):

- **Gravity anchors** are placed on the seafloor (often utilising short skirts) and rely on their self-weight for vertical capacity and seafloor sliding resistance for horizontal capacity.
- **Pile anchors** are installed to a specified depth beneath the seafloor and referred to by their method of installation (e.g. driven, suction, vibro). Along with their self-weight, they obtain vertical capacity from the pile-soil interface and base response. Their horizontal capacity comes from mobilising the resistance of the surrounding soil.
- **Embedded anchors** are completely buried beneath the seafloor. Once installed the anchor is proof loaded, so the final embedment depth is not known until this has been applied. The plate of the embedded anchor mobilises the resistance of the surrounding soil to provide its capacity.

There are anchor types which are more established in their application, and others that are emerging (Table 1). Established anchors may have more well-defined design methods (in most instances) and to date have been more commonly adopted in projects. The motivation driving emerging anchor designs includes increasing anchor efficiency, such as through weight and cost reduction, as well as reducing the installation effort or vessel size required. Installation of anchors in rock are often more challenging and costly, such that innovations for

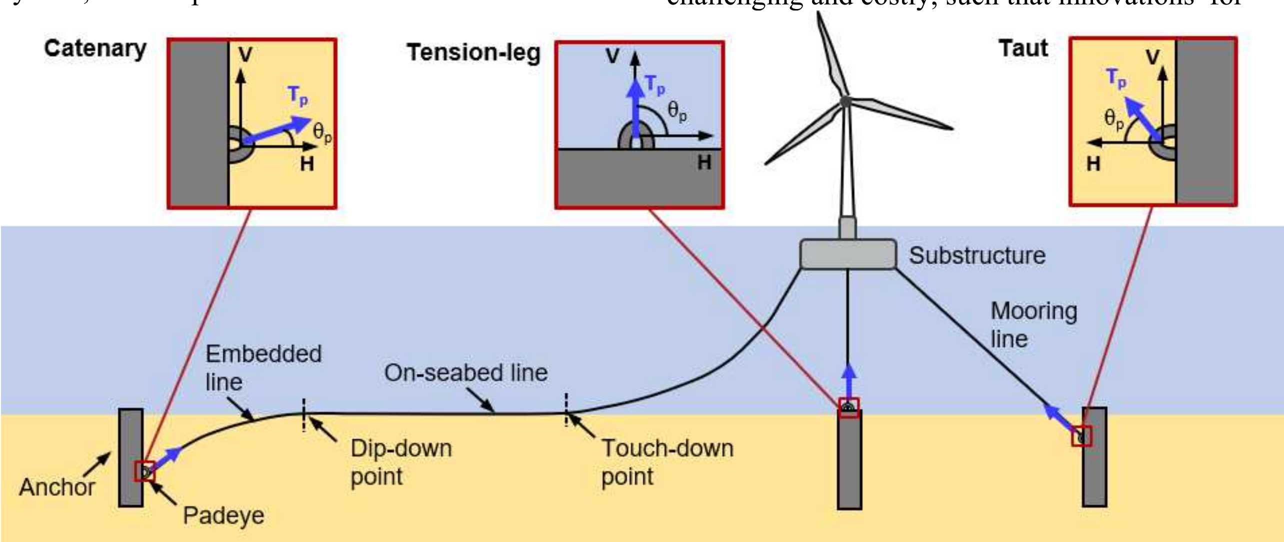

Figure 2. Types of mooring systems with examples of padeye tension load (T_p) (scales exaggerated for illustration)

Table 1. Examples of anchor types

Anchor type	Gravity	Pile	Embedded
Established	Block anchor Ballasted box anchor	Driven pile Suction pile Drilled & grouted pile	Drag embedment anchor (DEA) Torpedo anchor (dynamically installed anchor, DIA)
Less common / Emerging	Ballasted grillage	Vibro-pile Drive-drill-drive pile Helical pile (screw pile) Subsea micropiles Groutless rock anchor	Vertically loaded anchor (VLA) Suction embedded plate anchor (SEPLA) Hybrid DIAs Multiline ring anchor (MRA)

anchoring solutions in rock has received particular attention (e.g. see Section 3.1.1). Emerging anchors may have less developed design guidance, limited scale of application and project use. This means there may be more uncertainty in their use, although ongoing research and development is seeking to address this.

The anchor type selected for a project should be the one that meets the geo-performance criteria and maximises project benefit. This requires assessing the geotechncial drivers for anchor feasibility (Section 3) against the project conditons and constraints.

2.2.2 Padeye location

The padeye is the connection point for the mooring line to the anchor. The selection of padeye location/depth can influence anchor performance as it impacts how the mooring line load is applied to the anchor (Figure 2). For a gravity anchor, the padeye is located above the seafloor. For pile anchors, the optimal padeye location can be some depth below the seafloor, which can be selected to maximise the lateral capacity provided by the anchor. For suction piles, the optimal depth may be in the region of 2/3 down the length of the pile, with optimal depth increasing slightly with increasing padeye load angle, θ_p (Andersen et al. 2005). However, the depth of the padeye is often a balance between maximising the lateral capacity of the anchor and ensuring that the vertical load applied to the anchor, which will increase as the padeye is located deeper, is within the allowable axial capacity. In strong soils or rock, the padeye may need to be located near or above the seabed. For embedded anchors, the padeye is located at the end of the shank that is connected to the anchor plate. The shank length (and therefore padeye eccentricity) can be optimised for achieving deeper anchor embedment.

2.2.3 Mooring line embedment

After anchor installation the mooring line is preloaded. For anchoring systems with a padeye location below seafloor, this results in a new configuration of mooring line from the padeye to seafloor (Figure 3). During operation, the embedded mooring line length may change further as loads greater than the preload is experienced (i.e. chain slack uptake). This change in mooring line length needs to be assessed as it may affect the design of overall mooring system. In addition, the increasing length of embedded mooring line changes the load magnitude and load angle at the padeye. Thus, the mooring line-seabed interaction must be considered together with the anchor assessment as it influences anchor performance.

The motion of the embedded mooring line has the potential to induce trench formation in front of the anchor (Colliat et al., 2018). The trench can progressively develop down to padeye depth, which can significantly reduce anchor capacity. The potential of a trench to form and its impact should be considered.

3 GEOTECHNICAL DRIVERS FOR ANCHOR FEASIBILITY

Geotechnical drivers influencing anchor feasibility can include i) ground conditions, ii) loading conditions and iii) project factors.

3.1 Ground conditions

The ground conditions are a key driver for anchor feasibility. The geo-engineering inputs related to ground conditions are i) ground profile and properties,

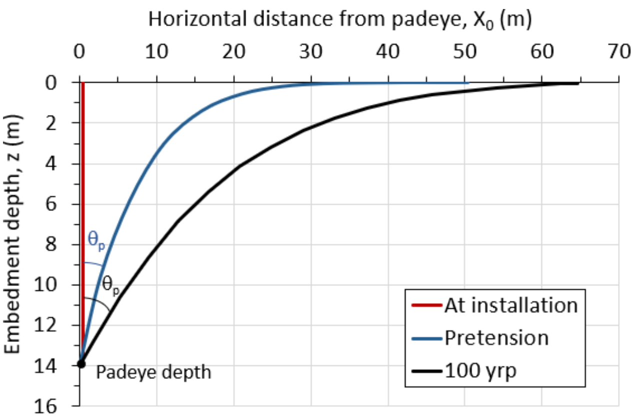

Figure 3. Project example of embedded mooring line profile under different loading conditions

ii) geo-engineering constraints and iii) geohazards. Section 4 describes the site characterisation process to obtain these inputs.

3.1.1 Ground profile and properties

The material making up the ground profile impacts the anchor types that may be feasible (Table 2). When strongly cemented layers/rock is present, drilled & grouted piles are a typical anchor type adopted, although other options are emerging, e.g. subsea micropiles and groutless rock anchors. Most anchor types are suited for soil conditions such as sand and clay. However, layering of different soil types can pose challenges, particularly for installation. For drag anchors, layer changes can impact embedment depth. For suction anchors, soil layering can alter the seepage flow during installation and should be considered in the installation assessment (Klinkvort et al., 2019). Driven piles are typically less sensitive to layered soils, assuming they can be driven with available hammers.

The properties of the ground profile, described by geotechnical parameters defined for each layer, influence anchor feasibility. Soil/rock strength is an important parameter. Low strength may require larger anchor sizing to meet the required capacity. High strength, while beneficial for capacity, may introduce installation challenges. As the moorning line loads are cyclic in nature (Section 3.2.3), a key consideration is degradability of a materials‘ strength under cyclic laoding. The potential reduction in strength due to cyclic loading should be quantified and incorporated into the anchor assessment (Andersen, 2015).

3.1.2 Geo-engineering constraints

Geo-engineering constraints can be defined as an existing ground feature that is a static engineering constraint to the development (Dimmock et al., 2023). Geo-engineering constraints are surface and subsurface features selected from the ground model that are deemed to be of consequence to the anchoring system (or other project infrastructure). Examples of geo-constraints can include seabed slope, faults (when static), boulders and debris (Figure 4). Geo-engineering constraints are addressed by routine project engineering. If it is not possible to avoid the constraint, then it is to be accommodated by the engineering design of a feasible anchor type. For example, gravity anchors may not be feasible for a steeply sloping site, whereas it might be possible for a piled anchor to be designed to accommodate the slope.

Table 2. Ground condition feasibility

Anchor type	Soil: Clay	Soil: Sand	Rock: Weak	Rock: Strong
Gravity anchor	Likely feasible	Likely feasible	Likely feasible	Likely feasible
Torpedo anchor	Likely feasible	Likely not feasible	Likely not feasible	Likely not feasible
Drag anchor	Likely feasible	Likely feasible	Likely not feasible	Likely not feasible
Suction pile	Likely feasible	Likely feasible	Likely not feasible	Likely not feasible
Driven pile	Likely feasible	Likely feasible	Likely feasible	Likely not feasible
Drilled & grouted pile	Likely not feasible	Likely not feasible	Likely feasible	Likely feasible

Key: Likely feasible (green); Likely not feasible (red)

3.1.3 Geohazards

Geohazards can be defined as a dynamic process which is a risk to the development (Dimmock et al., 2023). Geohazards are identified from the current and potential ground activity identified by the ground model. Examples of geohazards include fault movement, fluid explosion, earthquakes, liquefaction, slope instability and mobile bedforms (Figure 4). Geohazards are addressed using project risk management frameworks. The risk and consequence of a geohazard to the anchoring system is defined to decide whether a risk may be tolerated/ monitored or if it should be mitigated. Mitigation could include avoiding if possible, or geohazard-resistant engineering of a feasible anchor type. For example, if liquefaction risk was deemed high, a drag anchor with a shallow embedment depth may not be feasible compared to a pile anchor installed to a deeper depth.

3.2 Load conditions

The feasibility of an anchor type can depend on the characteristics of the mooring line loading applied. These can include i) magnitude of the peak load, ii) dominant loading direction, and iii) nature of the cyclic loading applied.

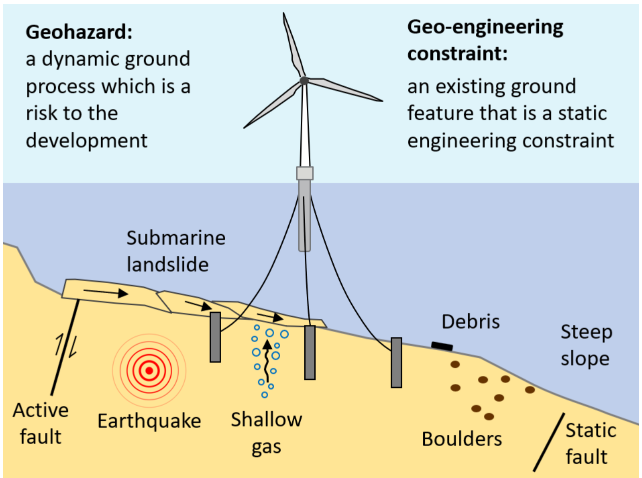

Figure 4. Geohazards and geo-engineering constraints

3.2.1 Peak load magnitude

The magnitude of the peak mooring line tension load, T_p required to be withstood by the anchor can affect anchor feasibility. While anchor size can be increased to achieve higher load capacity, there are factors limiting the anchor size that is practical to install. Figure 5 shows a generalised comparison of mooring line load levels that can be withstood by gravity, pile and drag anchor types. Gravity anchors, whilst can be the heaviest anchor type, can only resist a lower- level mooring line load. Embedded anchors are significantly more efficient in the resistance provided based on their weight (reducing slope in Figure 5 represents increasing efficiency). However, the level of loading required to install and proof load that is practical to be applied by a vessel offshore limits the size and thus mooring line load that a drag anchor can be used for. The pile anchor sizes that are typically feasible to install means these are often the anchor type able to support the highest level of mooring line load.

3.2.2 Dominant loading direction

Figure 2 illustrates loading directions that may be applied at the padeye depending on the mooring line configuration. A catenary mooring line lies along the seafloor resulting in lower load inclination at the padeye, θ_p. The tension load T_p is therefore applied to the anchor predominately as a horizontal load. To reduce the footprint of the mooring system, taut mooring lines are pretensioned to meet the seafloor at a higher angle, resulting in a higher θ_p compared to a catenary mooring. In this case both vertical and horizontal loads may be significant. A near-vertical load is applied for the case of tension-leg moorings.

The load direction can impact anchor feasibility. For example a drag anchor is only suitable for horizontal dominated loading, as it may unembed under vertical loading. The load direction can also impact anchor sizing. Figure 6 shows an example of suction pile capacity for different load angle inclinations. The pile has more capacity under horizontal loading compared to loading applied vertically. Thus, a pile size that is sufficent for a catenary mooring may not be adequate for a TLP.

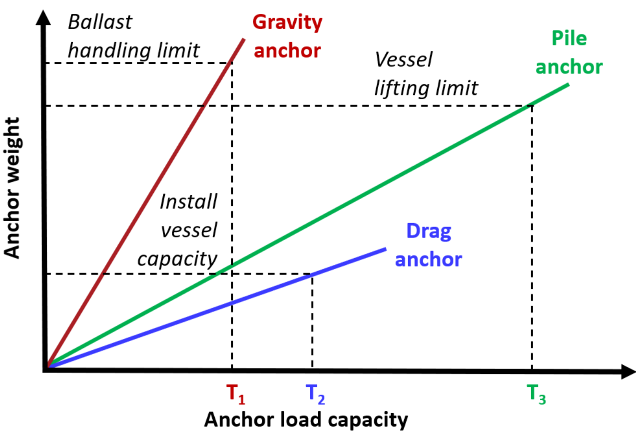

Figure 5. Generalised anchor load capacity comparison

3.2.3 Cyclic loading

The environmental loads acting on the wind turbine substructure and transferred to the anchors are cyclic in nature. The peak load acting on an anchor is made up of a mean load component and a cyclic load component. Figure 7 shows an example where the mean load is 0.35 times the peak load. Cyclic loading of the anchor can induce pore pressure development in the soil, and depending on its magnitude the anchor capacity may reduce (Section 3.1.1). An anchor type should be selected that is able to accommodate the level of cyclic loading imposed.

3.3 Project factors

The geotechnical anchor design may be influenced by other project factors in addition to the ground and loading conditions. These may include:

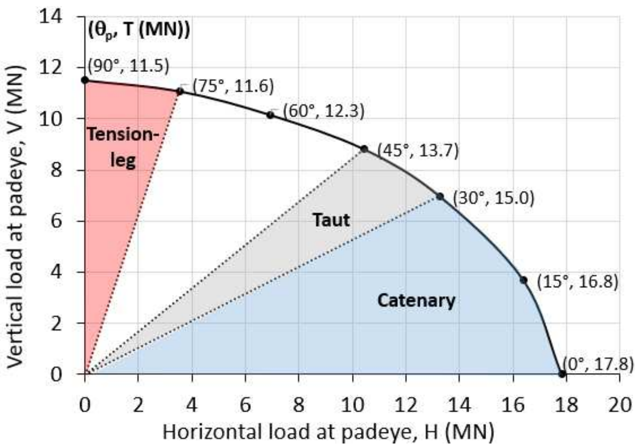

Figure 6. Project example of suction anchor capacity envelope under vertical (V) and horizontal (H) loading

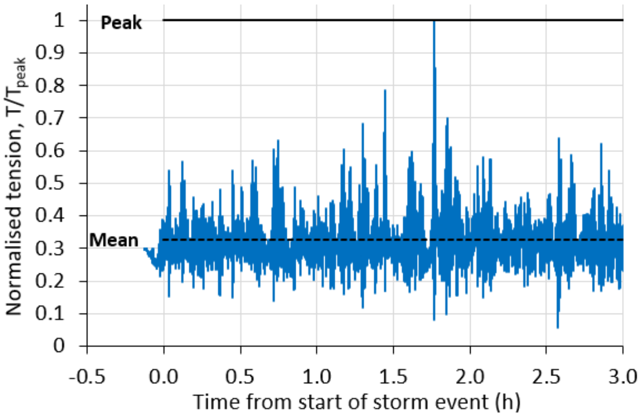

Figure 7. Example of anchor storm load-time history

- **Design standards & certification** – projects may require certain design standards to be followed. This could limit the use of anchor types that do not have established design methods covered by codes and standards.
- **Environmental requirements** – noise restrictions if they apply can influence anchor choice. For example, driven piles using hammers cause high installation noise which may require mitigation, but noise is minimal for suction piles.
- **Installation constraints** – anchor types have different installation spread requirements. Limitations on the availability or operational capacity of installation options may influence anchor feasibility.
- **Shared anchor requirements** – to reduce the number of anchors, projects may consider shared anchors where mooring lines from different turbines are connected to the same anchor (Xu et al., 2024). Some anchor types, e.g. drag anchors, may not be suitable as shared anchors.
- **Decommissioning requirements** – if anchors need to be completely removed at the end of the project life then this will limit the anchor type to those where this can be achieved.

3.4 Summary

Table 3 summarises some of the key geotechnical drivers for anchor type selection that were discussed.

4 SITE CHARACTERISATION REQUIREMENTS

Site characterisation activities should be carefully planned to provide the required geo-engineering inputs for assessing anchor feasibility (Section 3.1). Key to deriving the inputs is the development of a ground model that integrates all geological, geophysical and geotechnical data for the site (Figure 8). The process starts from the desk study stage where available data is used to create an initial ground model. This provides initial geo-engineering inputs for screening of potentially feasible anchor types. Site surveys can then be planned and the results used to update the ground model. The process is repeated to enable selection and progress design of the most optimal anchor solution.

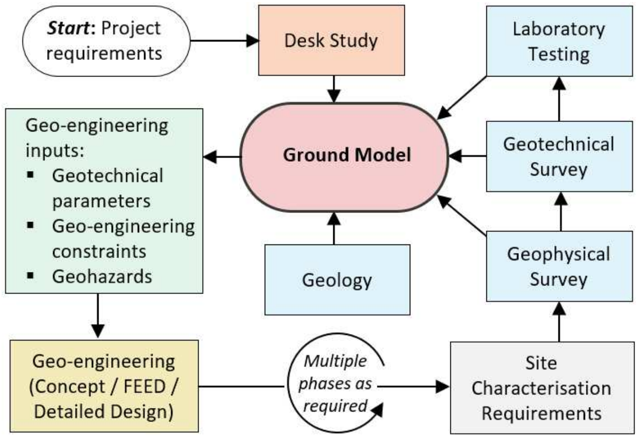

Figure 8. Example of site characterisation process

It is not uncommon for mooring line layout updates to be made during a project, resulting in changes to the anchor locations. Site characterisation should aim to facilitate this with the integrated ground model by using geophysical data for interpolation between geotechnical test locations. In this way the ground model may be able to provide geo-engineering inputs at the updated anchor locations without requiring additional site survey to be performed.

5 CONCLUSIONS

To support the increasing growth forecasted for floating offshore wind projects, anchors must be selected that meet project geo-performance criteria while maximizing project benefit. This paper details geotechnical drivers for anchor performance that can be considered in anchor feasibility assessments to help inform optimal anchor selection. The importance of the site characterization process to provide the inputs necessary to support anchor selection is also highlighted.

Table 3. Geotechnical drivers for anchor type feasibility

Anchor type	Ground conditions	Loading conditions		Project requirements		
	Ground type suitability	Peak load level capacity	Load direction suitability	Silent installation	Shared anchor suitability	Removal
Gravity anchor	Soil, rock	Low	H & V	Yes	Yes	Yes
Torpedo anchor	Clay	Medium	H & V	Yes	No	Yes
Drag anchor	Soil	Medium	H	Yes	No	Yes
Suction pile	Soil	High	H & V	Yes	Yes	Yes
Driven pile	Soil, weak rock	High	H & V	No	Yes	No
Drilled & grouted pile	Rock	High	H & V	No	Yes	No

AUTHOR CONTRIBUTION STATEMENT

First Author: Conceptualization, Writing - Original draft. **Second Author**: Conceptualization, Writing - Reviewing and Editing.

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