



Sustainable anchor concepts/D3.1

WP3, T3.1

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Executive Summary

This report paves the way for the TAILWIND geotechnical activities as it identifies the challenges of typical anchors for floating offshore wind (FOW) turbines and guides thereby the selection of the anchors to be advanced further in the project. This is done by:

- Proposing a taxonomy to categorise and systematically review emerging anchor types to point out potential technological and methodological innovations;
- Estimating the suitability of five typical anchor technologies – suction anchor, pile anchor, gravity anchor, plate anchor, fluke anchor – to different FOW project scenarios on the basis of their industrial feasibility.

Using the mooring loads provided in WP1, existing commercial anchor technologies have been sized using state-of-art design methods and industry guidelines under DNV standards. Industrial feasibility is then assessed by considering economic, environmental, social, and technical sustainability. For this purpose, relevant key performance indicators (KPIs) covering material sustainability, fabrication and transportation capacities, installation efficiency, decommissioning and recyclability, and the impact on marine environment are defined.

Evaluation matrixes are presented and offer a guide to the selection of anchor concepts for further development in Tasks 3.2, 3.4 and 3.5. Similar approaches could be used in the anchor screening phases of FOW projects to select the most suitable anchor concept given a specific scenario.

Acronyms and abbreviations

DSS = *Direct simple shear*

FOW = *Floating offshore wind*

KPI = *Key performance indicator*

LCOE = *Levelised cost of energy*

MODU = *Mobile offshore drilling unit*

RL = *Reference location*

SI = *Site investigation*

TLB = *Tension leg buoy*

TLP = *Tension leg platform*

TRL = *Technology readiness level*

WTH = *Wind turbine generator*

WP = *Work Package*



1. Review of anchor types including innovations

Section 1 of this report aims to define a set of five anchor types to take forward in the sizing and evaluation process in the later sections of the report, providing the baseline anchor cases on which the TAILWIND research programme is founded.

Section 1 comprises the following components:

- 1- A taxonomy of anchor types is first introduced (Section 1.1), based on the mechanisms for their installation and for their in-service design capacity
- 2- Using this taxonomy, listings of anchor types with summary details are presented. Firstly, Section 1.2 presents an overview of anchors that are already used commercially, from which a subset is taken forward for analysis in the main scenario modelling of this report. Secondly, Section 1.3 reviews emergent concepts that have not yet reached commercial use, but which provides a platform for guiding the research focus within TAILWIND.
- 3- In addition, to further guide TAILWIND research, Section 1.4 provides a summary of emergent concepts for improved assessment of in-service design capacity.

1.1 Classification of anchors: a systematic taxonomy

Many anchor types have been used in the field over the last decades, mainly to secure oil and gas facilities. Some anchors have a generic form, evolved over millennia (e.g. piles) and some have particular characteristics that have been developed by specific companies (e.g. the geometric form of the Umack anchor). However, all these anchors can be classified using a taxonomy based on (1) how they are installed; and (2) how they resist the load applied by the mooring line. Some anchors are hybrids, which combine several installation methods or resistance mechanisms.

The installation process can be classified into three main categories (Figure 1-1):

- 1- **Self-weight installation:** the anchor reaches its final position under its self-weight only, either after being laid on the ground (e.g., gravity foundation) or dropped from above (e.g., dynamically installed anchor).
- 2- **Mechanical action:** a mechanical action is necessary to embed the anchor to its desired position. This can be an axial compressive force (driving, jacking or vibrating), a tensile force (pulling a drag embedment anchor) or torque (e.g. screw piles).
- 3- **Hydro-mechanical action:** the installation relies on the effect of hydro-mechanical couplings, induced by some controlled water flow, such as suction installation or jetting. The differential water head created can have a “driving” effect that moves the anchor to its final depth, while the water flow can have a penetration resistance reduction effect.

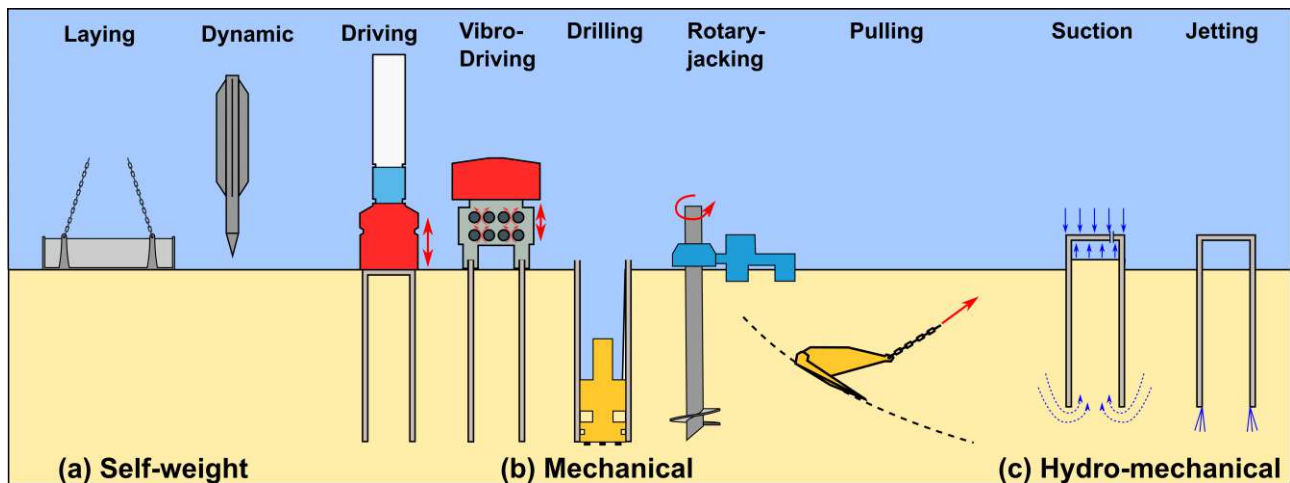


Figure 1-1 Anchor installation methods

Similarly, the resistance of the anchor to the load applied by the mooring line can be classified into three main categories (Figure 1-2), which depends on the origin of the mechanism that provides the resistance of the anchor (Cerfontaine et al., 2023):

- 1- The resistance **of gravity anchors**, which rest on the seafloor, is governed by the submerged weight of the anchor (with any ballast) and the resulting sliding resistance under lateral load, which typically only mobilizes a small volume of soil close to the surface.
- 2- **Pile-type** anchors are embedded into the seabed but extend to the surface. They resist axial load via interface shear mobilization and lateral load by soil bearing mobilization.
- 3- **Plate-type** anchors are totally buried, and mobilize soil bearing resistance against the face of the plate.

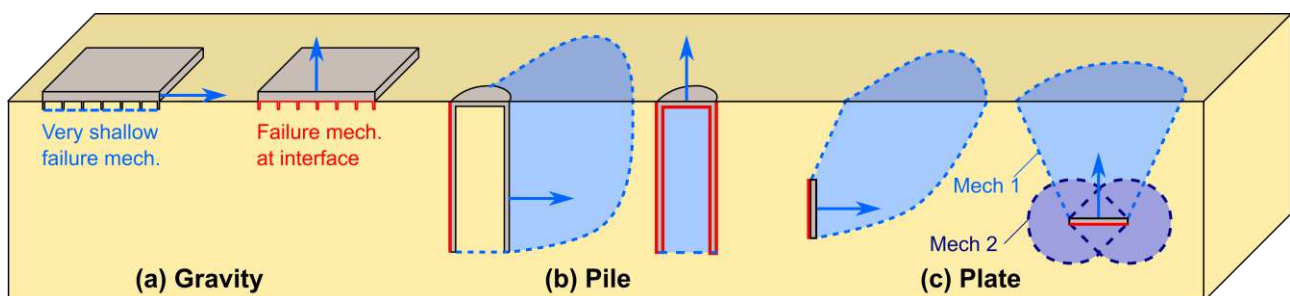


Figure 1-2 Anchor modes of resistance against loading by a mooring line in the horizontal or vertical directions (Cerfontaine, et al., 2023)

Using this taxonomy it is possible to classify anchors by their installation method and resistance mechanism in the matrix form illustrated in Figure 1-3. Certain anchor types cover secondary cells by being a hybrid of multiple types – for example, a suction bucket with ballast added post-installation, as illustrated in Figure 1-3.

This taxonomy is used in the following sections to systematically organize the wide range of anchor types.

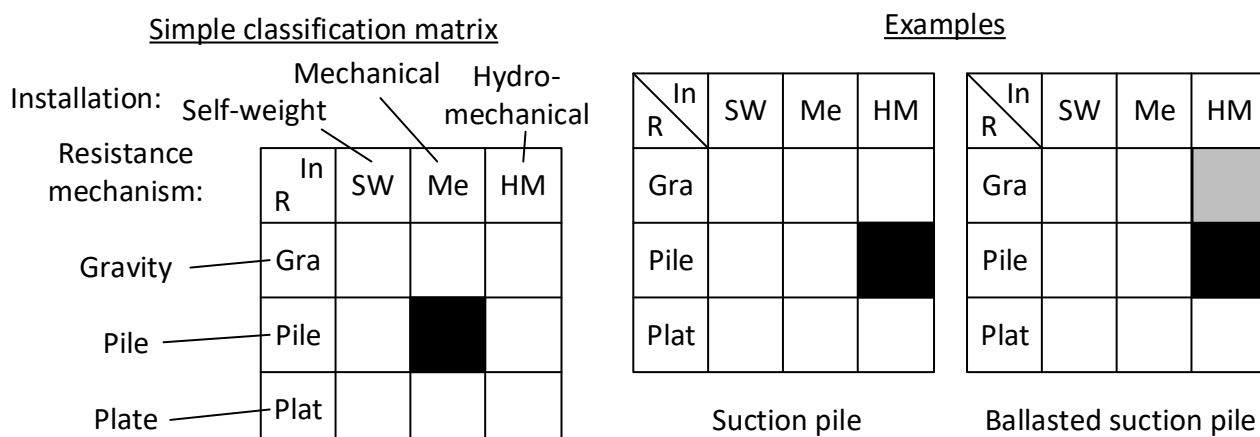


Figure 1-3 Classification of anchor types using simple taxonomy

1.2 Summary of commercially-used anchors

Table 1-1 provides a summary of commercially-available anchor types, defined broadly as those that are offered as products by commercial suppliers. Table 1-1 is divided into one row for each of the resistance mechanism types, and the taxonomy classification for each anchor is shown. Brief information is provided on the operating principles and typical dimensions. Example case studies are also given, where possible from floating offshore wind (FOW) applications. Where FOW examples are not available, examples are selected of comparable design loads and anchor dimensions to FOW applications, where possible. Due to the early stage of FOW development, few public anchor design case studies exist.

For the scenario modelling that forms the main part of this report, only the commercially-available anchor types are considered. This is because information is only readily available for these anchor types on their design approaches and commercial cost, allowing detailed comparisons to be made. In addition, anchor types that are not DNV-certifiable are excluded.

The resulting five anchor types are shown in Figure 1-4.

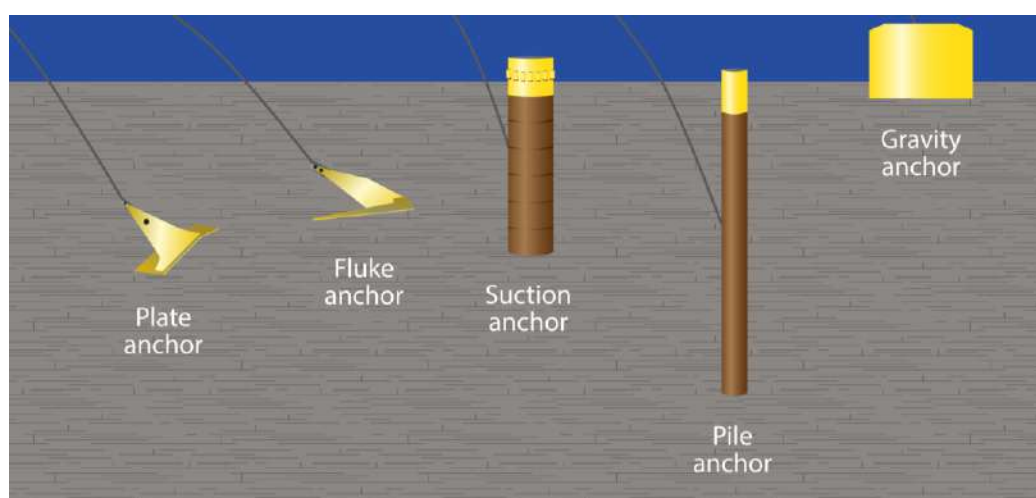
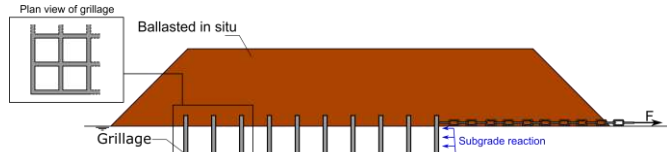
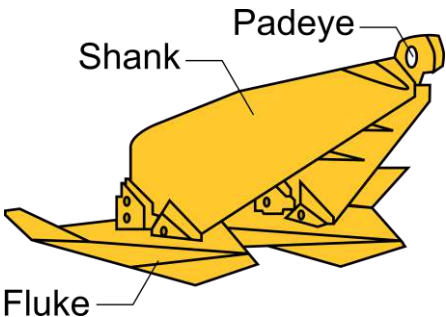
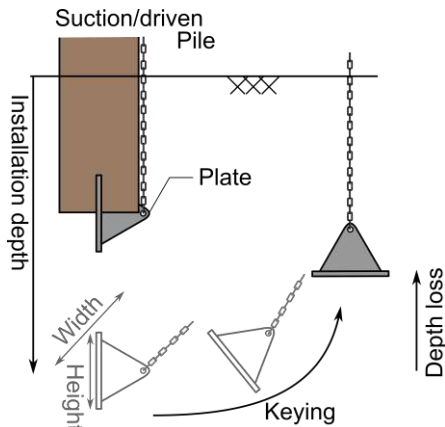


Figure 1-4 Selected commercially-available anchor types taken forward for scenario modelling

Table 1-1 Summary of commercially available anchor types

Gravity-type anchors																																																																																
Ballasted grillage		Description: A flat steel grillage that is placed on the seafloor and buried by a rock-fill or iron ore berm, e.g. using martite ($G_s = 4.3$). Grillages use less steel than a mudmat or box anchor. Their slight embedment ensures soil-soil friction at failure. Typical size: 20m × 10m grillage (×2 for berm plan area) Example use: Apache Stag field CALM buoy anchoring (Erbrich and Neubecker, 1999), for FPSO. Key references: Erbrich and Neubecker (1999), Bransby et al. (2011), Knappett et al. (2012).		<table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat					Precast blocks or ballasted box																																																		
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		 Washington State Dept of Transportation, CC BY-NC-ND 2.0 https://www.flickr.com/photos/wsdot/7302930476/in/photostream/		Description: Large precast concrete gravity anchors can be cast onshore and installed with appropriate lifting capacity. Box anchors reduce the lifting requirement by adding the weight via dumping or pumping of rock or iron ore after placing the empty box. Precast shapes can be optimized, e.g. by 3D concrete printing. Skirts on the box add sliding resistance. Typical size: up to 20m inside length – box or concrete Example use: Box anchor for North Rankin Flare Tower (Woodside Offshore Petroleum, 1988), Key references: Mostyn (1988), Lu et al. (2021)	<table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat																																																						
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Driven and vibro-driven piles		Suction pile		Screw pile	Torpedo pile	Description: Torpedo piles are cylindrical tubes filled with ballast to maximise the weight. Side fins provide additional shaft resistance. They are installed by free fall into the seabed. Impact speeds of up to 30 m/s lead to embedments of up to 3 times the length in soft soils. Mooring loads are applied via a chain attached to the tail of the pile. Typical size: D = 0.8-1.2 m, L = 12-15 m. Example use: Common in Campos Basin for MODUs. Key ref.: Randolph et al. (2011)																																																																										
						<table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat																																																					
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Description: Steel tubular piles are widely used as monopiles to support fixed offshore wind structures, and can also be used as anchor piles, with the pad-eye located at the top or down the shaft. Vibratory methods have a reduced environmental impact compared to hammers. Typical size: D=2-12m, L/D=3-60 Example use: For loads comparable to FOW: Ichthys FPSO/ CPF anchors (Erbrich et al. 2017) Key ref.: Cerfontaine et al. (2023) <table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>			In	SW	Me	HM	R					Gra					Pile					Plat					Description: Suction piles are installed into the seabed by pumping water from inside the pile creating a pressure difference across the caisson lid. This force relieves or overcomes the penetration resistance. Typical size: up to D = 16 m, L/D ≤ 1 in sand, L/D ≤ 8 in clay Example use: Hywind Scotland FOW and Hywind Tampen FOW (as shared anchors). Key ref.: Kay et al. (2021) <table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>			In	SW	Me	HM	R					Gra					Pile					Plat					Description: Screw (or helical) piles have a cylindrical shaft connected to one or more helices. Installation by static torque causes less noise than hammering. Tensile load is resisted by bearing on the helix which also enhances lateral load. Typical size: up to 1m helix diameter onshore, up to 0.3 m offshore, to date. Larger offshore concepts exist. Example use: Advanced Mooring Systems (AMS) for boat moorings in SW UK. Key ref.: Cerfontaine et al. (2024) <table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat					
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Plate-type anchors																																																																																
Drag-embedded (fluke-type)		Suction-embedded plate		Dynamically-embedded plate		Description: Dynamically-embedded plate anchors (DEPLASs) represent a combination of the torpedo pile concept for installation and the SEPLA for in-place capacity. Due to the dynamic installation process, the plate has a cruciform shape and may rotate about the vertical axis during installation and keying. Field trials and centrifuge test data exist, and the anchor is offered by a commercial supplier, but no field use is reported. Typical size: Fluke area ~ 10-35 m ² Example use: None in field Key ref.: Tom et al. (2024)																																																																										
				 Reproduced with permission, Copyright Conleth O'Loughlin		<table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat																																																					
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Description: Drag embedment anchors consist of a plate (the fluke) attached to a shank, to which the mooring line is attached. After lowering to the seabed they are dragged forward, embedding into the seabed. As the anchor embeds deeper, the resistance rises to the ultimate holding capacity (UHC). The bollard pull applied during installation is often used as verification of the installed capacity. Typical size: Fluke area ~ 15-50 m² Example use: Kincardine FOW farm Key ref.: Cerfontaine et al. (2023) <table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>			In	SW	Me	HM	R					Gra					Pile					Plat					Description: Suction-embedded plate anchors (SEPLAs) are installed using a 'follower' suction pile to push the plate to the installed depth. The plate fits into a slot at the base of the suction pile during this process. The follower is then removed by overpressure leaving the plate oriented vertically. As the attached mooring chain is loaded up, the plate is 'keyed' (i.e. rotates) to face the load direction, mobilizing the full available capacity. Typical size: Plate area ~ 15-50 m² Example use: Common in Gulf of Mexico for MODUs. Key ref.: Brown et al. (2010) <table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>			In	SW	Me	HM	R					Gra					Pile					Plat						<table><tr><td></td><td>In</td><td>SW</td><td>Me</td><td>HM</td></tr><tr><td>R</td><td></td><td></td><td></td><td></td></tr><tr><td>Gra</td><td></td><td></td><td></td><td></td></tr><tr><td>Pile</td><td></td><td></td><td></td><td></td></tr><tr><td>Plat</td><td></td><td></td><td></td><td></td></tr></table>		In	SW	Me	HM	R					Gra					Pile					Plat				
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1.3 Summary of emergent anchor technologies

The existing anchoring solutions were developed in the context of oil and gas facilities. The advent of floating offshore wind motivates innovation to suit its specificities, which include:

- 1- The number of anchors to be manufactured annually is two orders of magnitude higher than required for the demand associated with oil and gas facilities.
- 2- The need to reduce the (carbon) footprint of wind energy and reduce the associated resource use will push for less use of material, so anchor efficiency is more important.
- 3- The need for anchors with enhanced uplift resistance to meet design requirements for semi-taut and taut mooring lines and to suit tension leg (TLP) design situations.
- 4- The common requirement to increase the local content in all components of floating wind systems will need anchors that can be manufactured in Europe (and other FOW development regions) at a competitive price.

To meet these and other innovation drivers, many emergent anchor technologies exist. The innovation goal is to outperform existing solutions. For anchors, outperformance, in simple terms, can be by (i) increasing the design resistance of an existing anchor type or (ii) creating a novel anchor with improved efficiency (e.g. resistance per unit mass, or resistance per unit cost or time of installation).

Potential anchor technology innovations can be classified in the following four ways, and are illustrated relative to two existing anchor types (denoted A1 and A2) in Figure 1-5:

- 1- **Hybrids:** a new single anchor is created by combining existing concepts to achieve an enhanced performance or efficiency (A1-2 in Figure 1-5).
- 2- **Groups:** multiple smaller anchors of an existing technology are grouped together in a way that leads to enhanced performance or efficiency ($N \times A2$ in Figure 1-5).
- 3- **Enhancements:** the performance or efficiency of an existing anchor type is improved by changing its design properties, such as the skin friction or bearing capacity ($A3'$ from A3 in Figure 1-5). These enhancements could be a change to the anchor or could emerge from improved design methods that allow higher performance to be utilised.
- 4- **Invention:** a wholly new anchor technology could be introduced, with better performance or efficiency than existing ones ($A3$ in Figure 1-5).

An overview of emerging anchor types and technologies is provided in Table 1-2, based on a review of published literature, and divided according to these four classifiers.

In addition, improved anchoring performance can be unlocked at the scale of a wind farm, by using shared anchors – where multiple mooring lines are attached to a single anchor (Fontana et al., 2018). This leads to a reduction in the total number of anchors required. However, it is still unclear which park topology and which mooring layout and components are optimal, and how best to evolve anchor design to allow for the multidirectional loading from multiple attached lines.

A shared anchor must mobilise geotechnical capacity that balances the resultant from the connected mooring lines – as illustrated for the case of three line tensions, T_1 , T_2 and T_3 in

Figure 1-6, which lead to resultant force R . Numerical simulations of floating wind systems show that sharing can result in a reduction in peak lateral load, H , of between 30% and 50% (Pillai et al., 2022; Fontana et al., 2018) relative to a unidirectionally loaded anchor, as the mooring lines pull in opposite directions. However, the inclination of the resultant load to the horizontal direction is always greater than the angle of the mooring lines themselves, because the horizontal components of each line oppose each other, but vertical components add up. For this reason, the peak resultant vertical load, V , exceeds the unidirectional case. This effect is most significant for taut mooring lines, which may become more common with the development of synthetic mooring lines, but can also be true for catenary mooring lines, especially if the anchor padeye is below ground level.

In addition, the loading multi-directionality may change the effect of cyclic loading on the soil surrounding the anchor compared to unidirectional loading. This may have implications for the treatment of cyclic loading in the selection of design soil parameters.

Pile type anchors are the most adapted to anchor sharing, due to their vertical symmetry (Cerfontaine et al., 2023), but they can be vulnerable to cyclic inclined loading. Indeed, it was shown by (Huang et al., 2020) that such loading caused an increase in the lateral capacity, but a decrease in the vertical capacity. The risk associated with shared anchors is increased by the lack of data and prior experience with this technology. One commercial floating wind farm (Hywind Tampen) is secured by shared anchors and has been fully in operation since summer 2023.

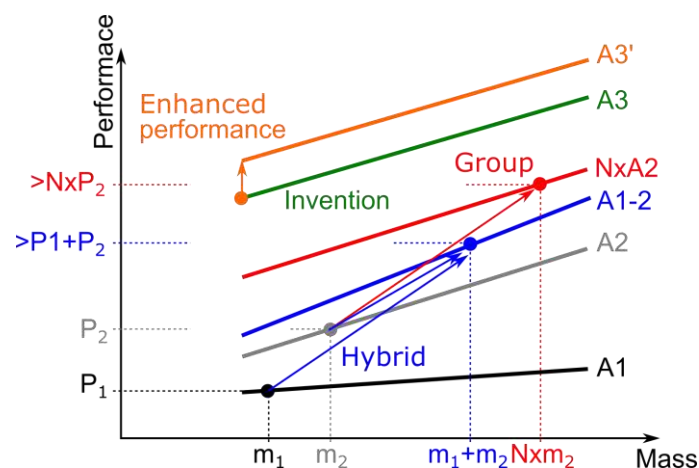


Figure 1-5 Illustration of anchor technology innovation types relative to existing anchors A1 and A2

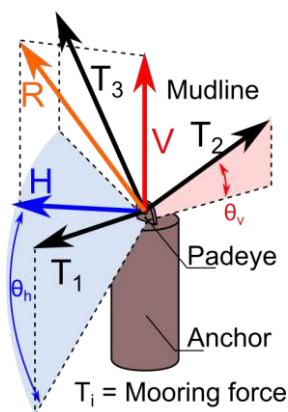
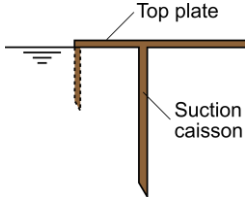
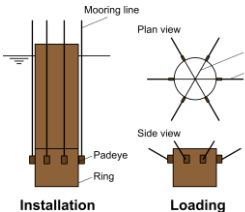
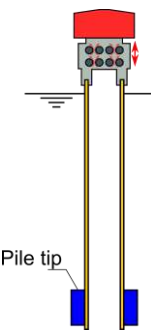
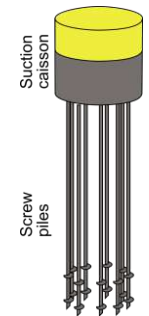
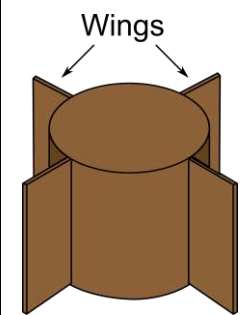
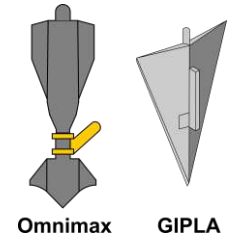
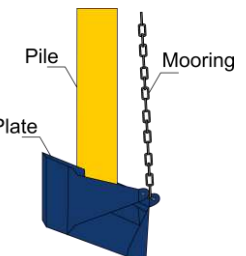
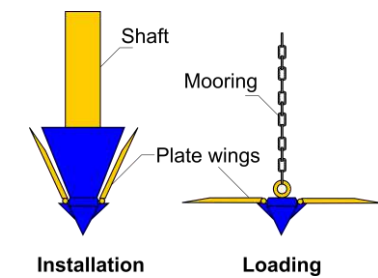
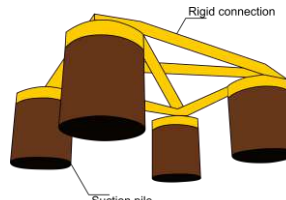
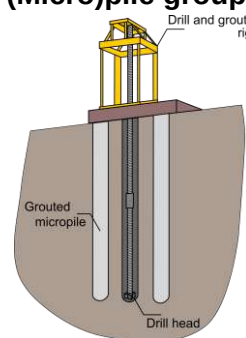
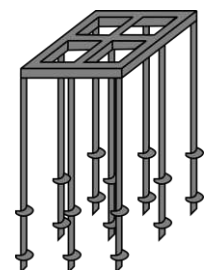
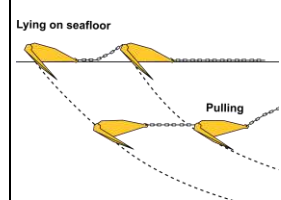
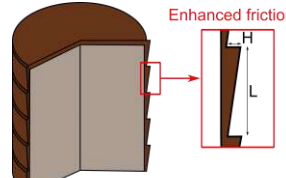
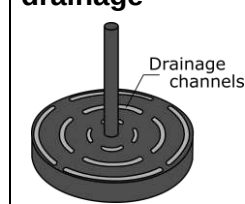
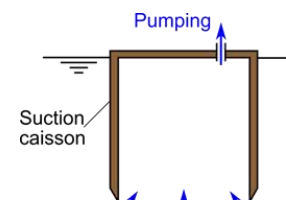


Figure 1-6 Illustration of loads on a shared anchor from three mooring lines (Cerfontaine et al. 2024)

Table 1-2 Summary of emergent anchor types and technologies

Hybrids – novel geometric combinations of anchor elements																							
Plate/dual-caisson 		Principle: Under lateral load, the plate enhances the ground stress and changes the failure mode from translation to rotation. Adding outer skirts creates a dual caisson: short outer and long inner. TRL: 4 References: Rui, et al. (2023), Zhang et al. (2022)		Multi-line ring 		Principle: The ring is installed by a 'follower' suction pile and the upper part is retrieved. The ring acts like an axi-symmetric plate anchor when loaded. Lateral flaps can be added to increase capacity. TRL: 4 Reference: Lee and Aubeny (2021)		UMACK 		Principle: The pile tip is shaped to penetrate easily during vibratory installation but offer high resistance during uplift loading (15MN capacity stated by manufacturer). TRL: 8 Reference: https://corp.powerocean.com/corpower-ocean-first-anchor-deployed/		Caisson-screw piles 		Principle: A combined suction caisson and set of helical piles optimizes lateral and vertical resistance. Installation is silent. Field trials have taken place. TRL: 6 Reference: https://www.tritonanchor.com/technology		Winged piles 		Principle: A suction pile or conventional pile is augmented by 'wings' or 'fins' over the upper part of the length. These add only minimal additional installation resistance but provide significant extra lateral capacity. TRL: 4 Reference: Faizi et al. (2023), Bienen et al. (2012)					
Hybrids – novel combinations of installation method and anchor type																							
Free-fall + drag-embedding plates 			Principle: This class of anchor combines the self-weight dynamic embedment of a torpedo anchor, with the high bearing capacity of a plate, achieved through rotation and keying of the anchor during loading. The Omnimax anchor has been used commercially but the GIPLA and Flying Wing Anchor have not. TRL: 4 References: Omnimax: Zimmerman et al. (2009) GIPLA: Han et al. (2020), Flying Wing Anchor: Hande et al. (2016)			Driven or jetted plates 			Principle: This class of anchor is a variation on the SEPLA, but using conventional pile driving techniques – hammering, vibration and jetting – to penetrate the multi-functional follower and attached plate. It is marketed as a 'flexibly-installed plate anchor' (FEPLA). TRL: 4 References: https://acteon.com/blog/flexibly-embedded-plate-anchors-for-floating-wind/			Jetting and activating plate 			Principle: This 'umbrella' anchor concept involves penetration of the folded plates using the follower with water jetting through the tip to reduce the resistance. The follower is then removed and pull-out force is applied to the mooring line. As the anchor moves upwards it opens to create an embedded plate anchor. The concept has been proven at small scale field trials. TRL: 4 References: Sivakumar et al. (2022)								
Groups – combinations of individual anchors to create a composite system																							
Suction pile group 			Principle: Multiple suction piles are linked by a rigid frame. The group is installed as a single unit. The resulting combined vertical and horizontal capacity can be optimized by varying the number and dimensions of the caissons. TRL: 8 Reference: Andersen et al. (1993), Zhu et al. (2020)			(Micro)pile group 			Principle: A group of closely spaced piles are used to provide the capacity of a larger foundation from smaller components. Grouted micropiles have been proposed as an option. These require a smaller drilling system than used for a single larger diameter pile. The piles are installed sequentially through a surface template foundation. TRL: 5 Reference: https://subseamicropiles.com/technology/			Helical pile group 			Principle: Closely-spaced screw piles are installed in sequence and connected by a pile cap to provide high pull-out resistance within a small footprint, and requiring only small installation forces and torques. The mooring load is transferred to the piles by a frame at the ground surface. Field tests indicate measured efficiencies of 0.6-1.0. TRL: 5 Reference: Bradshaw et al. (2022)			Piggyback anchors 			Principle: A pair of drag embedment anchors are connected using a line from the padeye or the rear of the shank of the front anchor to the shank of the rear anchor. This concept is available commercially. Field data shows that the pair of piggybacked anchors have more than double the capacity of a single anchor. TRL: 8 Reference: Lai et al. (2022), Walker and Taylor (1984)		
Enhancements – component modifications that are applicable to many anchor types																							
Directional friction 			Principle: This enhancement uses directional friction, inspired by biological surface textures such as snakeskin. The aim is to achieve greater friction under in-service loading compared to during installation. Doubling of friction has been shown in onshore pile tests (Martinez et al., 2024) and coating an entire suction pile has been examined in lab tests (Li et al., 2024). TRL: 3 Reference: Martinez et al. (2024), Li et al. (2024)			Accelerated drainage 			Principle: This enhancement uses passive drainage from permeable elements to raise rates of drainage and consolidation, for beneficial capacity effects in clay. Lab studies confirm this effect for plates (Wang et al., 2023) and piles (Ni et al., 2018). TRL: 5 Reference: Wang et al. (2023), Ni et al. (2018)			Active drainage / consolidation 			Principle: This enhancement uses actively-imposed suction (negative excess pore pressure) continuously or intermittently during the operating phase to raise the foundation capacity. In soft clay this suction can lead to permanent consolidation that raises the undrained bearing capacity. In sand a temporary rise in effective stress raises the drained capacity. The method has been used for gravity platforms (Eide et al., 1982) and in the lab on suction anchors (Helfrich et al., 1976). TRL: 8 References: Eide et al. (1982), Schofield (1974), Helfrich et al. (1976), Fiumana et al. (2018)								

1.4 Summary of emergent anchor in-service design capacity approaches

The offshore industry has a long track record of progressively unlocking better geotechnical performance by refining the accuracy and realism of design methods and improving understanding of the underlying mechanisms of the soil response. As knowledge increases, uncertainty reduces, and the performance that can be relied on in design increases.

Methods to calculate design values of ultimate limit state (ULS) anchor capacity are well-established and codified for commercially-available anchor types. These methods can also generally be adapted for the emergent anchor types, albeit with a need to validate the assumptions involved. Certain aspects of the design process are fully established and difficult to refine further. For example, numerical methods such as finite element analysis and finite element limit analysis (FELA) are readily available to establish bearing capacity factors to link soil strength parameters to ultimate anchor capacity, for any geometry of anchor and specified soil strength properties (Sloan 2013; Martin 2011).

However, there are wider aspects of the design capacity assessment that remain open to refinement, with potentially significant impact on the design capacity and required anchor size. These include (1) the definition ULS loads and failure criteria, (2) assumptions regarding the mobilized strength at the ULS and (3) the approach to input uncertainty and system reliability.

These aspects are each summarized below with illustrations in Figure 1-7. Further discussion is found in Cerfontaine et al. (2023) and Cerfontaine et al. (2024).

- 1- **Definition of ULS loads and failure criteria:** ULS loads are often treated as a static value for comparison with the static anchor resistance. In practice, the peak load may only be applied for a brief period – either related to the wave period, or for an even shorter period of around a second if linked to a snatch load in the mooring line. Because of the brief loading period, three additional considerations exist:
 - a. Even if the geotechnical capacity is exceeded momentarily, the anchor movement may be tolerable due to the short time period of the loading, so a displacement-based ULS could be more appropriate, and the design load could be permitted to exceed the static ULS geotechnical capacity. Also, in some other areas of civil engineering, the design action is defined as a peak load coupled with an impulse magnitude – the same could be appropriate here.
 - b. If anchor movement is permissible, then additional anchor resistance due to inertial effects may be mobilized. For example, Kwa et al. (2021) showed that for a plate anchor in soft clay, inertial effects can add 50% to the static capacity, due to the large volume of soil mobilised around the plate.
 - c. Also, if anchor movement is permissible, the ductility of the anchor is important, i.e. the variation in resistance with displacement beyond the initial capacity (Figure 1-7g). Some types of embedded plate-type anchor are deliberately designed to ‘dive’ deeper when loaded, meaning that the holding capacity is sustained indefinitely as the anchor is loaded and displaced. Similarly, the capacity of a gravity anchor may also be sustained over large

displacements. In contrast, the failure mechanism of pile-type anchor will generally lead to a loss of capacity after a short movement, although innovations could mitigate this effect and the actual displacement under a snatch load could still remain small and leave the anchor in a serviceable state.

2- Mobilized strength at the ULS:

- a. The soil strength that can be mobilized at the ULS may differ significantly from the in-situ value measured at conventional strain rates during the site investigation. Three different effects contribute: (i) installation-induced changes in soil properties (*'set-up'*), (ii) *whole-life* changes in soil properties due to operational loading and (iii) ultimate (ULS) load-induced effects on soil strength (*'loading rate effects'*). Each is discussed separately below.
- b. *Set-up* (Figure 1-7e-f): Anchor piles can show an increase in capacity following installation that can be linked to progressive decay of installation effects, such as excess pore water pressure dissipation or stress relaxation due to creep. For axially-loaded piles there are cases of a doubling in capacity over the months after installation (e.g. Jardine and Standing, 2012).
- c. *Whole life*: Conventional geotechnical design applies a reduction factor to allow for a damaging cumulative influence of cyclic loading. In many situations the opposite effect can occur: cyclic loading in combination with consolidation can lead to a gain in the strength of soft clays, and can lead to densification of sand. In both cases, the anchor or foundation can have higher long-term strength and stiffness by a factor of 2-3 (Kwa et al. 2023). For adoption of this concept it is useful to redefine the ULS requirement as 'the design resistance at any instant must exceed the design action at *that instant*', so that changes in design resistance with time can be incorporated (Gourvenec, 2020).
- d. *Loading rate effects*: The high loading rate during ULS design events also has an influence on the applicable soil strength. It is already well recognized in design that the undrained strength may be enhanced to reflect the strain rate during wave loading as compared to the standard laboratory testing rate (Andersen, 2015). There is also the potential influence of a change in drainage conditions to consider. For example, the partially drained or undrained strength of dense sand can far exceed the drained resistance. Roy et al. (2022) measured a five times increase in plate anchor capacity in medium-dense and dense sand from drained to undrained conditions. Even a small level of partial drainage can lead to a significant gain in capacity. In their study a 10 times increase in loading rate from the drained limit leads to a doubling of the anchor resistance. Similar effects have also been quantified for suction piles under uplift in sand (Cerfontaine et al. 2016).

3- Approach to uncertainty and reliability:

- a. The difference in failure consequences for floating offshore wind turbines compared to oil and gas structures justifies a revisiting of the reliability implicit in inherited design codes. This can be achieved through a reassessment of load and resistance partial factors, and also through wider adoption of probabilistic methods, via which a target reliability can be explicitly met. With greater clarity on geotechnical reliability, it is more likely that the optimum design solution is reached from both a cost and safety perspective.

- b. A benefit of assessing design reliability using a probabilistic approach is that uncertainties and variations that feed into design from the ground model can be readily incorporated and their effect on reliability to be quantified. For example, as well as the natural temporal variations in annual maximum storm intensity, it is also possible to allow for the uncertainty in designed capacity across the multiple structures in a wind farm, as well as temporal variations in geotechnical properties due to whole life effects the approach to input uncertainty and system reliability (Cerfontaine et al. 2024).

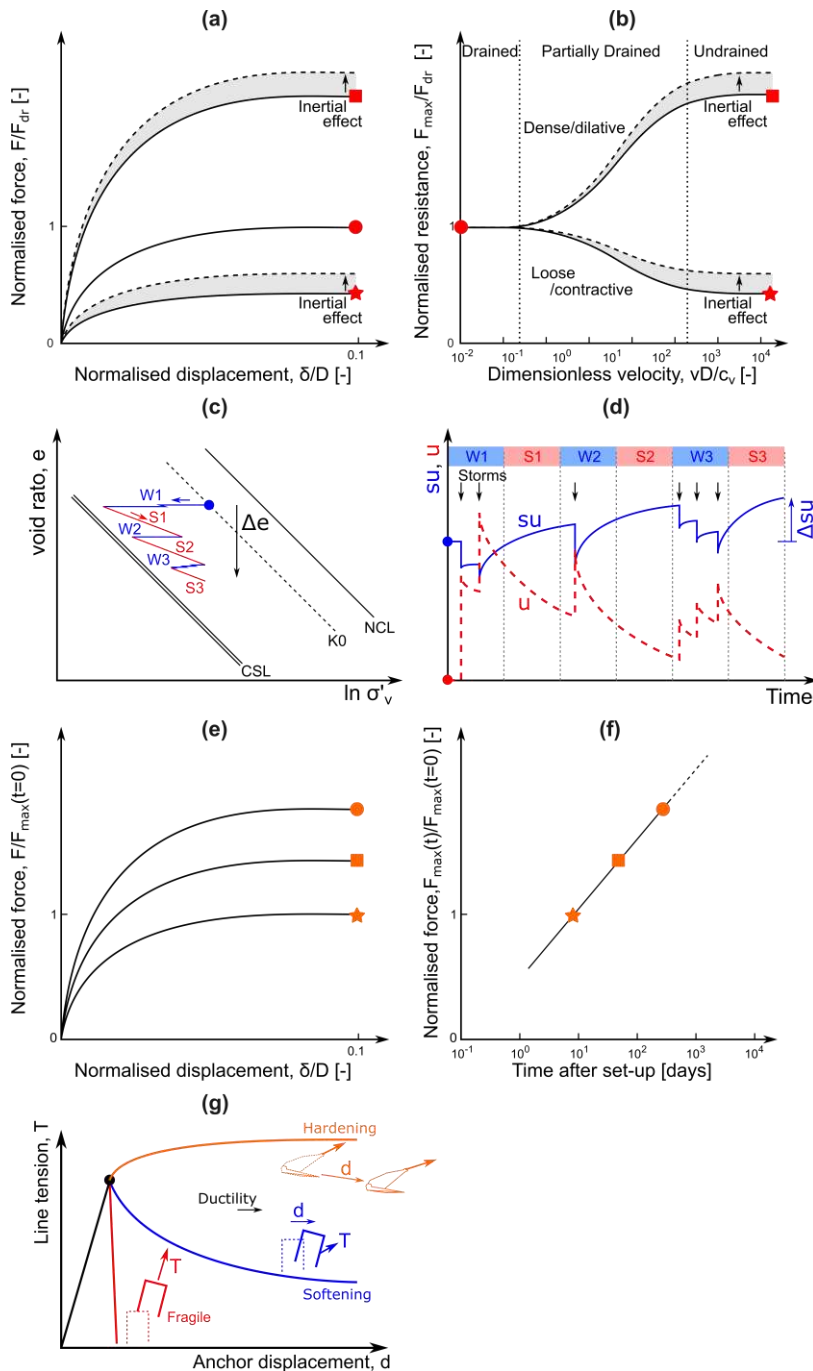


Figure 1-7 (a,b) Rate effect on anchor resistance in sand (F_{max}), normalised by drained resistance (F_{dr}), after Kwa et al. (2021) and Roy et al. (2022); (c) Changes in void ratio and effective vertical stress of an element of soil close to an anchor due to episodes of cyclic loading during winters (W) and summer (S) periods. (d) Change in pore water pressure (u) and mobilizable undrained strength in the soil element (s_u) with time. Schematic representation of whole-life effect, not to scale. Based on Laham et al. (2021); (e, f) Set-up effect on a pile resistance, normalised by the pile load just after installation ($F_{max}(t = 0)$) (Jardine and Standing, 2012); (g) Ductility, fragility and hardening of anchors at large displacements

2. Scenarios

TAILWIND scenarios include: (i) Floater type, (ii) Location featuring soil condition, metocean data and water depth, (iii) Mooring type, and (iv) Mooring line material. Details on floater type, mooring type, mooring line material and metocean data are given in the TAILWIND deliverable D1.1 (TAILWIND, 2024a). This Section will focus on soil conditions and load analyses results, which are necessary for the anchor assessment.

Given the screening scope of this deliverable, it was deliberately chosen to define general profiles based on existing data in the literature and the NGI soil database, rather than choosing real and thereby overly complex soil profiles. The WP3 members reckon that in the tasks 3.1, 3.2, and 3.3, which refer to the screening and experimental phases of the project, soil types should be kept separated for the sake of simplicity. In tasks 3.4 and 3.5 – i.e. numerical modelling and design tool – layered soil profiles will be considered.

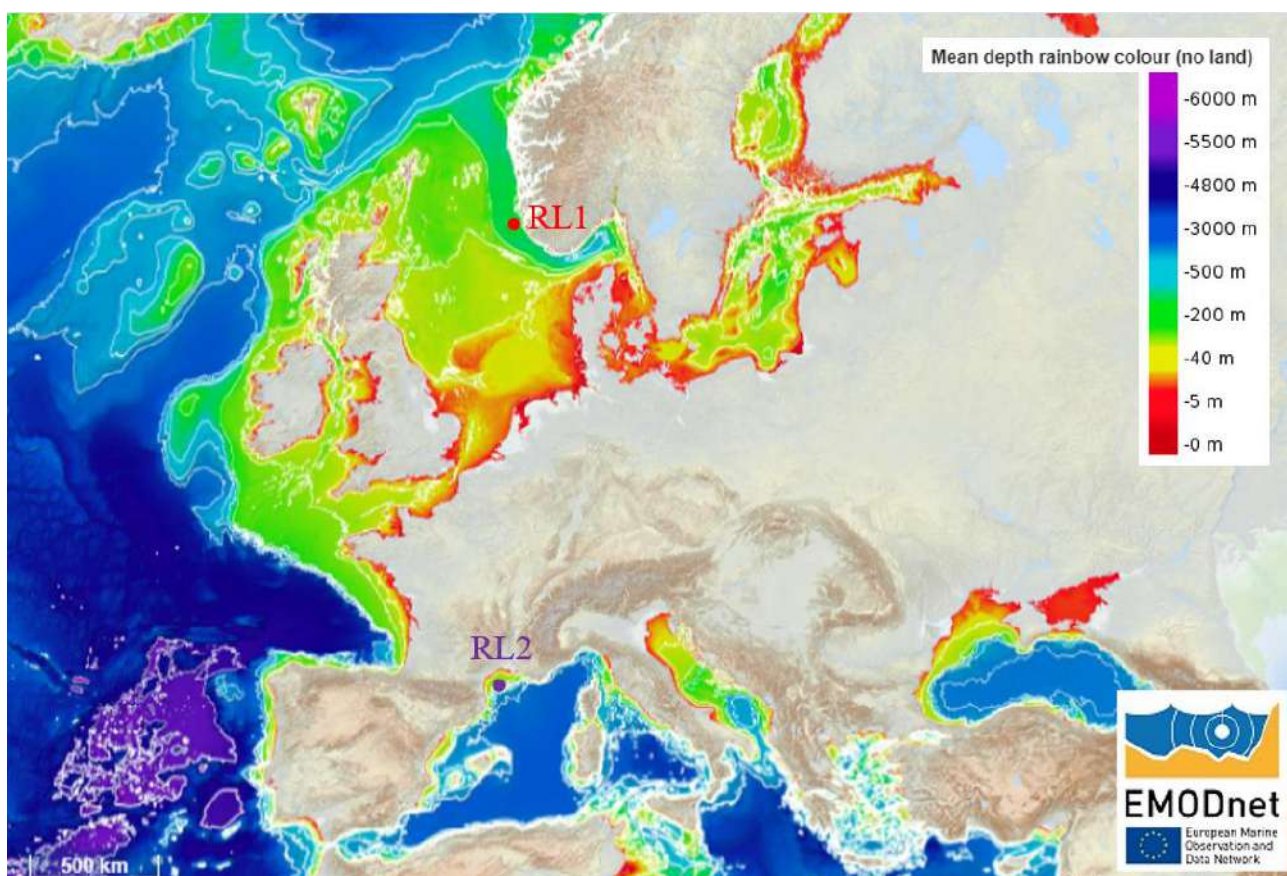


Figure 2-1 Mean water depth map taken from EMODnet (European Commission, 2024) with indication of Reference Location 1 (RL1) – Utsira Nord and Reference Location 2 (RL2) – Provence Grand Large

2.1 Soil profiles

To obtain metocean data and water depth for load analysis and soil profiles for anchor sizing, reference locations (RLs) were defined. Two reference locations were selected in TAILWIND: Reference Location 1 (RL1) – Utsira Nord in the North Sea, and Reference

Location 2 (RL2) – Provence Grand Large in the Mediterranean Sea. Figure 2-1 shows the reference locations on the mean water depth map of Europe taken from EMODnet (European Commission, 2024).

2.1.1 Utsira Nord - Reference location 1 (RL1)

RL1 has a water depth of 265 m and features clayey soil. The soil profile was based on the Troll Field data (Lunne et al., 2006) and was proven to be representative for this North Sea area by comparing it with the NGI soil profile database. Figure 2-2 shows the position of RL1 relative to the Troll Field on the Folk 16-class classification map taken from EMODnet (European Commission, 2024).

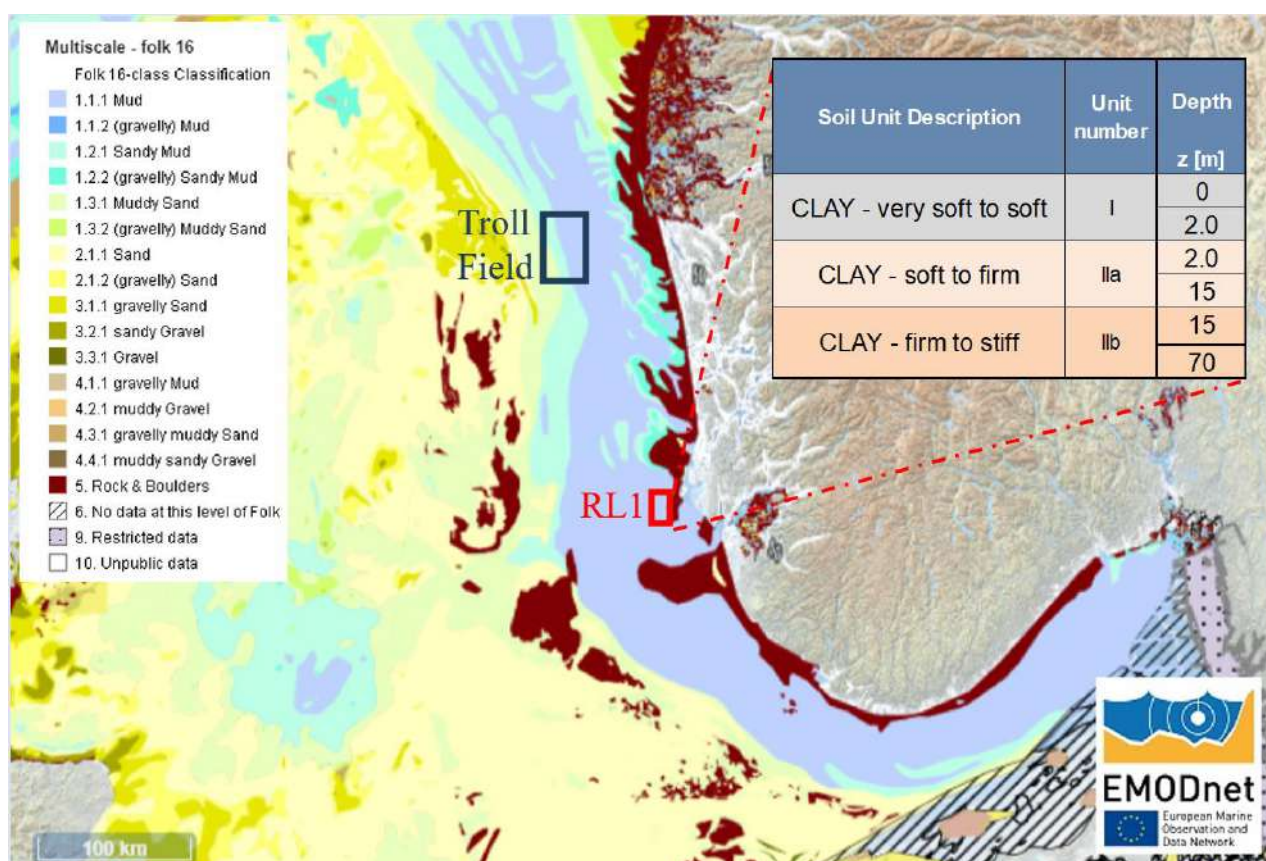


Figure 2-2 Position of RL1 relative to the Troll Field (Lunne et al., 2006) on the Folk 16-class classification map taken from EMODnet (European Commission, 2024)

Table 2-1 Properties of the RL1 soil profile

Soil Unit Description	Unit number	Depth	Unit weight	Best estimate cone resistance	Triax. comp. undrained shear strength	Soil sensitivity	Shear strength factor	Plasticity index	Overconsolidation ratio
		z [m]	γ [kN/m ³]	q_t [MPa]	s_{uc} [kPa]				
CLAY - very soft to soft	I	0	17.50	0.0	0				
		2.0	17.50	0.20	11.0				
CLAY - soft to firm	IIa	2.0	18.00	0.30	17.67	3	0.5	20.0	1.0
		15	18.00	1.00	48.73				
CLAY - firm to stiff	IIb	15	18.50	1.20	62.07				
		70	18.50	4.20	194.23				

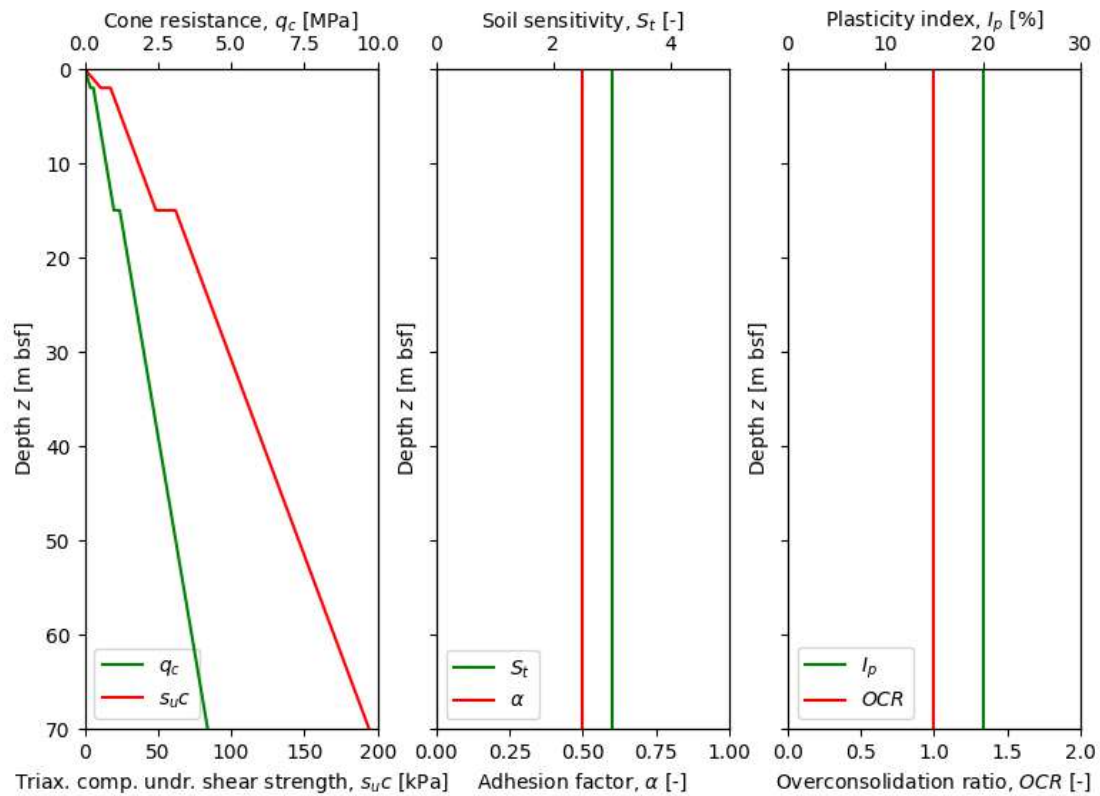


Figure 2-3 Properties of the RL1 soil profile

RL1 consists of three layers featuring very soft to stiff clay sediments. The main properties of the RL1 profile are given in Table 2-1 and plotted against depth in Figure 2-3.

2.1.2 Provence Grand Large – Reference location 2 (RL2)

RL2 has a water depth of 100 m and features sandy soil. The soil profile was based on the CPT data from Gulf of Lion reported by Lafuerza et al. (2008). In the latter article location PRGL2 shows medium dense to dense sand layers for the first 25 m followed by clay layers. As mentioned above under Section 2, a requirement for the WP3 was to have uniform soil profiles – i.e. one with sandy soil only and one with clayey soil only. This requirement led to the sand layers shown in Figure 2-4 together with the position of RL2 relative to the PRGL2 location (Lafuerza et al., 2008) on the Folk 7-class classification map taken from EMODnet (European Commission, 2024). The main properties of the RL1 profile are given in Table 2-2 and plotted against depth in Figure 2-5.

Table 2-2 Properties of the RL2 soil profile

Soil Unit Description	Unit number	Depth z [m]	Unit weight γ [kN/m ³]	Cone resistance q_t [MPa]	Relative density Dr [%]	Angle of internal friction ϕ [deg]	Steel-soil interface friction angle δ [deg]
Sand - Very loose to loose	I	0	20.0	0	35	28	
		2	20.0	2	35	28	
Sand - Medium dense to dense	IIa	2	20.5	10	70	33	29
		15	20.5	15	70	33	
Sand - Very dense	IIb	15	21.0	20	90	37	
		70	21.0	25	90	37	

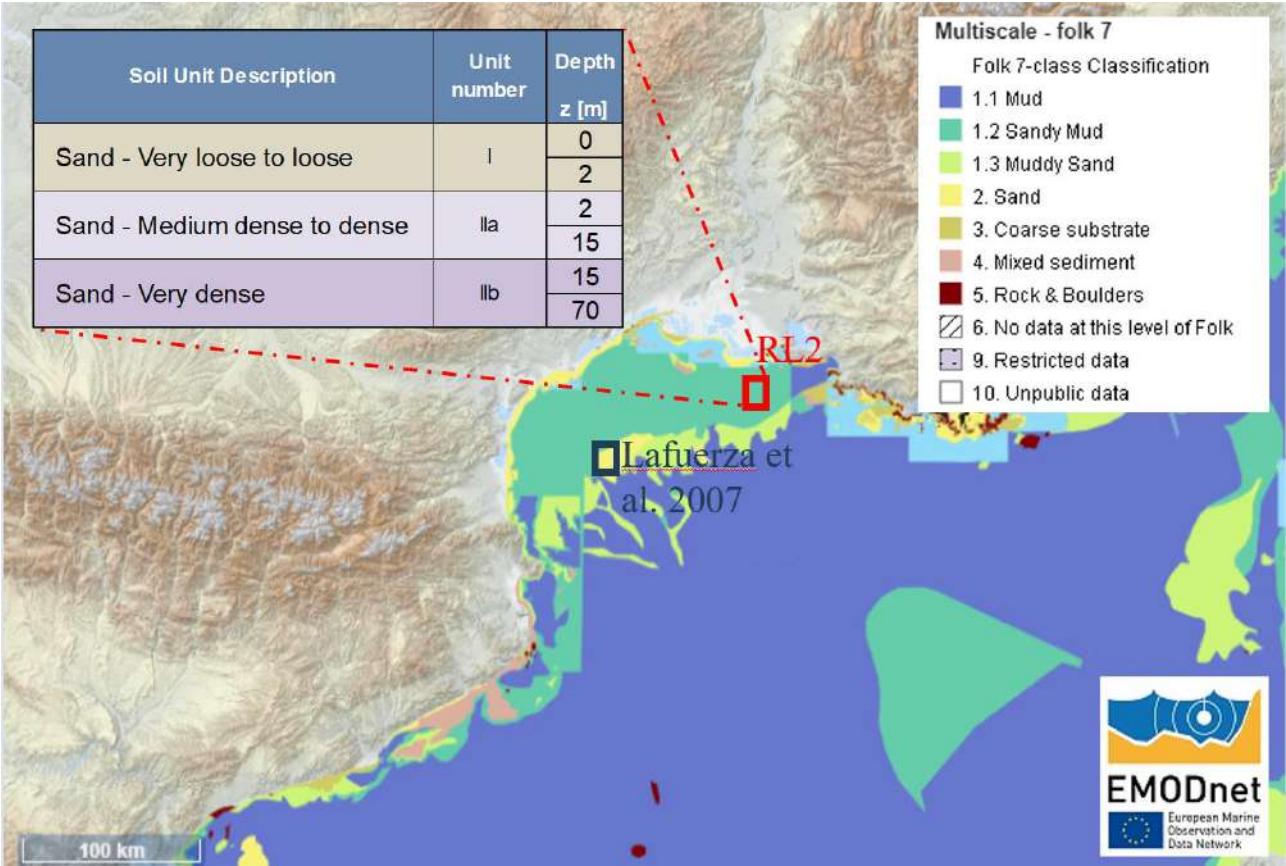


Figure 2-4 Position of RL2 relative to the PRGL2 (Lafuerza et al., 2008) on the Folk 7-class classification map taken from EMODnet (European Commission, 2024)

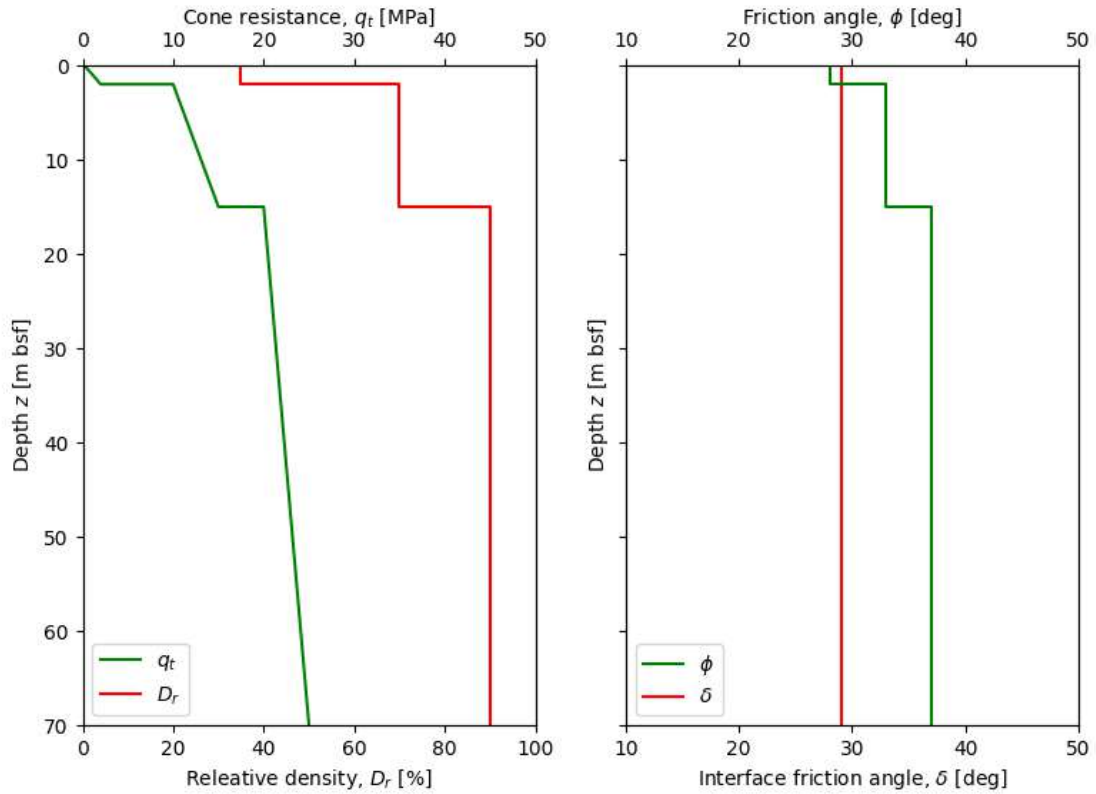


Figure 2-5 Properties of the RL1 soil profile

2.2 Load analyses

The load analyses were run by the WP1 partners NAUTILUS and TECNALIA with the software OrcaFlex. A wind turbine with 15 MW nominal power was used for the simulations. Three floater concepts were considered:

- 1- **Semi-submersible** - The NAUTILUS semi-submersibles achieve stability mainly through the ballast provided by the four columns that form the platform.
- 2- **Tension Leg Buoy (TLB)** - The TECNALIA TLB is a mooring stabilised platform that achieves stability mainly through the robust station keeping system with mooring lines featuring pretension.
- 3- **Tension Leg Platform (TLP)** - The TLPs are mooring stabilised platforms anchored to the seabed by means of tendons. The TLP considered in this study was taken from Phillips (2022).

Moreover, four mooring configurations were considered:

- 1- **Catenary** - Line configuration that never induces vertical load to the anchor.
- 2- **Semi-taut** - Line configuration that in some load cases applies a vertical load component to the anchor.
- 3- **Taut** - Line configuration that reaches the anchor at an angle to the seabed so that a vertical force component is always present.
- 4- **Tendons** - Where the platform is held in position by highly pre-tensioned vertical tendons. Anchors of this type are subjected to high vertical loading.

Overall, 20 scenarios were defined in WP1, from the applicable combinations of the two sites, three floaters and four mooring configurations. Not all of them were eventually selected for load analyses. Details regarding the selected scenarios for load analysis such as metocean data, design load cases, load safety factors, mooring line material and mooring type are given in the TAILWIND deliverable D1.1 (TAILWIND, 2024a). In this report, only the information strictly necessary for the anchor assessment is given.

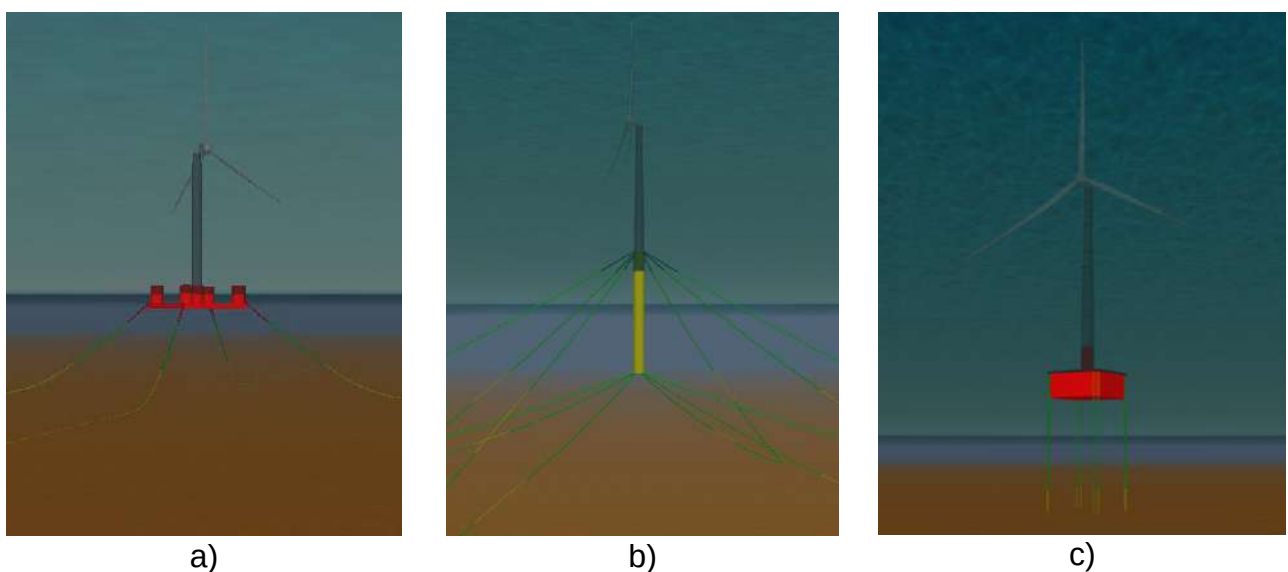
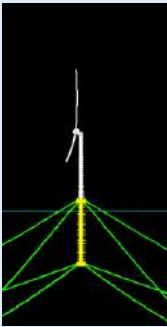
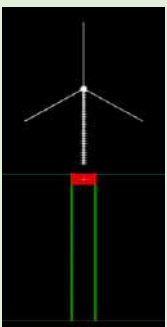


Figure 2-6 OrcaFlex rendering of the FOW platforms: a) Semi-submersible; b) TLB; c) TLP

Table 2-3 Summary of the load analysis results

Platform	Site	Mooring concept	Scenario	Design tension T_d [MN]	Loading angle relative to horizontal [deg]
Semi-submersible 	RL1 - Utsira Nord (265 m)	Semi-taut	3	12.2	6.0
			3b	11.7	7.6
	RL2 - Provence Grand Large (100 m)	Semi-taut	7	20.3	9.6
TLB 	RL1 - Utsira Nord (265 m)	Taut	10	35.2	23.7
			10b	38.7	13.6
TLP 	RL2 - Provence Grand Large (100 m)	Tendons	20	82.2	90.0
			20c	17.6	

The scenarios taken from WP1 that are considered in this report for the assessment of the anchor technical reliability and industrial feasibility are Scenario 3, Scenario 3b, Scenario 7, Scenario 10, Scenario 10b, and Scenario 20c. Semi-submersible scenarios use hybrid chain and polyester mooring line. The TLB scenario uses hybrid steel and dyneema mooring lines. The TLP scenario uses steel tendons. Scenario 3b and 10b feature shared anchors. In Scenario 20c a nominal design tension was used for anchor assessment. Justifications for this selection are given in the following sections and the load analysis results are summarised in Table 2-3. The design tensions T_d of each scenario, was calculated by identifying the peak load among all load series of a given scenario and applying load factors after (DNV, 2021b):

$$T_d = \gamma_{mean} \cdot T_{c,mean} + \gamma_{dyn} \cdot T_{c,dyn}$$

Where $T_{c,mean}$ and $T_{c,dyn}$ are the characteristic mean and dynamic tensions whereas γ_{mean} and γ_{dyn} are the load factors for mean and dynamic load component respectively. γ_{mean} was 1 for TLB and TLP and 1.3 for the semi-submersible. γ_{dyn} was 1.3 for TLB and TLP and 1.75 for semi-submersible. The reader is referred to the WP1 report TAILWIND (2024a) for more details on the load analysis.

Scenarios 3 and 7

The semi-submersible concept of NAUTILUS is the platform with the highest technology readiness level (TRL) among the platforms considered in WP1. This is also globally true, as ERM (2024) states that semi-submersible will likely be the most deployable solution globally. For these reasons, the WP3 partners decided to explore this platform in both RL1 (Scenario 3) and RL2 (Scenario 7).

There were two alternative mooring concepts available for semi-submersible: catenary and semi-taut. After discussing potential mooring concepts with the TAILWIND partners and stakeholders, the semi-taut mooring configuration was selected on the basis of its high likelihood to be used in real projects due to its more efficient material usage as opposed to catenary systems. The semi-submersible is anchored to seabed by means of four anchor points.

Scenario 10

The TLB concept of TECNALIA is anchored by means of 12 mooring lines in six directions. For each direction there is an upper and a lower mooring line. Each upper and lower mooring line is connected to a separate anchor.

The TLB has a lower TRL than the semi-submersible and is investigated in TAILWIND as a concept that can potentially decrease the cost of the platform component at the cost of larger station-keeping elements. As a result of that, the loads of Scenario 10 are significantly larger than those of Scenario 3 and are deemed to be too large for feasible deployment. Nonetheless, Scenario 10 is considered for anchor technical reliability assessment to explore their logistical and economical limitations. During the project, it will be attempted to reduce the TLB loads by optimising mooring material, platform or by selecting wind turbines with smaller nominal power.

Scenario 20c

Existing TLPs in the FOW market such as those designed by SBM¹ and BLUEWATER² have been optimised and have high TRLs. The TLP concept taken from Phillips (2022) was not optimised and this resulted in very large load magnitudes in the range 70 MN to 90 MN per anchor, considering 4 anchor points and 2 tendons per anchor point. After internal discussions among the TAILWIND partners as well as interface with external stakeholders, it was decided to design TLP anchors for nominal design tension – i.e. Scenario 20c.

Anchors for Scenario 20 have been designed for completeness. As expected, the calculated anchor dimensions are comparable to those used for large oil and gas facilities (Randolph and Gourvenec 2011), which make the station keeping system for Scenario 20 not feasible for large scale floating wind deployment.

Scenarios 3b and 10b – Shared anchors

¹ Link to website: <chrome-extension://efaidnbmninnibpcapjpcglclefindmkaj/https://www.bluewater.com/wp-content/uploads/2024/01/Leaflet-Floating-Offshore-Wind-TLP.pdf>

² Link to website: <https://www.sbmoffshore.com/what-we-do/floating-offshore-wind/>

As part of the WP3 scope, the assessment of anchors shared among more than one FOW platforms was performed. These are the Scenarios 3b and 10b whose layout is shown in Figure 2-7. From literature the main layout criterion for shared anchor systems is that the minimum clearance between two turbines should be at least 7 times the rotor diameter (Catapult, 2024). To run Scenario 10b, Scenario 10 was modified to achieve a minimum clearance between the turbines. The layout of Scenario 3b was not modified and the minimum distance between two turbines was 6.5 times the rotor diameter. For Scenario 3b it was reasonably assumed that the difference in loading conditions between 6.5 and 7 times the rotor diameter will not affect the anchor size significantly.

The shared anchor design tension and the loading angle were estimated by calculating the resultant of the mooring line loads relevant to the shared anchor (Fontana et al., 2018; Catapult, 2024)

In Table 2-3 it is seen that the design tension for shared anchors (Scenarios 3b and 10b) is not decreasing as suggested in literature (Fontana et al., 2018; Catapult, 2024). This is due to the specific layouts and the mooring concepts chosen. The shared anchor of Scenario 3b is characterised by four mooring lines and a semi-taut mooring concept. Since four mooring lines contribute to the resultant – not three as in Fontana et al. (2018) and Catapult (2024) – the downwind mooring line is barely loaded whereas the two mooring lines perpendicular to the wind and wave direction do not affect the upwind mooring line significantly.

Considering the above, it seems that depending on mooring concept, loading direction, and layout, the compensating effect on shared anchors might not be substantial. This was acknowledged also in Catapult (2024) where the load reduction for taut mooring systems was smaller than that of catenary and semi-taut mooring configurations. Nevertheless, as shown in Section 4, shared anchors can be quite advantageous as the total number of anchors is 20% to 40% less so that installation and site investigation time can be reduced.

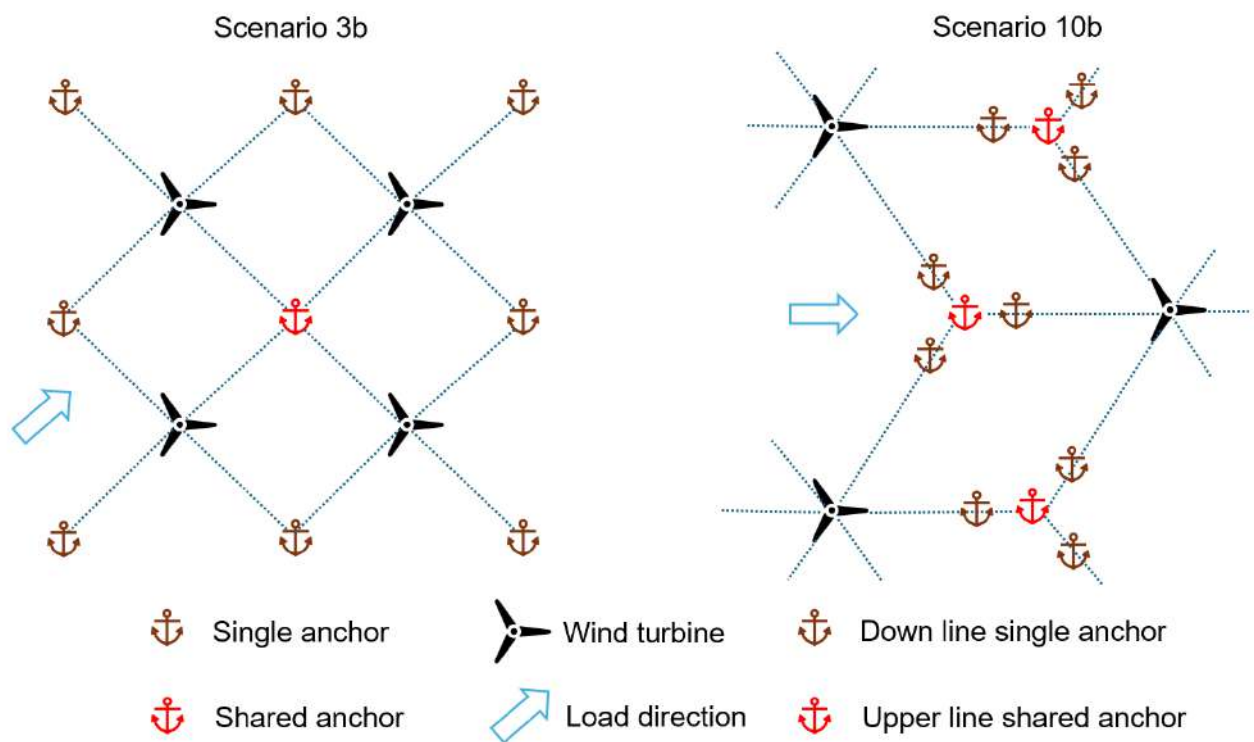


Figure 2-7 Layouts of shared anchor scenarios: Scenario 3b and Scenario 10b.

3. Technical reliability

In this section five anchor types are designed on the basis of the loads and soil conditions described in Section 2. The technical reliability is assessed for the five common anchor types shown in Figure 3-1: Gravity anchor, pile anchor, suction anchor, fluke anchor, and plate anchor.

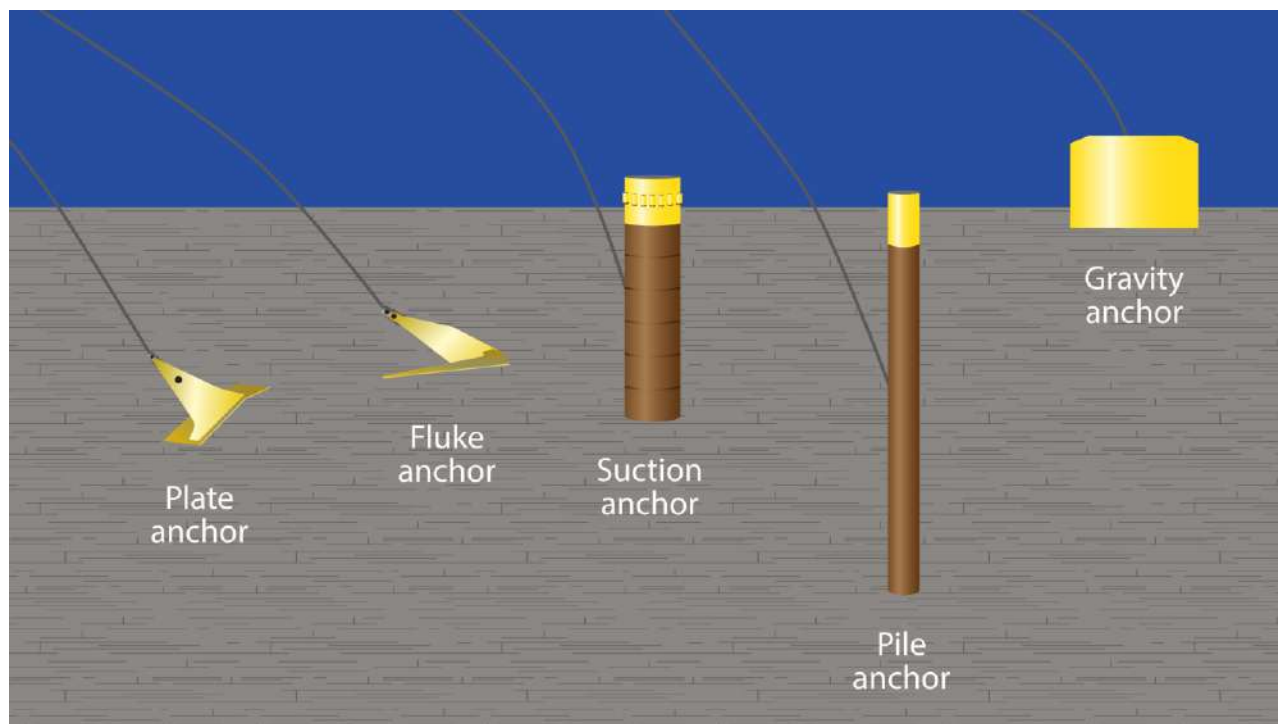


Figure 3-1 Five anchor types for which the technical reliability is assessed

Material factors

DNV (2021b) defines the material factors as shown in Table 3-1. In the table the ALS factors are shown for the sake of completeness; in this task only ULS analyses are performed. Each anchor type is sized using state-of-the-art capacity methods under ULS conditions. Anchor installation feasibility is not analysed in detail. However, considerations on installation feasibility are made for each anchor type.

Table 3-1 Material factor used for technical reliability according to DNV (2021b). ALS shown for the sake of completeness. Technical reliability is performed for ULS conditions only

	Material factor - γ_m		
	ULS	ALS	
		Consequence class 1	Consequence class 2
Pile anchor	1.3	1	
Gravity anchor	1.3	1	
Suction anchor	1.2	1	1.2
Fluke anchor	1.3	1	1.3
Plate anchor	1.4	1	1.3

Loading angle at padeye

To calculate the loading angle at padeye the internal NGI software ChainConfig NGI (2006) was used. This software implements limit equilibrium to estimate the chain configuration from seabed to padeye using design tension, loading angle, chain properties, and soil properties as main input parameters.

3.1 Pile anchor

Driven piles are open-ended steel piles with circular cross section installed by hydraulic hammers – typical driven pile relative dimensions are $7D < L < 20D$. Piled foundations are the most used offshore foundations given their reliable and well-established installation procedure and good material efficiency. The foundation geometry features axial symmetry so pile anchor can be shared among more than one floater.

3.1.1 Methods and assumptions

Axial capacity

To fulfil the ULS check, the bearing capacity calculations were run with the NGI software PACER, which implements axial bearing capacity methods for several methods. For both sand (RL2) and clay (RL1) the Unified CPT-based method was used (Lehane et al., 2020; Lehane et al., 2022). The calculated axial bearing capacity was compared with the vertical tensile portion of the design tension considering the loading angle.

Lateral response check

A further check included horizontal displacement at pile head to be smaller than 10% of D , which is a typical requirement used by Industry. The NGI software SPLICE, which is a tool that implements different load-transfer curves for piles in sand and clay, was used for this analysis. The p - y curves after ISO (2007) were adopted. The padeye was assumed to be down at $1/3 L$ in clay (RL1) and down at 4 m for sand (RL2). The wall thickness was assumed to be 50 mm or 65 mm.

Installation feasibility

No project specific pile drivability analysis was performed. The installation feasibility of the pile anchors was comparatively checked against recent projects, where pile drivability analysis was performed. The comparison involved pile dimensions, pile tonnage, and soil profiles. The following hydraulic impact hammers were chosen:

- Menck MHU 800S for piles with $D < 4$ m;
- Menck MHU 1200S for piles with $D > 4$ m.

3.1.2 Results

An overview of the results is given in Table 3-2. The piles for Scenario 10 and 10b are notably the largest given the high design tension. Note that as mentioned above in Section 2.2, Scenario 20 requires pile clusters that are comparable to oil and gas platforms. This is deemed to be not viable in the FOW sector, so this scenario is not further pursued here.

Instead, Scenario 20c, for which a nominal T_d was identified based on discussions with TAILWIND partners and external stakeholders, was further analysed.

Table 3-2 Summary dimensions for pile anchors or driven piles

Scenario	Diameter [m]	Diameter [inch]	Embedment length [m]	Wall thickness [m]	Dry weight [t]
3	3.35	132	32	0.05	132
3b	3.35	132	29	0.05	120
7	3.35	132	24	0.05	99
10	4.27	168	46	0.05	246
10b	4.27	168	50	0.065	341
20*	3.35	132	45	0.05	928
20c	3.35	132	45	0.05	186

* 5-pile cluster

Sand

Clay

3.2 Gravity anchor

Gravity anchors are ballasted shallow foundations. Typical gravity anchors are grillage plus berm systems or box anchors where a large steel box (alternatively with skirts and made of concrete) is filled with ballast to reach the necessary buoyant weight. Recent steel box anchors have been conceived to be modularly installed to reduce the maximum installation weight³. Shallow foundations are usually not considered in soft sediments such as the normally consolidated soil of RL1 due to the seabed having insufficient bearing capacity for the weight. In this study box anchors have been designed for Scenarios 7 and 20c.

3.2.1 Methods and assumptions

The design methods depend on the type of mooring configuration. For Scenario 7, the box anchor design was based on a sliding check assuming an interface friction angle, δ , of 29 degrees in sand. For Scenario 20c the vertical force is counteracted only by means of the buoyant weight of ballast and steel box.

The ballast used was iron ore with a dry unit weight of 25.5 kN/m³. The steel box used were assumed to feature: (i) length equal to width (square surface); (ii) enough height to contain the required ballast; (iii) H-beams as interim stiffeners; (iv) wall thicknesses between 5 and 10 mm; (v) installation modules with a maximum weight of 200 t.

3.2.2 Results

An overview of the results is given in Table 3-3. The gravity anchor for Scenario 20c is smaller given the less onerous design tension and the absence of horizontal load component.

³ Link to website: <https://www.offshorewinddesign.com/gravity-anchors/>

Table 3-3 Summary dimensions for gravity anchors

Scenario	Width [m]	Length [m]	Height [m]	Dry weight box [t]	Dry weight ballast [t]
7	20	20	8	727	7982
20c	14	14	5	321	2564

Sand
Clay

3.3 Suction anchor

Suction anchors are caissons closed at the top and installed to target depth by pump-induced under pressure – typical suction anchor relative dimensions in clay are $3D < L < 6D$. Given the physical limitations of installing these anchors by underpressure they are mainly used in fine-grained materials, where the risk of piping failure is prevented by the comparatively small soil permeability.

3.3.1 Methods and assumptions

To fulfil the ULS check, bearing capacity calculations were carried out with the NGI software Bifurc which is a 2D finite element program where 3D effects are included by calibrated roughness factors for side shear both for soil-soil and steel-soil side surfaces. As many other NGI geomechanical analysis tools, Bifurc models anisotropic shear strength according to the critical failure mechanism found – see for instance Andersen (2015).

All Bifurc analysis accounted for the cyclic loading effects by modelling the cyclic soil shear strength. All the analysis was performed using undrained shear strength, independently of the material. The main parameters required for the software are:

- Cyclic undrained shear strength from DSS tests, $\tau_{f,cyDSS}$;
- Cyclic undrained shear strength from compression triaxial tests, $\tau_{f,cyC}$;
- Cyclic undrained shear strength from extension triaxial tests, $\tau_{f,cyE}$;
- Skirt wall friction (shear strength factor of 0.5 for both coarse and fine grained material);
- Design tension from Section 2;
- Loading angle at padeye from ChainConfig

For the bearing capacity analysis, the following assumptions and simplifications were made:

- The padeye is assumed at $2/3 L$ below mudline in clay (RL1) and 2 m below mudline in sand (RL2);
- The foundation is idealised as an embedded rectangular solid structure with a width equal to the anchor diameter;
- No open crack on the active side of the suction anchor is considered;
- The wall thickness, t , is 40 mm if $D \leq 5$ m, 50 mm if $5 \text{ m} < D \leq 10$ m, and 60 mm if $D > 10$ m;
- The equivalent lid thickness used to estimate the suction anchor weight is 100 mm;

- No detailed structural design for transportation, marine operations, and installation were made;
- Fines content of the sand for the cyclic shear strength evaluation is assumed smaller than 5% ;
- Drained frictional parameter $\beta = K \tan(\delta) = 0.35$ (used to calculate the unit skin friction $f = \beta \sigma'_v$).

Ballast and drained analysis for TLP – Scenario 20c

Suction anchor or clusters of suction anchors for TLPs can be designed with substantial ballast taking the help of counteracting the average load – see for instance Støve et al. (1992). The suction anchor for Scenario 20c was designed with substantial ballast to counterbalance static vertical load. Ballast and drained external and internal skin friction resistance were designed to take the average part of the design tension, which was calculated as 10.5 MN. For the drained frictional capacity of the foundation $\beta = K \tan(\delta) = 0.35$ was taken. For a suction anchor with $D = 10$ m, $L = 6$ m, and $t = 0.06$ m the drained capacity was 6.19 MN (5.16 MN after factoring with $SF = 1.2$). Note that to allow for the inclusion of the internal friction, it was checked that the soil plug was heavier than the internal friction contribution.

The required ballast counterforce to cover an average load of 10.5 MN was 5.34 MN. Assuming an iron ore ballast type with a density of 2.6 t/m^3 and subtracting the self-weight of the foundation, 282 m^3 of ballast were estimated. By placing the ballast material in an extended stick up part of the skirt, the height of the deposited material is 3.6 m. Use of clump weights such as those shown by Offshore Wind Design AS (2024) might be advantageous over the use of iron ore. This was however not considered in this report due to lack of knowledge about the related cost.

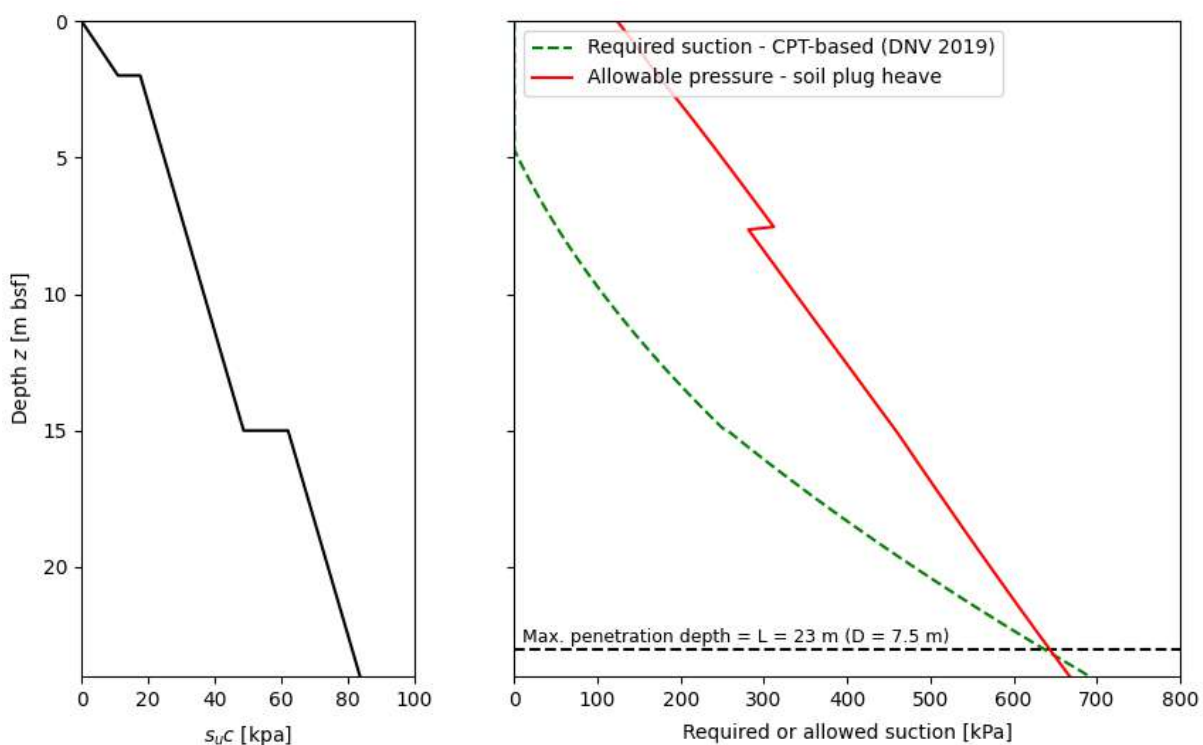


Figure 3-2 Installation feasibility analysis for Scenario 10 (clay and anchor diameter $D=7.5$ m)

Installation feasibility

The installation feasibility of the suction anchors was checked with the NGI internal software AnchorPen (NGI, 2008). The required suction was calculated using the CPT-method, for which the most probable empirical coefficients according to (DNV, 2019) were used. DNV (2017) gives the empirical coefficients: k_p , that relates the cone resistance q_c to the end resistance (0.3 for sand and 0.4 for clay) and k_f , that relates q_c to the skin friction (0.001 for sand and 0.03 for clay). These factors are multiplied by the cone resistance q_c and integrated over the relevant surface – either the annulus or the skirt wall – to obtain the penetration resistance contributions of shaft and skirt tip.

In sand, the required suction was checked against the cavitation pressure. In clay, the required suction was checked against the soil plug failure. A typical result is shown in Figure 3-2, where allowable and required suction are shown next to the soil profile of Scenario 10. It is worth pointing out that suction bucket installation in layered soils and/or very competent soils still poses challenges. To use suction anchors at scale the latter challenges should be addressed.

3.3.2 Cyclic strength parameters

The cyclic parameters are estimated following the approach recently proposed in Andersen et al. (2023), which is based on the comprehensive work described in detail in Andersen (2015). The work flow for the estimation of the cyclic strength parameters is given in Figure 3-3:

- Identification of the cyclic storm load series
- Rain flow analysis of the load series to obtain the parcels of cyclic load components;
- Estimation of cyclic to average ratio τ_{cy}/τ_a based on cyclic and average component of the peak load in the analysed load series;
- Calculation of the equivalent number of cycles based on cyclic load history using the strain or pore pressure accumulation method (Andersen, 2015) N_{eq} ;

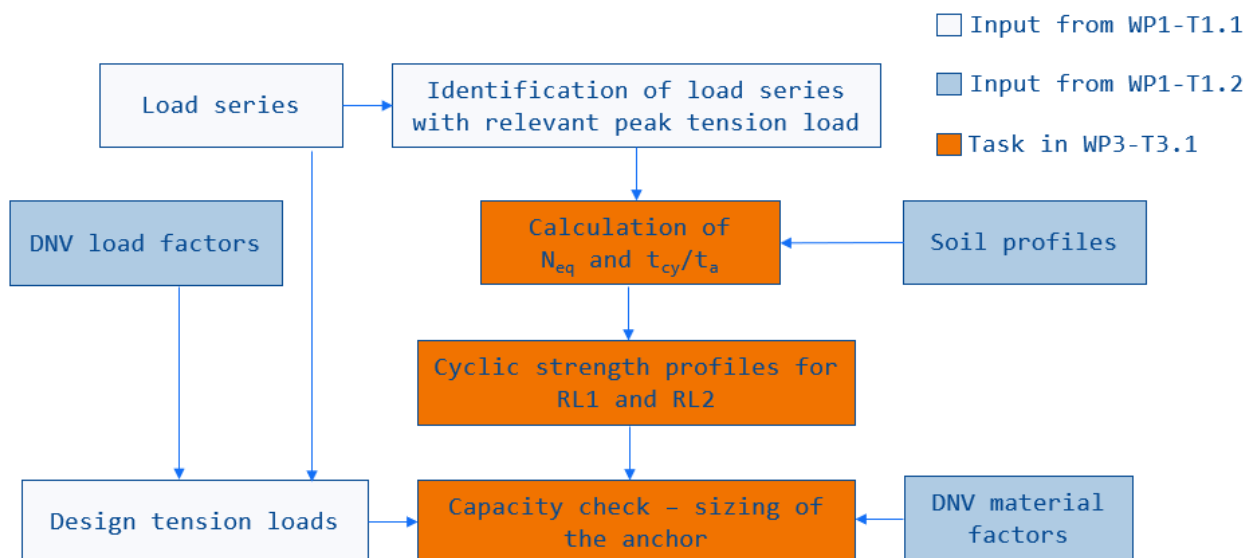


Figure 3-3 Workflow for the estimation of the cyclic strength parameters and capacity check

- Calculation of cyclic strength from direct shear tests $\tau_{f,cy}DSS = f(\tau_a \tau_{cy})$
- Use of the anisotropy ratios for cyclic loading given in Andersen et al. (2023) to calculate $\tau_{f,cy}C$, and $\tau_{f,cy}E$. In clay $\tau_{f,cy}DSS / \tau_{f,cy}C = 0.69$ and $\tau_{f,cy}E / \tau_{f,cy}C = 0.54$. In sand the anisotropy ratio depends on the relative density and the drainage condition (i.e. is the average shear stress drained or undrained) of a given layer as detailed in Andersen et al. (2023) and shown in Table 3-4.

The above-described calculation gave larger cyclic strength than static strength for the clay layers in RL1. This is because the effect of the higher loading rate under the cyclic design load compared to the monotonic lab test outweighs the effect of the cyclic degradation. Out of conservatism, no increase of strength was considered. As an example, the cyclic shear strength of the sand layers of RL2 for Scenario 7 are given in Table 3-4.

Table 3-4 Cyclic shear strength for Scenario 7

Soil Unit Description	Unit number	Depth z [m]	Governing drainage condition of cyclic component	Anisotropy		
				$\tau_{f,cy}DSS$ [kPa]	$\tau_{f,cy}DSS / \tau_{f,cy}C$	$\tau_{f,cy}E / \tau_{f,cy}C$
Sand - Very loose to loose	I	0	Undrained	0.2	0.8	0.4
		2		5.7	0.8	0.4
Sand - Medium dense to dense	IIa	2	Undrained	13.9	0.6	0.6
		15		75.3	0.6	0.6
Sand - Very dense	IIb	15	Drained	134.9	0.7	0.4
		70		560.2	0.7	0.4

3.3.3 Results

An overview of the results is given in Table 3-5. It can be noted that suction anchors are quite effective in clay given the high L/D potential. Installation feasibility does not allow high L/D in sand which make the shape of suction anchor less efficient in coarse grained materials.

Table 3-5 Size overview for suction anchors

Scenario	Diameter [m]	Skirt length [m]	Wall thickness [m]	Lid thickness [m]	Dry weight [t]	Dry weight ballast [t]
3	5.00	16.5	0.04	0.10	97	n/a
3b	5.00	17	0.04	0.10	100	n/a
7	12.00	11	0.06	0.10	287	n/a
10	7.50	23	0.05	0.10	249	n/a
10b	8.00	23.5	0.05	0.10	273	n/a
20c	10.00	6	0.06	0.10	152	733

Sand

Clay

3.4 Fluke anchor

Fluke anchors are widely used for mooring offshore energy floating facilities – such as Mobile Offshore Drilling Units MODUS – and have been adapted as permanent mooring

solutions for floating wind farms (e.g., Hywind Demo, Fukushima, WindFloat Atlantic, Kincardine). The anchors consist of a fluke plate attached to a shank, with a padeye located at the top of the shank. Fluke anchors achieve holding capacity through embedment, penetrating the seabed as they are dragged horizontally. The connecting chain forms an inverse catenary between the mudline and the padeye, lying horizontally along the seabed. Starting from a surface position, the anchor gradually embeds deeper as tension on the chain increases until it reaches its maximum holding capacity, at which point it moves horizontally without further embedment (see Figure 3-4). The achievable embedment depth is typically much larger in clay compared to sand.

In most cases, anchors are installed to hold the required line tension for the design application rather than reaching their maximum capacity, due to the limited capacity of the anchor handling vessel (AHV). Fluke anchors have been successfully employed in many offshore floating wind projects, particularly with catenary mooring systems where the anchors primarily experience horizontal loads. They are suitable for most seabed conditions, except hard rock. In general, fluke anchors can provide high holding capacity but require significant embedment depth and thereby possibly a long drag distance, as well as a high installation proof load.

It is common that the capability of the anchor to resist the design load must be 'proven' at the installation by applying and holding this load via the bollard pull of the installation vessel. During the proof load operations, anchor slippage might occur. The design loads considered in this report exceed those for smaller wind turbines or less onerous temporary mooring systems for MODUs. Therefore, they move beyond the capabilities of current installation vessels. This raises the challenge of needing to improve anchor proof loading techniques to reduce the slippage risk, or potentially address whether the full design load must be proven at installation.

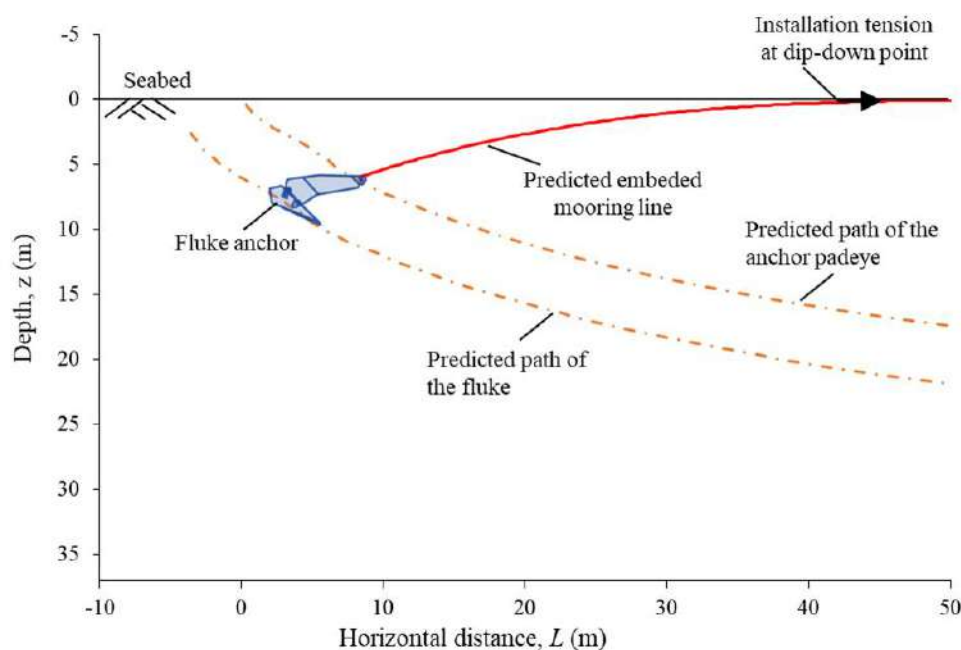


Figure 3-4 Fluke anchor embedment process (after Zhang et al. 2022)

3.4.1 Methods and assumptions

The anchor is installed by pulling it with an anchor handling vessel (AHV), and its capacity depends on the trajectory and soil strength along its embedment path. To predict anchor capacity, it's essential to capture the anchor's trajectory, orientation, and embedment depth. In this study, a macro-element model approach (as described by O'Neill et al., 2003) is applied for fluke anchors in clay. In this model, the anchor orientation is primarily controlled by the fluke, and the displacement and rotation of the fluke are determined using plasticity concepts and yield loci in the V-H-M load space (see Figure 3-5). This macro-element method is primarily used to evaluate the required drag distance for the clay soil. For verifying anchor capacity, an empirical approach - the fluke design chart developed by Vryhof - is in this study used to determine the anchor weight and ultimate capacity for both clay and sandy seabeds based on this Suppliers testing data.

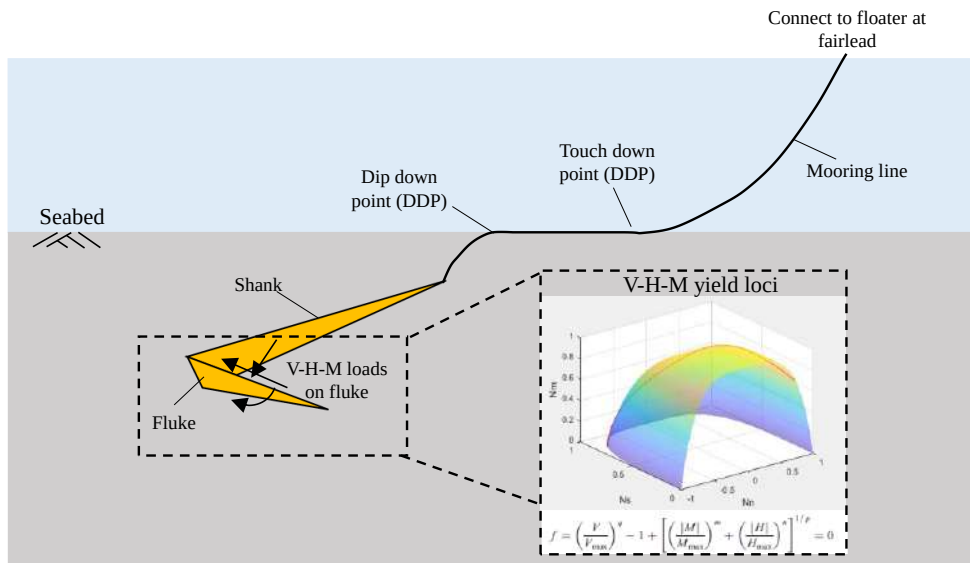


Figure 3-5 A macro element model for prediction of performance of fluke anchors

In the macro element model, the vertical load (V), horizontal load (H) and overturning moment (M) on the anchor fluke are calculated through a limit equilibrium method with loads at padeye and anchor weights considered. The yield loci defined by a simply function in H-V-M domain that can be determined by Finite Element analysis. The best fit to the analysis results is shown below:

$$f = \left(\frac{V-V_1}{V_{max}-V_1} \right)^q - 1 + \left[\left(\frac{M-M_1}{M_{max}-M_1} \right)^m + \left(\frac{H-H_1}{H_{max}-H_1} \right)^n \right]^{1/p}$$

where the maximum load values V_{max} , M_{max} , and H_{max} , along with the offset load values V_1 , M_1 , and H_1 (noting that the offset load values are zero for a rectangular fluke), are obtained from the FE analyses and the exponents m , n , p , and q are determined via the least squares regression scheme to obtain a best-fit solution. All yield loci parameters used in this study are presented in Table 3-6. Note that the yield surface varies based on both anchor geometry and soil layering conditions. In this study, the anchor geometry is assumed to be rectangular (see Figure 3-6), as Vryhof does not publicly disclose the exact geometry. Therefore, the yield surface parameters for a wedge-shaped fluke (reported in O'Neill et al. 2003 via a set of FE analysis) are selected to represent the MK6 anchor as an example.

Table 3-6 Yield loci curve-fitting parameters (recommended for a wedge shape of the fluke in O'Neill et al. 2003)

Parameter	Value (fluke anchor)
$H_{max}/(L_f S_u)$	3.34
$V_{max}/(L_f S_u)$	11.53
$M_{max}/(L_f L_f S_u)$	1.6
$H_1/(L_f S_u)$	0
$V_1/(L_f S_u)$	-1.25
$M_1/(L_f L_f S_u)$	-0.57
m	2.37
n	2.14
p	0.93
q	3.41

As the anchor penetrates into the soil, the mobilized resistance reaches a steady-state value, determined by the local average shear strength of the soil at the fluke centre's location. The line tension at the padeye (T_a) and its inclination angle are calculated using an anchor-chain model (Neubecker and Randolph, 1995), which transfers the mooring line load from the dip-down point on the seabed to the anchor padeye. By adjusting T_a , the vertical (V), horizontal (H), and moment (M) loads vary accordingly, and the forces acting on the fluke are determined until they meet the yield locus (i.e., $f(H, V, M) = 0$).

Using the plastic normality rule, the resulting displacement and rotation of the fluke are then calculated. The model's validity is confirmed through comparison with the simulation results reported by O'Neill et al. (2003). In this study, Vryhof MK6 (Vryhof anchor manual 2021) is selected, and simplified fluke and shank plates are adopted. The geometries are shown in Figure 3-6. The anchor chain with a nominal diameter (bar thickness) of 0.084m and an effective (equivalent) chain diameter of 0.24m is adopted.

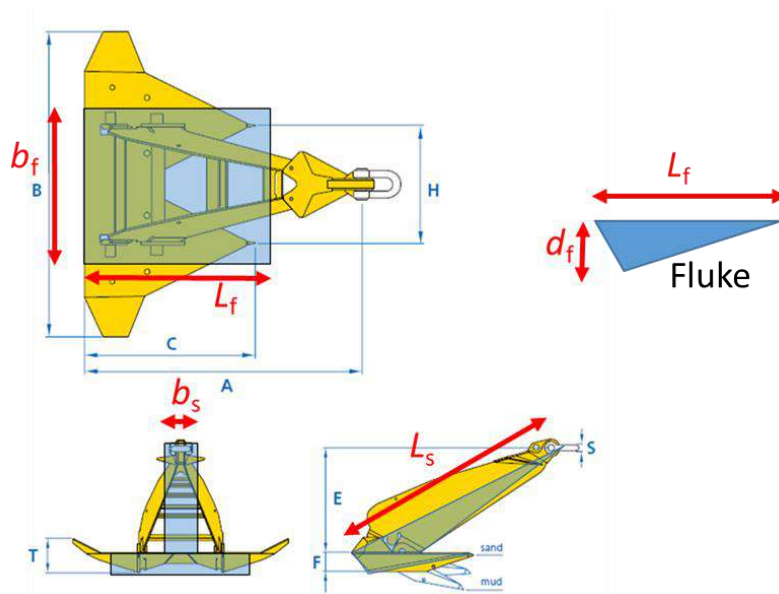


Figure 3-6 Simplified anchor geometry for macro element model analyses (data is reported in the Vryhof official website: <https://delmarsystems.com/products/anchors/stevpris-mk6/>)

From a practical perspective, the penetration trajectory and the anchor capacity are significantly influenced by the predefined fluke-shank angle, θ_{fluke} . Three θ_{fluke} are recommended for different seabed type (please note that the angles can be slightly changed for different fluke anchor):

- $\theta_{\text{fluke}} = 50$ deg: is appropriate for anchor penetration in very soft and soft clay soils to obtain high geotechnical resistance.
- $\theta_{\text{fluke}} = 40$ deg: is good for layered or complex soil condition.
- $\theta_{\text{fluke}} = 30$ deg: is easy for anchor penetration in dense sand/stiff clay soils.

Alongside the macro-element model method, the general design chart method, as recommended by ISO 19901-7 (ISO, 2013) and ISO 19901-4 (ISO, 2016), is also considered (see Figure 3-7). This method provides a correlation between ultimate anchor capacity and anchor weight, assuming the anchor reaches its maximum penetration depth in a single-layer soil, either sand or clay. In this study, the design chart is primarily used to estimate anchor weight, complementing the macro-element model method, especially for anchors in sandy seabeds. The more conservative (i.e. larger) anchor weight determined by these two methods will be selected for the final design.

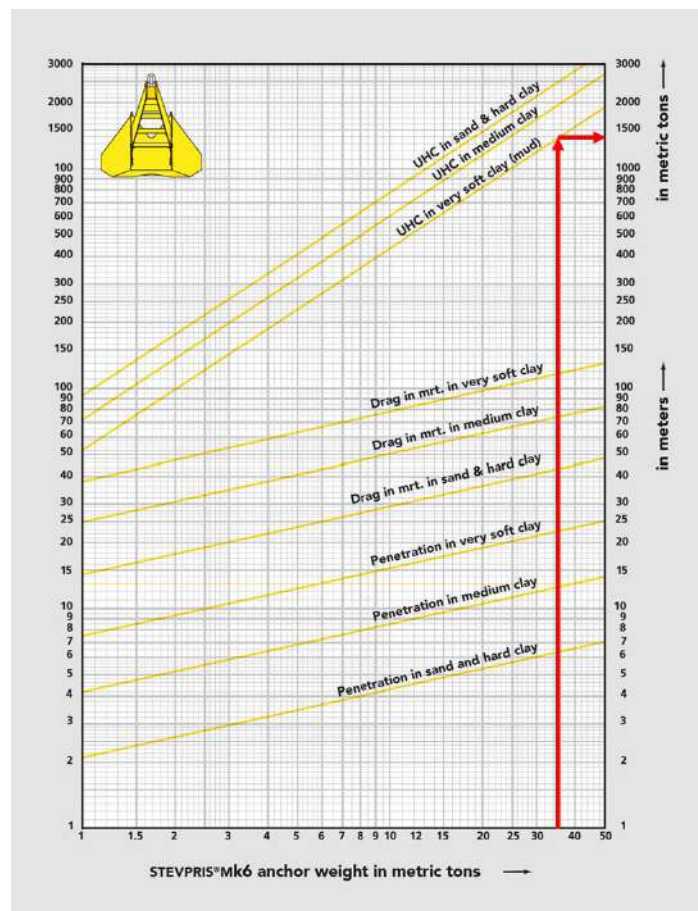


Figure 3-7 Design chart method for evaluation of the Vryhof STEVPRIS®MK6 fluke anchor (data is reported in the Vryhof official website: <https://delmarsystems.com/products/anchors/stevpris-mk6/>)

3.4.2 Results

The evaluation result is listed below in Figure 3-7. Please note that the fluke anchor is recommended for catenary and semi-taut (with a relative low uplift angle at dip-down point) moorings. In this study only scenarios 3 & 7 consider fluke anchors.

Table 3-7 Size overview for fluke anchors

Scenario	Seabed type	Mooring type	Anchor type	Anchor weight [t]
3	Clay	Semi-taut	MK6 (or Stevshank REX)	35
7	Sand	Semi-taut	MK6 (or Stevshank REX)	38

Sand

Clay

3.5 Plate anchor

The plate anchor is an efficient anchor type for mooring offshore floaters and is generally classified into two types based on installation method: (1) drag-in plate anchor (DIPA) and (2) suction embedded plate anchor (SEPLA). The DIPA, similar to a fluke anchor, is installed by pulling it through a winch or Anchor Handling Vessel (AHV), with its capacity varying based on the installation trajectory and seabed soil strength at the embedment depth. In contrast, the SEPLA is installed using a dedicated suction bucket with the anchor plate attached at the bottom and has gained widespread use, making it the focus of this study for clay sites. The suction bucket used to install plate anchors is also called follower. Two critical design considerations for SEPLA are its installation and anchor capacity. A schematic of the installation process and keying mechanism (the process by which holding capacity is activated) is shown in Figure 3-8. The installation involves embedding the anchor by pumping out water from the follower as in a regular suction anchor installation. Once the design depth is reached, the suction process is reversed and an overpressure is gained, and thereby the follower is retrieved, leaving the anchor plate vertically embedded. Tension is then applied to the slack mooring line connected to the anchor padeye, causing the SEPLA to rotate – known as "keying" – until it aligns nearly perpendicular to the local chain orientation. In this study, the more reliable SEPLA anchor is selected for evaluation in clay. In sand, the anchor installation is still immature, but it will very unlikely be suction installed as for the SEPLA given the installation limitations of a suction follower in coarse grained material.

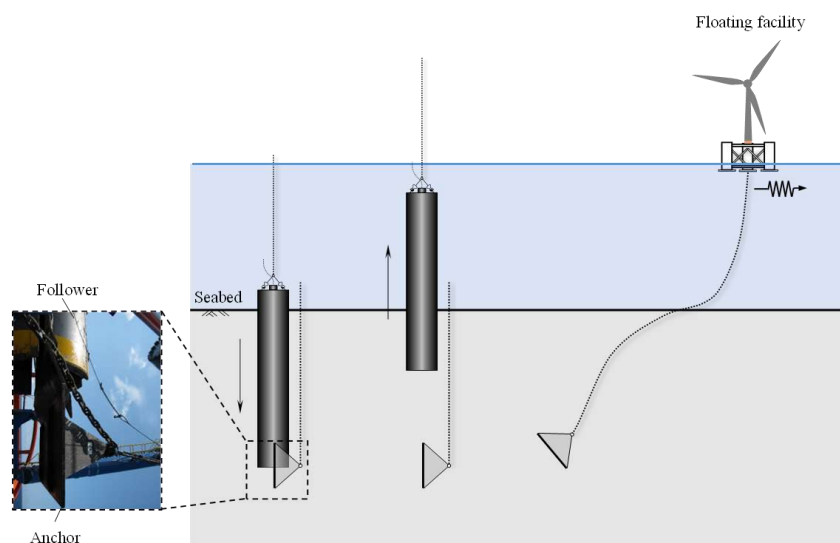


Figure 3-8 Schematic of SEPLA installation and operation (Wang, 2023)

Recently, flexibly embedded plate anchors (FEPLAs), that use additional installation techniques – including vibration, driving or jetting – to better suit coarse grained soils, were proposed by the company ACTEON⁴.

3.5.1 Methods and assumptions

For the plate anchor evaluation, there are two assessment steps – keying process and anchor holding capacity. In this study the methods for use in clay and sand are listed below:

- For the embedded chain, the integrated chain solution, with governing equations provided by Vivatrat et al. (1982), is employed. This approach uses governing equations for both normal and tangential directions, solving numerically to determine the angle and tension at the padeye. This method accounts for the chain link's weight and geometry;
- For clay, plate anchor keying is predicted using both the semi-numerical method by Chen et al. (2021) and the DNV empirical method, as detailed in DNV-RP-E302 (DNV, 2021a);
- For sand, no established method exists to predict the embedment loss of a plate anchor. Therefore, the keying depth is estimated based on centrifuge data reported by O'Loughlin and Barron (2012), indicating a typical embedment loss between 0.75 and 1.0 times the plate width (B). In this project, a conservative assumption of a 1.0B embedment loss is applied. The anchor capacity in dense sand is estimated using the method reported in White et al. (2008) based on a limit equilibrium approach;
- The plate anchor is considered for taut/semi-taut and TLP moorings in this study. However, for the taut or semi-taut mooring, the keying of the plate anchor in sand is assumed to be a fully 90-degree keying process under a purely vertical loading condition (i.e., perpendicular to the horizontal plane). This assumption leads to the worst-case scenario, leading to the maximum loss of embedment, due to the lack of the prediction method. This assumption is conservative for both keying loss embedment and anchor holding capacity in a dense sand;
- Given the limited application of plate anchors in offshore floating wind projects, a conservative result based on these predictions is adopted in this project.

Plate anchor in clay

For the plate anchor in clay seabed, the DNV method – DNV-RP-E302 (DNV, 2021a) – introduces an empirical equation for rough prediction of the keying induced loss in embedment, Δz_k , as follows:

$$\Delta z_k = (0.6 \pm 0.2)B$$

An alternative approach used to estimate the loss of embedment for plate anchor keying process is based on the results of LDFF simulations and empirical fittings. The semi-numerical equation used in the calculation is:

$$\frac{\Delta z_k}{B} = a \left[\left(\frac{e}{B} \right) \left(\frac{t}{B} \right)^c \right]^d \tanh \left[b \left(\frac{s_u}{(\gamma'_a - \gamma'_s) \sqrt{te}} \right)^r \right] \exp \left[- \left(\frac{e}{B} \right)^l \left(\frac{e_p}{B} \right)^g \right] \left(0.32 + 0.68 \frac{B}{L} \right) \left(\frac{\theta_a}{\pi/2} \right)$$

⁴ Link to website: <https://acteon.com/blog/flexibly-embedded-plate-anchors-for-floating-wind/>

where the notation for each parameter is listed below:

- e: eccentricity of padeye;
- e_p : offset of padeye;
- t: plate thickness;
- γ'_a and γ'_s : submerged unit weight of the anchor and soil;
- a, b, c, d, r, g, i: fitting parameters.

More details are provided in Chen et al. (2021).

For both methods used for clay, the characteristic resistance of plate anchors is calculated based on the DNV method:

$$R_c(z_i) = N_c \cdot s_c \cdot \eta \cdot s_{u,mean}(z_i) \cdot A_{plate} \cdot U_{cy}$$

where s_c is the shape factor; $s_{u,mean}(z_i)$ is the mean undrained shear strength within the mobilised region around the anchor; N_c is the bearing capacity factor. More details are provided in DNV-RP-E302 and section 3.5.2.

Plate anchor in sand

For the plate anchor in sandy seabed a limit equilibrium method is used based on the assumption of drained condition. The core theoretical concept involves calculating the mobilized soil resistance by ensuring force equilibrium along the assumed failure planes, while incorporating the effects of soil dilatancy through the dilatancy angle (Ψ). The characteristic anchor resistance is calculated by:

$$R_c(z_i) = N_\gamma \cdot (\gamma' H) \cdot s_c \cdot A_{plate}$$

Where N_γ is the bearing capacity factor. More details are provided in White et al. (2008).

Based on the equation above, the anchor embedment loss during keying may reach up to approximately one plate width (1.0B) for both clay and sand. It's important to note that embedment loss is significantly influenced by soil type and layering, thus, the 1.0B guideline recommended in the DNV standard may be adjusted if the seabed is not a uniform soft soil. In this study a conservative embedment loss of 1.0B will be applied.

3.5.2 Strength parameters

From a conservative perspective, the drained condition is adopted in the design for plate anchors in sand (RL2), with the soil parameters listed in Table 3-8. The latter parameters are a conservative simplification of those shown in Table 2-2. The dilatancy angle was taken from Andersen and Schjetne (2013).

Table 3-8 Soil parameters used in design at RL2

Depth z [m]	Unit weight γ [kN/m ³]	Relative density Dr [%]	Angle of internal friction ϕ [deg]	Vertical stress σ'_v	Dilatancy angle at peak shear stress ψ [deg]
0	20	70	33	0	10
40	20	70	33	400	

For the SEPLA design in clay (RL1), the mean undrained shear strength, $s_{u,mean}(z_i)$, for the anchor at a certain depth (initially assumed to be 4 times the anchor width) is calculated

based on the weighted average method to account for the effects on the failure mechanism due to the layering characteristics. The plate is assumed to divide the soil volume influencing the anchor resistance into two half-spheres, one located above and the other below the plate, termed zone I and Zone III, respectively. Each of these zones is assigned an average undrained shear strength termed $s_{u,I}$ and $s_{u,III}$, respectively.

Then $s_{u,mean}(z_i)$ can be calculated by:

$$s_{u,mean} = (s_{u,I} + s_{u,III})/2$$

Where the soil volume is assumed to be divided by 12 slices, with each slice is multiplied by a weighting factor a_i and b :

$$s_{u,I} = \sum_{i=1}^6 s_u \left[z_i + \frac{B}{b} (1 - 2 \cdot i) \right] \cdot a_i$$

$$s_{u,III} = \sum_{i=1}^6 s_u \left[z_i - \frac{B}{b} (1 - 2 \cdot i) \right] \cdot a_i$$

It should be noted that the size of the ‘influence spheric zone’ is different when anchor is located above or beneath the boundary of two layers, z_1 . More details are provided in DNV-RP-E302 (DNV, 2021a).

3.5.3 Results

The overview of the calculation results for plate anchors is given in Table 3-9. Relatively good anchor efficiency can be seen from the estimated anchor size and weight. However, as previously mentioned, the installation of plate anchors into stiff soils or sands is challenging (Scenarios 7 and 20c). Installation feasibility is not further explored here but in the Industrial feasibility section (Section 4) the uncertainty of plate anchor installations is considered through the technology readiness level.

Table 3-9 Size overview of plate anchors

Scenario	Mudline chain angle [deg]	Wall thickness [mm]	Diameter [m]	Length [m]	Dry weight [t]	Installation depth [m]	Padeye depth in operation [m]	Angle at padeye in operation [deg]
3	6	0.1	5.5	8.53	37.3	22	15.5	11
10	23.7	0.1	8	12.4	78.9	32	19.2	60.5
7	9.6	0.1	5.2	8.1	33	16	9.6	90
20c	90	0.1	4	6.2	19.7	15.4	9	90

Sand

Clay

4. Industrial feasibility

For a given anchor to be proven industrially feasible, it is proposed that four criteria must be fulfilled:

- 1- **Social sustainability** - Local communities and supply chains must profit from the production and deployment of the technology.
- 2- **Economic sustainability** - Production, transportation, and installation cost must be optimised to ensure supply at scale.
- 3- **Environmental sustainability** - Industrial environment during fabrication and transportation and marine environment during installation and operation must be protected.
- 4- **Technological sustainability** - A given anchor must have been through enough tests and offshore deployment so that the risk of installation refusal and failure during operation is low.

Economic, environmental and technological sustainability are expressed by means of different key performance indicators (KPIs). The best performing anchor type will feature KPI equal to 1 in each category. The other anchor types will feature KPIs proportionally lower. The identification of relevant KPIs was supported by TAILWIND (2024b).

4.1 Social sustainability

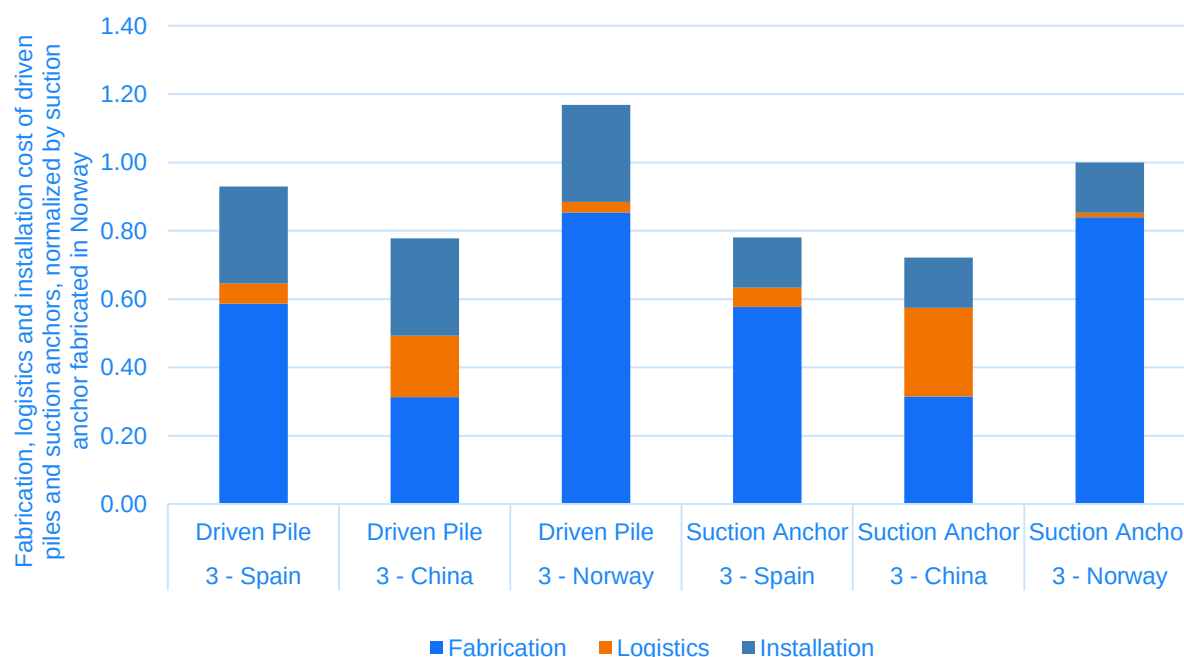


Figure 4-1 Cost of supply and installation of suction anchors and driven piles for Scenario 3 for three different fabrication locations: China, Norway, Spain. Results are normalised by the cost of suction anchors produced in Norway

Social sustainability was taken into account by performing a preliminary study on supply and installation costs from three different locations – Norway, China, and Spain – on Scenario

3. The results normalised by the suction anchor total cost produced in Norway are shown in Figure 4-1 and, as expected, clearly indicate that the location of anchor fabrication influences the supply and installation cost. To reach a compromise between environmental and societal sustainability and to make sure that the study focuses on supply chains located in Europe, all the estimations shown in this section assume Spain as the anchor fabrication location. This choice was corroborated by the global supply chain study ERM (2024), where Spain is shown to be the most economical fabrication location for a representative destination port in Stavanger.

4.2 Economic sustainability

In this study the economic sustainability is evaluated through two key performance indicators (KPIs):

- KPI_1: Cost of fabrication, installation, and logistics;
- KPI_2: Site investigation effort.

The calculations for the economic sustainability relating to fabrication and purchasing, logistics, and installation were performed using a cost model of the partner Subsea7. The calculations for the site investigation effort were based on NGI experience. Costs are based on a 500MW floating wind development, with 33 turbines of 15MW. Scenarios 3, 3b, 7 and 20c are based on four anchors per floater, while scenarios 10 and 10b are based on 12 anchors per floater. For shared anchors it is assumed that the number of anchors per turbine is reduced by 20% for Scenario 10b (9.6 anchors per turbine for Scenario 10b instead of 12 for Scenario 10) and by 40% for Scenario 3b (2.4 anchors per turbine for Scenario 3b instead of 4 for Scenario 3). Note that these are conservative estimations based on layout simulations for 33 turbines. The only shared anchors installed so far in the FOW industry is Hywind Tampen. The latter FOW park has 1.7 anchors per turbine for a 3-line mooring system which adds up to 43% reduction in anchors number (Catapult, 2024). It should be noted that this percentage is much dependent on layout and mooring system, so it is an indicative estimation in this study.

4.2.1 Fabrication and Purchasing

Fabrication prices are based on industry quotes for fabrication in Northern Spain, for suction anchors, plate anchors, fluke anchors and gravity anchors. For driven piles, the fabrication cost is 25% lower, because this type of tubular structure benefits heavily from automation – like monopile fabrication in bottom-fixed wind.

4.2.2 Logistics

Logistics comprises costs for transportation and marshalling.

Transportation

Transportation costs are based on shipping from Northern Spain to Haugesund for Utsira Nord (RL1), and from Northern Spain to Fos-sur-Mer for Provence Grand Large (RL2). The same type of transport vessel is assumed for all cargoes. Two assumptions made for loading and offloading:

- Loading and sea fastening in Northern Spain: 2 days;
- Offloading at marshalling port: 1 day.

The number of voyages for all anchors varies between scenarios and anchor concepts. In general, suction anchors require more voyages, as these structures have high volume. Driven piles are assumed to be stacked in two layers. Plate anchors and fluke anchors are the most efficient in transport, as they can be stacked and transported in two parts, respectively.

Marshalling

Marshalling costs cover the cost of storage and logistics at the marshalling yard. Four different types of equipment are selected to move anchors over the marshalling yard:

- Self-Propelled Modular Transporters (SPMTs) used to move heavy anchors over the yard;
- MAFI trailers are used to transport light anchors;
- 750te crawler crane used to offload heavy anchors from transport vessels;
- 220te mobile crane used to offload light anchors from transport vessels.

Storage costs are based on:

- The combined footprint of all anchors x 3, to allow for efficient logistics at the yard;
- 6 months of storage duration.

Basic logistics costs are based on:

- 3 x SPMT units for moving heavy anchors over the marshalling yard;
- 3 x MAFI trucks assumed for moving light anchors over the marshalling yard;
- 220Te mobile crane assumed for lifting light anchors from cargo vessels and into storage yard;
- 750Te crawler crane assumed for lifting heavy anchors from cargo vessel and into storage yard;
- 6-month rental period for equipment mobilized for the project;
- 60 days of use, 120 days of standby.

While the MAFI trucks and mobile land crane are common equipment in both Stavanger/Haugesund and Fos-sur-Mer, the SPMTs and 750Te crawler crane need to be mobilized from elsewhere in Europe. The mobilisation cost for this equipment is considerable, and the anchor types that require this equipment will therefore have much higher marshalling cost.

Both the Stavanger/Haugesund and Fos-sur-Mer areas are developed industrial and logistical hubs, so no additional cost are added for personnel facilities.

4.2.3 Installation

Installation cost are the product of the vessel day rate and the duration of the installation:

$$\text{Installation cost} = n_{\text{days}} * \text{vessel day rate}$$

where the vessel day rate is dependent on vessel capability and demand in a certain market and is not linear with capability. When anchor dimensions exceed the capability of a small construction vessel and a larger crane vessel is required, there will be a significant step change in installation cost. The number of vessel days, n_{days} , is estimated as follows:

$$n_{days} = T_{mob} + (T_{trip} * n_{trips}) + (T_{anchor} * n_{anchors})$$

where:

- T_{mob} is the duration of the initial mobilisation of the vessel and its equipment, at the start of the project;
- T_{trip} is the fixed duration per trip, mainly dependent on the transit distance between the mobilization port and the field;
- n_{trips} is the number of trips required to complete the installation scope. This number is mainly dependent on how many anchors the vessel can take onboard. Larger anchors will require more trips than smaller anchors. Larger vessels will be able to take more anchors than smaller vessels;
- T_{anchor} is the fixed duration per anchor, mainly dependent on the installation method. Suction anchors have the shortest installation time, while plate and fluke anchors require double or triple the time per anchor due to cross-tensioning;
- $n_{anchors}$ is the number of anchors to be installed in total.

The transit distance from port to field is short for both Utsira Nord and Provence Grand Large. This means that the installation cost is most sensitive to the installation time per anchor (T_{anchor}).

Vessel assumptions

- Fluke anchors and plate anchors are installed with a high-spec AHTS (Anchor Handling Tug Supply vessel), as these vessels are best suited for handling large chains and proof-loading by cross-tensioning;
- Small suction anchors, small driven piles and gravity anchor blocks are installed with a HCV (Heavy Construction Vessel) with a 400Te crane;
- Large suction anchors and large driven piles are installed with an HCV with a 1000Te crane.

Equipment assumptions

- Piles of Ø3,4m are installed with a Menck MHU800 hammer, or similar;
- Piles of Ø4,3m are installed with a Menck MHU1200 hammer, or similar;
- Fluke anchors and plate anchors are proof-loaded with a reaction anchor and cross-tensioning device;
- Plate anchors are installed with a SEPLA follower. Note that this assumption is not realistic for the RL2 scenarios (Scenario 7 and 20c) where suction follower cannot be used as refusal would occur much earlier than target penetration depth is reached. However, very limited data is available for sand-suitable followers. Out of simplicity, the cost of SEPLA follower is taken also for the sand sites. To compensate for this inconsistency, the plate anchor installation challenges are taken into consideration within the technological sustainability through the TRL KPI.

Cost of ballasting

For scenarios that require ballasting, the cost of installing high density iron ore Magnetite is estimated. This material is commonly used on ballasting of offshore structures. The cost of installed ballast on the seabed is dependent on the cost of the raw material, and the cost for operating the installation vessel (day rate, fuel, mobilisation).

To protect the partners' data, the costs for fabrication, installation and logistics were given normalized by those of the suction anchor for Scenario 3 (note in Table 4-1 that the sum of fabrication, installation and logistics cost equals 4, which is the number of anchor per turbine). The sum of normalised costs for fabrication, installation and logistics are multiplied by the number of anchors per turbine and then normalized to obtain the KPI_1. In the example shown in Table 4-1, the anchor concept with the lowest fabrication, installation and logistics cost per turbine has KPI_1 = 1 whereas all the other anchor concepts have KPI_1 proportionally lower.

Table 4-1 Example of calculations of KPI_1 - Cost of fabrication, installation, and logistics for Scenario 3 and 3b

Anchor type	Normalised fabrication cost [-]	Normalised installation cost [-]	Normalised logistics cost [-]	Sum of fabrication installation and logistics costs / per turbine [-]	Fabrication installation and logistics KPI_1 [-]
Suction Anchor	0.74	0.19	0.07	4.00	0.62
Driven Pile	0.75	0.36	0.07	4.72	0.52
Plate Anchor	0.28	0.68	0.05	4.04	0.61
Fluke Anchor	0.27	0.55	0.06	3.52	0.70
Shared Suction Anchor	0.76	0.19	0.08	2.47	1.00
Shared Driven Pile	0.68	0.38	0.09	2.76	0.90

4.2.4 Site investigation effort

The site investigation (SI) effort (KPI_2) is a function of the foundation depth and, only if the scenario includes shared anchors, of the number of SI locations. The two criteria are weighed equally. An example of KPI_2 calculation is given in Table 4-2 for Scenario 3 and 3b. Note that Fluke anchor has the shallowest depth and feature therefore a "Normalized depth" of 1 whereas shared anchor systems have the least SI effort and feature a "Normalized # of SI locations" of 1.

Table 4-2 Example of calculations of KPI_2 - Site investigation effort for Scenario 3 and 3b

Anchor type	Depth [m]	Normalised # of SI locations [-]	Normalised depth [-]	Site investigation effort [-]	Site investigation effort KPI_2 [-]
Fluke anchor	15.00	0.60	1.00	0.80	0.85
Pile anchor	32.00	0.60	0.47	0.53	0.57
Plate anchor	22.00	0.60	0.68	0.64	0.68
Suction anchor	16.50	0.60	0.91	0.75	0.80
Shared pile anchor	29.00	1.00	0.52	0.76	0.81
Shared suction anchor	17.00	1.00	0.88	0.94	1.00
Weight		0.50	0.50		

4.3 Environmental sustainability

In this study the environmental sustainability is evaluated through two key performance indicators (KPIs):

- KPI_3: Material sustainability;
- KPI_4: Impact on marine environment.

4.3.1 Material sustainability

Material sustainability combines decommissioning and recycling potential and material efficiency. It is assumed that all anchor types, but driven piles, can be decommissioned and recycled. Material efficiency is defined as the ratio between the design tension and the dry anchor tonnage:

$$\text{Material efficiency} = \frac{T_d}{\text{Dry tonnage}}$$

To account for the inherent enhanced sustainability of shared anchors, the material efficiency for shared anchor configurations is increased as follows:

$$\text{Material efficiency shared anchors} = \frac{T_d}{\text{Dry tonnage}} \times \frac{\# \text{ single anchors}}{\# \text{ shared anchors}}$$

Given the uncertainty of decommissioning and recycling operations, this criterion is weighted 25%. An example of KPI 3 calculation is given in Table 4-3 for Scenario 3 and 3b.

Table 4-3 Example of calculations of KPI_3 – Material sustainability for Scenario 3 and 3b

Anchor type	Material efficiency [MN/t]	Decommissioning and recyclability [-]	Normalised material efficiency [-]	Material sustainability KPI_3 [-]
Fluke anchor	0.35	1.00	1.00	1.00
Pile anchor	0.09	0.00	0.27	0.20
Plate anchor	0.33	1.00	0.94	0.95
Suction anchor	0.13	1.00	0.36	0.52
Shared pile anchor	0.16	0.00	0.47	0.35
Shared suction anchor	0.20	1.00	0.56	0.67
Weight		0.25	0.75	

4.3.2 Impact on marine environment

Impact on marine environment include the disturbance to benthic zone and the installation noise. All foundation types, except the driven piles, are considered silent. The disturbance to the benthic zone is qualitatively assigned on the base of the seabed surface disturbed during installation operations. The latter is weighted 25% as it is in general quite uncertain, especially for plate and fluke anchors. The impact on marine environment of shared anchor system is decreased by 40% for Scenario 3b and 20% for Scenario 10b as the number of shared anchors is smaller than that of single anchor configuration – as stated in Section 4.2. An example of KPI_4 calculation is given in Table 4-4 for Scenario 3 and 3b.

Table 4-4 Example of calculations of KPI_4 – Impact on marine environment for Scenario 3 and 3b

Anchor type	Disturbance to benthic zone [-]	Installation noise [-]	Impact on marine environment [-]	Impact on marine environment KPI_4 [-]
Fluke anchor	0.8	0	0.20	0.23
Pile anchor	0.2	1	0.80	0.06
Plate anchor	0.4	0	0.10	0.45
Suction anchor	0.3	0	0.08	0.60
Shared pile anchor	0.2	1	0.48	0.09
Shared suction anchor	0.3	0	0.05	1.00
Weight	0.25	0.75		

4.4 Technological sustainability

The KPI chosen to describe technological sustainability, KPI_5, is a function of the technology readiness level (TRL⁵). The TRL for each anchor type is assigned distinguishing between anchor deployment in fine (clay such as RL1) or coarse (sand such as RL2) grained soils. An example of KPI_5 calculation for Scenario 3 and 3b is given in Table 4-5.

TRL in fine grained soils – RL1

- Suction anchor TRL= 9: Has been successfully used around the globe for decades in the oil and gas industry and also for FOW turbines;
- Pile anchor TRL= 9: Has been successfully used around the globe for decades in the oil and gas industry with comparable load magnitudes to FOW turbines;
- Gravity anchor TRL= n/a: Not suitable in soft sediments;
- Plate anchor TRL= 7: Has been successfully used in the oil and gas industry but not at scale. However, there is still uncertainty associated with partial keying or no keying.
- Fluke anchor TRL= 9: Has been successfully used in the oil and gas industry and for FOW turbines, though only pilot projects with limited loads;
- Shared suction anchor TRL= 5: Has been used only once in the FOW park Hywind Tampen;
- Shared pile anchor TRL= 3: Has never been deployed so far. Main uncertainty lies in the loading behavior since the installation is that of a standard driven pile.

TRL in coarse grained soils – RL2

- Suction anchor TRL= 8: Has been successfully used around the globe as foundation for bottom-fixed offshore wind turbines. Medium to high risk during installation process in complex soils;
- Pile anchor TRL= 9: Has been successfully used around the globe for decades in the oil and gas industry with comparable load magnitudes to FOW turbines;
- Gravity anchor TRL= 9: Has been successfully used around the globe for decades in the oil and gas industry with comparable load magnitudes to FOW turbines;
- Plate anchor TRL= 3: Has never been deployed so far. High-risk during installation/keying process;

⁵ Link to TRL definitions from the European Union: <https://op.europa.eu/en/publication-detail/-/publication/d5d8e9c8-e6d3-11e7-9749-01aa75ed71a1>

- Fluke anchor TRL= 8: Has been successfully used in the oil and gas industry and for FOW turbines, though only pilot projects with limited loads;
- Shared suction anchor TRL= 3: Has never been deployed so far;
- Shared pile anchor TRL= 3: Has never been deployed so far.

Table 4-5 Example of calculations of KPI_5 – Technological sustainability for Scenario 3 and 3b

Anchor type	TRL [-]	KPI_5 [-]
Fluke anchor	9	1.0
Pile anchor	9	1.0
Plate anchor	7	0.8
Suction anchor	9	1.0
Shared pile anchor	3	0.3
Shared suction anchor	5	0.6

4.5 Evaluation matrixes

The evaluation matrix is obtained for each scenario by using the KPIs described so far through the Weighted Sum Method, which is a formal Multi-Criteria Decision Analysis technique (Kolios et al., 2016). For description of the different scenarios reference is made to Table 2-3. Four sets of weightings have been defined with four different focuses:

- Weighting Set 1 – All weightings equal;
- Weighting Set 2 – Focus on costs;
- Weighting Set 3 – Focus on environment;
- Weighting Set 4 – Focus on technology.

4.5.1 Scenario 3 and 3b (Semi-submersible at clay site)

Table 4-6 is the evaluation matrix for Scenarios 3 and 3b. Even though the number of anchors per turbine was chosen relatively conservative (2.4 for a 4-line mooring system), shared suction anchors are the best scoring anchor type for Weighting Sets 1, 2 and 3. The low scoring under Weighting Set 4 indicates the need for further research to enhance the shared suction anchor TRL.

Table 4-6 Evaluation matrix for Scenario 3 and 3b

Anchor type	KPI_1 - Fabrication installation and logistics	KPI_2 - Site investigation effort	KPI_3 - Material sustainability	KPI_4 - Impact on marine environment	KPI_5 - TRL	Total score			
						Weighting Set 1	Weighting Set 2	Weighting Set 3	Weighting Set 4
Suction anchor	0.62	0.85	0.52	0.60	1.00	0.72	0.66	0.61	0.86
Pile anchor	0.52	0.57	0.20	0.06	1.00	0.47	0.48	0.27	0.73
Plate anchor	0.61	0.68	0.95	0.45	0.78	0.70	0.67	0.69	0.74
Fluke anchor	0.70	0.80	1.00	0.23	1.00	0.75	0.75	0.66	0.87
Shared suction anchor	1.00	0.81	0.67	1.00	0.56	0.81	0.90	0.85	0.68
Shared pile anchor	0.90	1.00	0.35	0.09	0.33	0.53	0.76	0.40	0.43
Weighting									
Set 1 - All equal	0.2	0.2	0.2	0.2	0.2				
Set 2 - Costs	0.6	0.15	0.15	0.05	0.05				
Set 3 - Environment	0.2	0.05	0.35	0.35	0.05				
Set 4 - Technology	0.1	0.1	0.1	0.1	0.6				

4.5.2 Scenario 7 (Semi-submersible at sand site)

Table 4-7 is the evaluation matrix for Scenario 7. The fluke anchor is the best scoring anchor type. However, as explained in Section 3.4, it should be emphasised that the proof loading required for their deployment exceeds current installation vessel capabilities.

The plate anchor obtained a good total score but its lack of substantial experience in coarse grained soils make it not viable (see Weighting Set 4).

Not surprisingly, the driven pile scores better than the suction anchor, when the focus is on costs. This is a consequence of the more unfavourable geometry of suction anchors in coarse grained soils (depth to diameter ratio typically ≤ 1) required to be able to install.

Shared driven piles were not considered for this scenario but judging by their performance in Scenario 3b, they could become competitive in a sand site.

Table 4-7 Evaluation matrix for Scenario 7

Anchor type	KPI 1 - Fabrication installation and logistics	KPI 2 - Site investigation effort	KPI 3 - Material sustainability	KPI 4 - Impact on marine environment	KPI 5 - TRL	Total score			
						Weighting Set 1	Weighting Set 2	Weighting Set 3	Weighting Set 4
Suction anchor	0.32	0.91	0.34	1.00	0.89	0.69	0.47	0.62	0.79
Pile anchor	0.92	0.42	0.25	0.09	1.00	0.54	0.71	0.38	0.77
Gravity anchor	0.11	1.00	0.00	0.30	1.00	0.48	0.28	0.23	0.74
Plate anchor	0.92	0.63	1.00	0.75	0.22	0.70	0.84	0.84	0.46
Fluke anchor	1.00	0.67	0.87	0.38	0.89	0.76	0.89	0.72	0.83
Weighting									
Set 1 - All equal	0.2	0.2	0.2	0.2	0.2				
Set 2 - Costs	0.6	0.15	0.15	0.05	0.05				
Set 3 - Environment	0.2	0.05	0.35	0.35	0.05				
Set 4 - Technology	0.1	0.1	0.1	0.1	0.6				

4.5.3 Scenario 10 and 10b (Tension leg buoy at clay site)

Table 4-8 is the evaluation matrix for Scenario 10 and 10b. As described in Section 2.2, this scenario features loads with very high magnitude, and it was considered to test how the different foundation types could be suitable to that. The plate anchor obtained the best scores for Weighting Sets 1, 2 and 3. However, it should be noted that, even if it's a clay site, plate anchors of this size have never been installed. Weighting sets 1, 2 and 3 assume that the plate anchor installation is feasible. Indeed, weighting Set 4 does not indicate plate anchor as the most suitable due to the uncertainties associated with high installation resistance and plate anchor keying with, which lead to a low TRL.

Somewhat surprising is that shared anchor concepts were thought to be advantageous in nearly all scenarios, which is not the case. It seems that the high geotechnical efficiency of plate anchors can be expressed at best at high loads.

Table 4-8 Evaluation matrix for Scenario 10 and 10b

Anchor type	KPI 1 - Fabrication installation and logistics	KPI 2 - Site investigation effort	KPI 3 - Material sustainability	KPI 4 - Impact on marine environment	KPI 5 - TRL	Total score			
						Weighting Set 1	Weighting Set 2	Weighting Set 3	Weighting Set 4
Suction anchor	0.57	0.91	0.49	0.80	1.00	0.75	0.64	0.66	0.88
Pile anchor	0.63	0.66	0.24	0.08	1.00	0.52	0.57	0.32	0.76
Plate anchor	1.00	0.77	1.00	0.60	0.78	0.83	0.93	0.84	0.80
Shared suction anchor	0.66	1.00	0.49	1.00	0.56	0.74	0.70	0.73	0.65
Shared pile anchor	0.63	0.74	0.24	0.09	0.33	0.41	0.54	0.30	0.37
Weighting									
Set 1 - All equal	0.2	0.2	0.2	0.2	0.2				
Set 2 - Costs	0.6	0.15	0.15	0.05	0.05				
Set 3 - Environment	0.2	0.05	0.35	0.35	0.05				
Set 4 - Technology	0.1	0.1	0.1	0.1	0.6				

4.5.4 Scenario 20c (Tension leg platform at sand site)

Table 4-9 is the evaluation matrix for Scenario 20c. Despite the ballast and the somewhat inefficient geometry ratio, ballasted suction anchors prove to be the most suitable anchor type according to Weighting Set 1. Plate anchors score quite well but the known difficulties with installation and keying in sand make it not attractive.

Table 4-9 Evaluation matrix for Scenario 20c

Anchor type	KPI_1 - Fabrication installation and logistics	KPI_2 - Site investigation effort	KPI_3 - Material sustainability	KPI_4 - Impact on marine environment	KPI_5 - TRL	Total score			
						Weighting Set 1	Weighting Set 2	Weighting Set 3	Weighting Set 4
Suction anchor	0.51	1.00	0.27	1.00	0.89	0.73	0.59	0.64	0.81
Pile anchor	0.56	0.13	0.08	0.09	1.00	0.37	0.43	0.23	0.69
Gravity anchor	0.24	0.86	0.01	0.30	1.00	0.48	0.34	0.25	0.74
Plate anchor	1.00	0.39	1.00	0.75	0.33	0.69	0.86	0.85	0.51
Weighting									
Set 1 - All equal	0.2	0.2	0.2	0.2	0.2				
Set 2 - Costs	0.6	0.15	0.15	0.05	0.05				
Set 3 - Environment	0.2	0.05	0.35	0.35	0.05				
Set 4 - Technology	0.1	0.1	0.1	0.1	0.6				

4.5.5 Summary of all scenarios

The histogram in Figure 4-2 shows the average scoring considering all four weighting sets. The black line on each bar indicates the standard deviation among the weighting sets for a given anchor type and a given scenario. The results of the industrial feasibility assessment are summarised in the conclusions of the document in the next section. Please note that not all anchor concepts are feasible in all four scenarios, which is why all scenarios have blank spaces between the bars. Moreover, normalisation of the scoring occurs within each scenario so each bar can be compared only to the other bars within the same scenario.

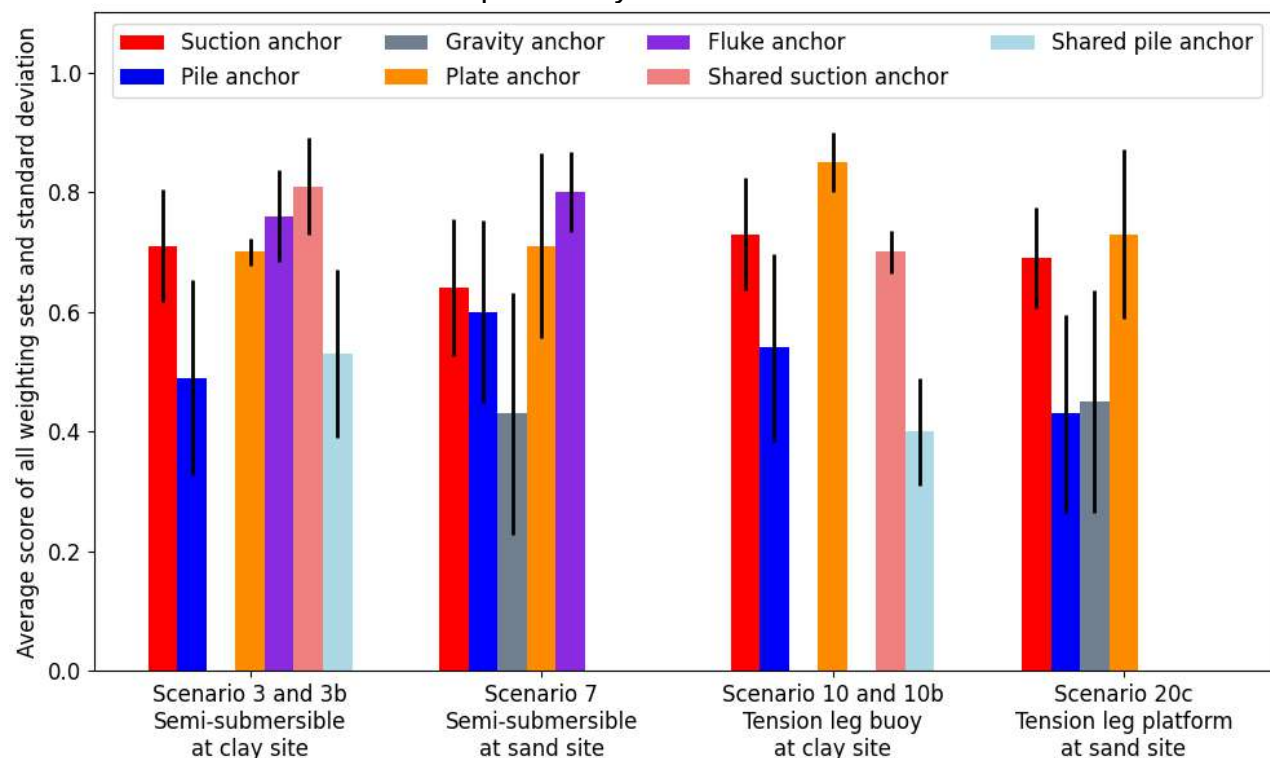


Figure 4-2 Summary of all four scenarios. Average score of all weightings for the seven anchor concepts considered in the industrial feasibility assessment

5. Conclusions

The examination of the evaluation matrix shows that:

- In early project stages, KPIs can be defined to assess the suitability of different anchor types considering societal, economic, environmental and technological sustainability aspects;
- As one may expect, there is not a one-size-fits-all anchor type. Each scenario has a most suitable anchor type mainly depending on soil type, mooring type and load magnitude;
- The environmental impact of FOW anchors as well as their recyclability potential proved to be the most difficult indicators to evaluate objectively. Quantitative environmental studies on the most common anchor types would be valuable;
- A KPI reflecting the installation risk was not considered in this study. Preliminary installation checks were made for suction and pile anchors but not for fluke and plate anchors. An installation feasibility assessment that includes the availability of the necessary vessels and hardware is crucial and should be encapsulated in a KPI in further studies;
- Gathering experience from installation of suction anchors (or suction buckets) in coarse grained and layered soils could increase the confidence in this anchor and make it available to sites beyond the typical clay sites;
- Plate anchors combine high geotechnical efficiency and suitability to all mooring concepts in principle. More data on installation methods and feasibility, keying and required proof loading for plate anchors in clay would enhance the confidence in this very promising foundation for FOW;
- Shared suction anchors in clay should be further explored for their seemingly high economic and environmental performance;
- Shared driven piles in sand were not explicitly considered in this assessment but given the confidence of the offshore industry in driven piles and the high score of shared suction anchors in clay, they could become competitive if the number of anchors per turbine is low enough and more environmentally friendly installation methods (e.g. vibratory-driven) are used;
- Efficient ways to provide suction anchors for TLP with the necessary ballast to sustain the large tensile loading should be explored;
- Fluke anchors might be a viable and efficient solution for catenary or semi-taut mooring systems with low loading angle relative to horizontal. However, the lack of vessel featuring the required capacity to apply the proof loading (especially for a sandy seabed) is an obstacle for their further deployment. Thus, the development of an appropriate design method to predict anchor trajectory is essential for accurately understanding anchor penetration, capacity, and drag distance.

The load analysis performed for three different floating WTG foundations at two distinct reference locations shows that:

- Mooring stabilised platforms – i.e. TLB and TLP – impose severe loads on the station keeping system. Load reduction measures such as platform and mooring system optimisation should be explored in TAILWIND;
- Loads on shared anchors are not always smaller than those of single anchors. This depends on the layout and the mooring concept along with the metocean data.

The technical reliability assessment shed light on some missing design tools and procedures that could accelerate the design process or be necessary for certification:

- Design procedure for shared anchor systems is not available. Understanding if there is any effect of multidirectional cyclic loading on such anchor systems is a priority;
- Design charts that can quickly identify a realistic range of anchor dimensions given simplified load and soil data could support anchor screening studies in the project early stages;
- The difference in failure consequences for floating WTG's compared to oil and gas structures justifies a revisiting of the reliability and design criteria implicit in inherited design codes. As an example, the typical deformation criterion for piles (maximum head displacement lower than 10% diameter) could be revisited.

A summary of emergent anchor technology and design methodologies outlines that potential anchor technological innovations can be achieved by:

- Developing a new single anchor that combines existing concepts to achieve an enhanced performance or efficiency (Hybrids);
- Multiple smaller anchors of an existing technology that are grouped together in a way that leads to enhanced performance or efficiency (Groups);
- Changing the design properties of an existing anchor type, such as the skin friction or bearing capacity (Enhancements);
- Considering the beneficial influence of loading rate, drainage condition, whole-life design, and ageing.

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