

Design Practices and Emerging Concepts for Anchoring Systems in Floating Offshore Wind Turbines

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Abstract

Offshore wind energy is a pivotal element in the transition to low-carbon electricity, with bottom-fixed turbines (e.g. Figure 1(a)) reaching 75 GW of installed capacity in 2023. However, the most promising wind resources lie in deep waters, necessitating floating offshore wind technology (e.g. Figure 1(b)), which unlocks areas with five to ten times the technical potential of fixed systems. Despite this potential, high capital costs and manufacturing challenges hinder widespread adoption. Foundation systems, critical for transferring loads to the seabed, account for up to 20% of total wind farm costs. Designing these systems is essential, and a key challenge is predicting performance under complex long-term multi-directional cyclic loads. This paper reviews anchoring design practices for floating wind, listing platform designs, mooring configurations and traditional and developmental anchor types. It evaluates fundamental principles, critical considerations, and limitations of current standards. Finally, the paper examines shared anchoring as a cost-effective solution, assessing its response to multi-directional cyclic loading and providing recommendations to inform the design of future floating wind farms.

Keywords: Anchoring systems; Anchors; Offshore wind turbines; Floating wind infrastructures; Foundation design; Geotechnical engineering; Multi-directional cyclic loads



Figure 1: Examples of (a) bottom-fixed offshore wind turbines supported on a monopile (St Nazaire Wind Farm, September 2024), (b) the Floatgen floating offshore wind turbine prototype (St Nazaire, France, June 2025)

1. Context and Motivation

Offshore wind energy has become a cornerstone of the global shift towards low-carbon electricity generation. Over the last thirty years, the sector has expanded at an exceptional pace, with bottom-fixed turbines (e.g. Figure 1(a)) dominating deployment and enabling a cumulative installed capacity of 75 GW by the end of 2023 (GWEC, 2023). However, the strongest and most reliable wind resources often lie far from shore, in water depths exceeding 80 m (Figure 2). In Europe, for example, around 80% of the offshore wind potential is located in waters deeper than 80 m, where bottom-fixed technology is neither commercially nor environmentally viable. Floating offshore wind (e.g. Figure 1(b)) taps into deep-water resources with a global technical potential 5–10 times higher than fixed-bottom systems—potentially exceeding 2040 global electricity demand by tenfold (IEA, 2019). With a 2025 market value of USD 1.15 billion projected to exceed USD 177 billion by 2037, this technology could deliver over 200 GW by 2050, becoming a key driver for energy security and decarbonization.

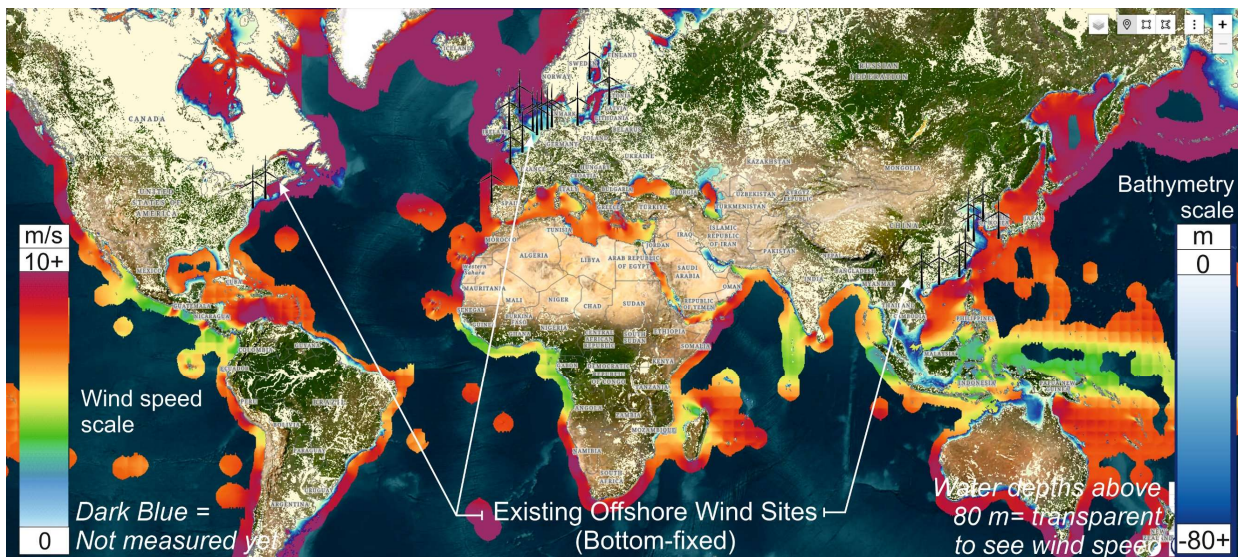


Figure 2: Superimposed world maps of water depths shallower than 80 m (m, blue), wind speed (m/s, rainbow) (created from: Global Wind Atlas). On this map, zones in green, orange, red and purple correspond to untapped wind potential above 80 m water depth

Several commercial-scale floating wind farms are now in advanced design stages. Nevertheless, widespread adoption remains constrained by substantial capital costs, limited grid infrastructure, and challenges in manufacturing and installation. In deep water, the expense of large floating platforms and extensive mooring systems is a dominant cost driver.

At the heart of every offshore wind project lies the foundation system (Figure 3), which transfers loads from the turbine's above-water and underwater structures to the seabed. These systems must resist vertical, lateral, bending and torsional loads within strict operational limits, ensuring structural safety and serviceability over decades of operation. Environmental forces—primarily wind and waves—typically account for 80–90% of horizontal loading, but site-specific factors such as seismic events, currents, ice, or snow can also be critical. A major technical challenge is predicting how foundations and anchors will perform under complex, multi-directional cyclic loads from wind, waves, and currents. Geotechnical models often rely on empirical approaches that do not fully capture long-term, non-linear load–response behaviour. This is particularly relevant for emerging shared anchoring systems, where multiple floating

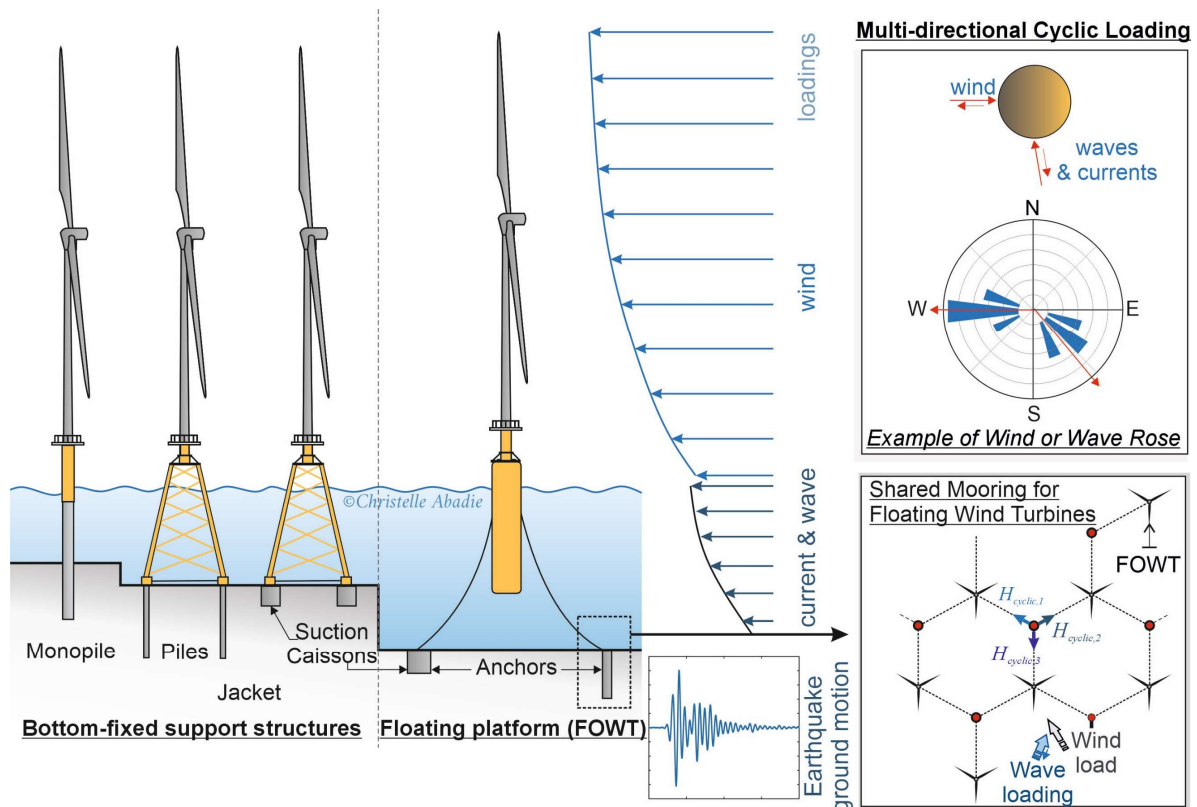


Figure 3: Foundation support structures for bottom-fixed and floating offshore wind turbines

turbines are connected to a single anchor (Figure 3, bottom right). Such systems can significantly lower mooring costs (Devin et al., 2021) and reduce maximum anchor loads by 11–16% (Fontana et al., 2018) through partial cancellation of opposing forces. In floating wind farms, mooring costs make up 20% of total expenses. Initial studies show that using shared anchors for 100 turbines could reduce these costs by 20%, making them a major financial consideration as well as a technical one. However, they also introduce higher reliability risks, with failure probabilities potentially increasing by around 12% due to cascading load transfer if a shared anchor fails.

2. Design considerations for floating offshore wind farms

Floating offshore wind turbines (FOWT) design benefits from knowledge transfer from oil and gas (O&G) but present distinct challenges and opportunities (Cerfontaine et al., 2024, Figure 4). These differences have significant implications for anchor design and risk assessment.

2.1. General considerations

- **Site scale:** FOWT farms extend over much larger areas than O&G developments.
- **Deployment scale:** While O&G platforms are isolated, FOWT farms may comprise hundreds of turbines over vast areas. This scale requires standardised, mass-produced anchor solutions rather than bespoke designs.
- **Investigation challenges:** Soil variability across such large sites makes exhaustive testing prohibitively costly. Anchor solutions must be resilient to these uncertainties.
- **Farm-wide risk:** Reliability assessments must be farm-wide, as identical storm conditions will impose uneven loads across turbines.

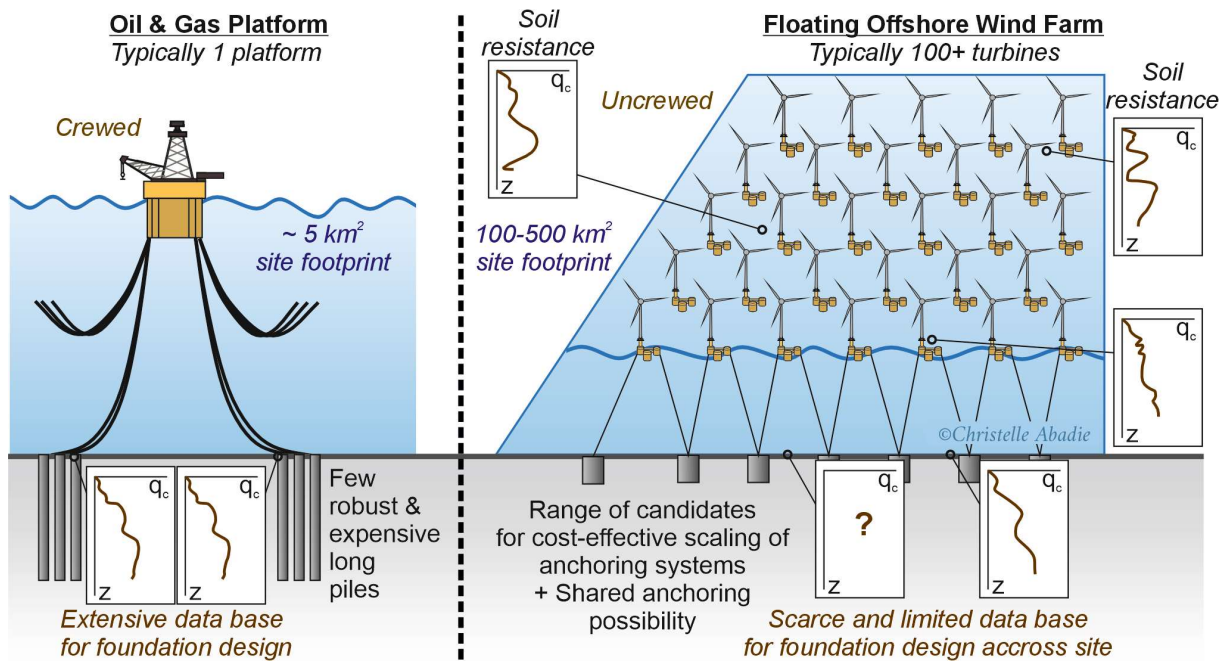


Figure 4: Key differences between Oil and Gas Platform and Floating Wind Turbine driving the design of the anchoring systems (redrawn and adapted from Cerfontaine et al., 2024)

- **Failure consequences:** FOWTs, unlike crewed O&G platforms, pose minimal risk to people or the environment, so higher failure probabilities may be acceptable if economically justified.

2.2. Implications for the geotechnical design and emerging technologies

- **Innovative cost-efficient solutions needed:** Unlike the oil and gas sector, which could justify conservative, robust, and costly anchors such as long piles (Section 4, p. 6; Figure 4, p. 6), floating offshore wind requires more economical approaches. The large number of turbines within a farm and the variability of seabed conditions across a site make it essential to develop a portfolio of innovative, cost-effective anchoring designs to choose from (Section 4.5, p. 11) in order to balance reliability, adaptability, and affordability at scale.
- **Multi-directional cyclic loading design:** The design of O&G platform anchors was mostly driven by the ultimate limit state, with cyclic loads being dampened by the mooring line configuration (catenary) and hence not driving the design. This is not the case for FOWT anchors. Realistic methods should capture long-term soil behaviour, including considerations of multi-directional loads (Abadie, 2025). This has implications for anchor design, but also life extension and decommissioning.
- **Shared anchors:** Connecting multiple turbines to a common anchor can reduce anchor numbers by up to 60% (Fontana et al., 2018), but this introduces complex load paths that may reduce cyclic performance and increase long-term strength degradation (Herduin, 2019; Abadie, 2025).
- **Mooring efficiency:** While Oil&Gas platforms typically have redundancy in the number of mooring lines (Figure 4), reducing the number of lines lowers steel use and seabed footprint. These, however, impose higher loads on anchors
- **Quiet installation:** Restrictions on underwater noise over large areas require quiet installation methods and developmental anchors (Cerfontaine et al., 2023).

3. Floater types and mooring systems

Modern floating wind platforms are based on four main floater designs—TLPs, barges, SPARs, and semi-submersibles (Figure 5)—from which hundreds of prototype designs are derived, each achieving stability through one of three fundamental static principles:

- **Mooring-line stabilised (TLPs)** – The platform is held in place by vertically tensioned mooring lines or tendons, which minimise motion by keeping the structure rigidly connected to the seabed.
- **Buoyancy stabilised (semi-submersibles, barges)** – Stability is achieved by distributing buoyancy over a wide footprint, with designs optimising the waterplane area to maximise righting moments.
- **Ballast stabilised (SPARs)** – An elongated, cylindrical hull, typically made from steel or concrete, houses dense ballast at its base to place the centre of gravity well below the centre of buoyancy.

Mooring systems secure the floater's position, limit its motions, and protect dynamic power cables from excessive bending or tension. A complete system comprises mooring lines (or tendons) and anchors, with the layout determined by a combination of site conditions, floater type, power cable configuration, cost reduction targets, and available local infrastructure. The mooring stiffness governs the floater's global motion response, which is generally described as:

- **Compliant** – allowing greater horizontal excursion but reducing the line tension and the loads transmitted to the anchor
- **Restrained** – limiting movement at the expense of higher mooring loads.

For compliant floaters, three main station-keeping arrangements are used. These are not tied to a specific floater type, except the TLP, which always uses a non-compliant vertical tendon system.

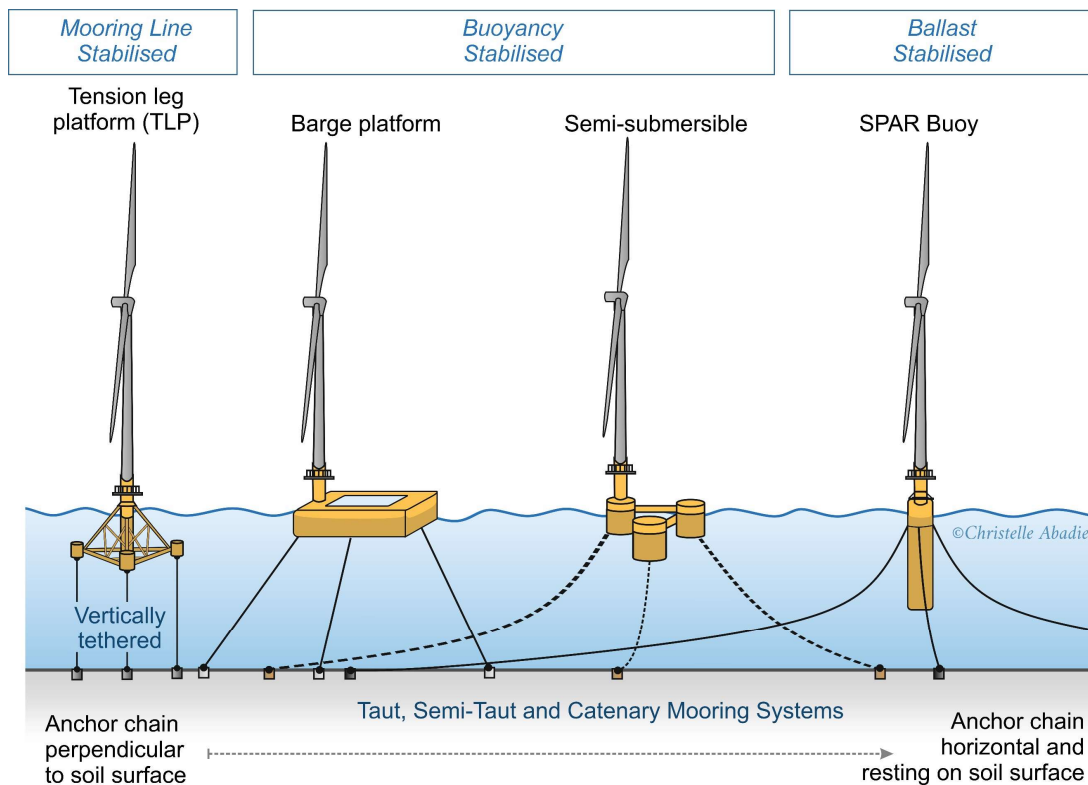


Figure 5: Types of foundation and support structures for offshore wind turbines and loading conditions

- **Catenary moorings** form a curved line profile between the floater and seabed, reducing vertical forces at the mudline. They are simple and reliable, but become less practical in deep water because of the increased weight and cost of long chains.
- **Taut moorings** maintain a fixed inclination to the seabed, offering better control of offsets, more consistent tension, improved load distribution, and a smaller seabed footprint, at the expense of higher loads on the anchor.
- **Semi-taut moorings** operate over a wider range of inclinations but can reach similar maximum angles under extreme conditions.
- **Vertical tethering:** Tension Leg Platforms (TLPs) adopt vertical steel tendons or pipes in a highly constrained configuration, delivering minimal motion at the cost of increased stiffness.

Material choice for mooring lines is linked to the mooring type, with load reduction devices (LRDs) increasingly integrated to enhance compliance, cut peak loads, and mitigate fatigue damage.

4. Anchoring solutions

Ship anchors have evolved from simple curved bars to sophisticated designs tailored for deep-sea floating platforms—first in oil and gas, and now in floating wind energy. The mooring system's anchors serve as stable seabed attachment points, designed to withstand the loads exerted by the mooring lines throughout the wind farm's operational life. The environmental loads transmitted to an anchor—both in magnitude and inclination—depend on the mooring configuration. Where the padeye is set below the seabed, the inverse catenary profile of the buried segment generates a modest vertical load on the anchor (Section 6, p. 16; Randolph & Gourvenec, 2011). Over time, the multi-directional cyclic forces from wind and waves, acting repetitively on each turbine, impose complex long-term loading patterns.

Anchoring solutions for floating wind moorings are typically divided into two main categories (Randolph & Gourvenec, 2011): surface (gravity) anchors and embedded anchors. A range of anchoring systems is available (Figure 6), with embedded anchors favoured for their high holding capacity and performance to meet demanding load requirements. Traditional options include piles, suction caissons, and drag anchors, leveraging extensive experience from oil and gas mooring applications. In contrast, emerging anchor designs lack standardised guidelines and comprehensive data on their holding capacity and long-term performance. They are currently less favoured due to limited performance and installation data, though further research could unlock their potential.

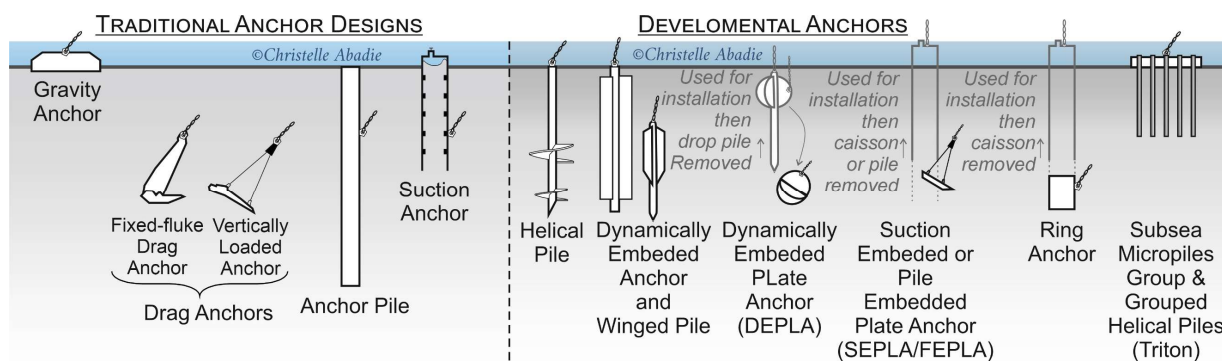


Figure 6: Conceptual representation of the range of anchor types for floating offshore wind turbines

4.1. Design guidelines and anchor selection

Although mooring system layouts vary from project to project, all must comply with recognised international and national standards to ensure the safety, reliability, and performance of floating offshore wind turbines. Key reference documents include:

- **IEC 61400-3** – International Electrotechnical Commission standard for offshore wind turbine design.
- **DNV-ST-0119** – Det Norske Veritas guideline for floating wind turbine structures.
- **API RP 2SK** – Design and Analysis of Station keeping Systems for Floating Structures
- **ABS** – American Bureau of Shipping rules and guides.
- **CFMS** – French guidelines for planning and designing anchor foundations of floating wind turbines
- **NORSOK N-003** – Norwegian classification requirements for floating wind turbines.
- **EN 61400 series** – European Norms for wind turbine standards.

An optimised anchor design must satisfy both capacity and installation criteria while keeping costs and risks low across the asset's economic, environmental, and end-of-life phases. Anchor performance is often expressed through its *holding efficiency*—the ratio between the anchor's maximum holding force and its weight (e.g. Table 1). Randolph and Gouvernec (2011) and Cerfontaine et al. (2023) indicate detailed geotechnical practice and methods. There is presently no guidance that permits the identification of the anchor type for a given soil profile and platform type. Feasibility and Concept design usually involves performing calculations on a range of potential candidates to elucidate the most suitable option and performance. Anchor design proceeds in four key phases:

- **Feasibility Study:** Assess seabed conditions (soil, stratigraphy, bearing capacity) and select an anchor type based on turbine specifications, environmental factors, and cost. Accuracy in geological modelling is critical to mitigate risks and refine cost estimates.
- **Conceptual Design:** Use simplified calculations to select and size the anchor, identify geological hazards, and address potential failure modes.
- **Front-End Engineering:** Apply advanced numerical methods to evaluate capacity, deformation, stiffness, scenario-based loads, and structural resistance.
- **Detailed Design:** Perform tailored analyses (e.g., Finite Element Analysis - FEA) to verify the design.

Decisions at each stage—technical and strategic—directly impact the anchor's resilience to dynamic and environmental loads, shaping the project's overall viability. Selecting the most appropriate anchor type requires consideration of several interrelated factors:

- Geotechnical characteristics of the seabed soil.
- Accuracy requirements for embedment location.
- Capabilities and availability of installation vessels.
- Type of floating structure and associated mooring system.
- Local metocean conditions and environmental compliance obligations.
- Cost constraints and supply chain availability of mooring components.
- Potential for shared anchoring across the wind farm.

Table 1. Compared performance of traditional anchors (data from Cerfontaine et al., 2023)

Anchor Type	Gravity	Plates		Piles		
	Gravity Anchor	Fixed fluke Drag Anchor	VLA	Driven Pile (DP)	Drilled & Grouted Pile (DGP)	Suction Caisson
Mooring	Any	Catenary	Any	Any	Any	Any
Suitable Soils	Most soils, except very loose	Firm cohesive soils	Sand or clay	Sand, clay, silt, gravel	Rock, bouldery ground	Clay, medium-dense sand
Material	Concrete and rebar	Welded steel plate	Welded steel plate	Rolled and seam-welded steel plate	Steel casing with high-strength cementitious grout	Rolled and seam-welded steel plate
Weight	600 – 1,000 tonnes e.g. 10-20 m diameter	24 – 65 tonnes	5 – 100 tonnes	40 – 100 tonnes	20 – 200 tonnes	60 – 100 tonnes
Typical Dimensions	grillage – 50 m diameter concrete	e.g. 11 m x 6 m x 6 m	e.g. 2 x 4 m	2 – 12 m OD, L/D up to 60 m	2 – 12 m OD, L/D up to 60 m	Up to 16 m OD, L/D up to 8 m
Efficiency	0.3–0.6	20-50	40–225	12–100	30-100	9–240
Installation Reliability	High accuracy	Uncertain embedment position		High accuracy	High accuracy	High accuracy (in-plane)
Installation Time (days)	3–6	3–4		3–5	8–9	3–4
Seabed Footprint	Large	Large	Small–Moderate	Small	Small	Small–Moderate
Environmental Impact	Large footprint, benthic damage risk	Large footprint impact	Moderate impact	Noise, permanent seabed intrusion	Grouting discharge	Minimal noise, recoverable
Shared Anchor	Yes	No	No	Yes	Yes	Yes
Design Standards	API RP2GEO, ISO 19900, DNV-ST-0126	DNV-RP-E301	DNVRP-E302	DNVGL-ST-0119	API RP 2A, DNVGL-ST-0126	DNV-RP-E303
Advantages	Simple concept, silent installation, potential artificial reef effect	Low cost, quick install, well-established	Resists vertical loads, compact footprint	High capacity, robust in hard soils	Only deep embedment option for rocky seabeds,	Silent, recoverable, accurate positioning
Limitations	Heavy/bulky, unsuitable for deep water, requires high seabed bearing capacity	Large footprint, embedment uncertain in hard/layered soils, unidirectional	Complex installation, embedment uncertainty	Noise during driving, refusal in very hard ground, non-recoverable	Long installation, grout discharge, complex process, non-recoverable	Limited in very hard or very soft soils, requires good soil data

4.2. Shallow gravity anchors

Gravity anchors rely on their weight to resist mooring loads, making them ideal for shallow waters but impractical for deep-sea use due to size and mass constraints. Their design prioritises sliding, overturning, and vertical bearing capacity, with settlement criteria tied to compliance tolerances. Design follows Terzaghi's (1943) bearing capacity equations, modified for load orientation, foundation shape, and soil strength, while advanced methods (e.g. failure envelopes) address the interaction of vertical, horizontal, and moment loads for capacity assessment (Randolph and Gouvernec, 2011). Key industry guidelines include API RP2GEO (2021), ISO 19900 (2015), and DNV-ST-0126 (2021).

4.3. Drag and Plate anchors

Originally derived from ship anchors, large plate-shaped flukes enhance holding capacity and are installed by dragging.

- **Fixed-Fluke Anchors:** consist of a broad fluke attached to a shank at a predetermined angle. They range up to 65 tonnes, with fluke lengths of approximately 6.3 meters. These anchors penetrate the seabed to depths of one to five fluke lengths, covering an area 10 to 20 times the fluke length. Their horizontal holding capacity—20 to 50 times the anchor weight—is derived from soil resistance in front of the fluke. However, they are not suited for significant vertical loads, making them ideal for catenary moorings but less effective for deep-water taut or semi-taut line applications.
- **Vertically Loaded Plate Anchors (VLAs):** overcome the vertical load limitations by incorporating a slender shank or wire bridle. This design allows the anchor to rotate, or "key," into an optimal position for loading upon reaching the target penetration depth. VLAs support both horizontal and vertical loads and are generally more compact, with fluke areas up to 20 m² and lengths up to 6 meters. They achieve deeper embedment, reaching 7 to 10 fluke lengths.

The holding capacity of both anchor types depends critically on installation depth, posing challenges for precise placement. Predicting performance requires advanced anchor simulation programs and analytical models. Neubecker and Randolph (1996) developed a limit equilibrium method consistent with traditional bearing capacity approaches. Additionally, manufacturers provide design charts detailing penetration, drag distance, and holding capacity (e.g., Vryhof Anchors, 2018). Drag anchors are typically not suited for shared mooring configurations.

4.4. Pile and suction anchors

4.4.1. *Most versatile and high-capacity option: Piles*

The pile stands as the most versatile and high-capacity anchor, typically constructed as an open-ended tubular steel structure (Figure 6). Its adaptability makes it suitable for diverse seabed conditions.

Design Considerations

Pile design focuses on several critical factors:

- **Axial Strength:** Ensure maximum holding capacity under vertical loading
- **Lateral Strength:**
 - Ensure maximum holding capacity under horizontal loading
 - Prevent excessive lateral movement or rotation (failure is typically defined by a pile head displacement exceeding 10% of its diameter or a rotation over 2° at the mudline).
 - Avoid bending failure under lateral loads.
- **Lateral Stiffness:** Ensure minimal pile deformation and displacement under operational loads.
- **Cyclic Loading Effects:** Addresses accumulated plastic deformation and stiffness changes due to repeated loading.
- **Bending Moment Distribution:** Mitigate fatigue damage along the pile.

Successful design requires modelling the soil-pile interaction, particularly the horizontal soil pressure against the pile shaft. Maximum lateral resistance in sand and clay is estimated using DNV-ST-0126 (2021). Design often employs a simplified 1D monopile model, traditionally using the non-linear p - y method (Matlock and Reese, 1960) and, more recently, the PISA 1D method (Byrne et al., 2019) for large-diameter piles. Advanced 3D finite element analysis is also used in detailed design phases to refine design and optimise geometry.

Installation Methods

Piles are primarily installed by hammering (driving/piling) using hydraulic hammers. Installation assessments follow DNV GL-ST-0126 (2021), API RP 2A (2021), and ISO 19901-4:2016(E), covering:

- **Soil resistance and driving stresses**
- **Fatigue** induced by driving
- **Noise and installation duration**
- Potential issues like:
 - **Refusal:** Soil resistance exceeds hammer capacity, preventing required penetration.
 - **Tip Damage:** Buckling or reduced capacity due to pile tip damage, potentially causing refusal.
 - **Pile Run:** Sudden, uncontrolled free-fall during installation (Erbrich and Randolph, 2025).

In challenging seabed conditions—such as rock or calcareous sand—drilled and grouted piles provide a viable alternative when driving is impractical (Table 1).

4.4.2. *Silent installation and increased capacity using suction anchors in clayey soils*

Suction caissons—also referred to as suction anchors, suction buckets, SICFs (Suction Installed Caisson Foundations), or SICAs (Suction Installed Caisson Anchors)—are large, hollow steel pipes sealed at the top and open at the bottom (Figure 7), installed by applying internal suction and offering a compelling alternative to piled foundations. Internal stiffeners can be incorporated to enhance both penetration resistance and plug stability (Figure 6). Originally developed for deep-water soft clay applications in oil and gas, suction buckets remain less proven compared to traditional piled foundations.

Their key advantages include:

- Near-silent installation, minimising marine life disruption and eliminating the need for costly noise mitigation measures, thereby reducing installation time and expenses.
- Seamless integration with tension-leg platform (TP) substructures in a single operation (Figure 5), potentially cutting offshore time and lifts.
- Lower installation costs, as they eliminate the need for pile-driving equipment. While pumps are required, they are lighter and easier to manage than piling hammers.
- Full extractability during decommissioning by reversing the installation process, ensuring no residual steel remains on the seabed.

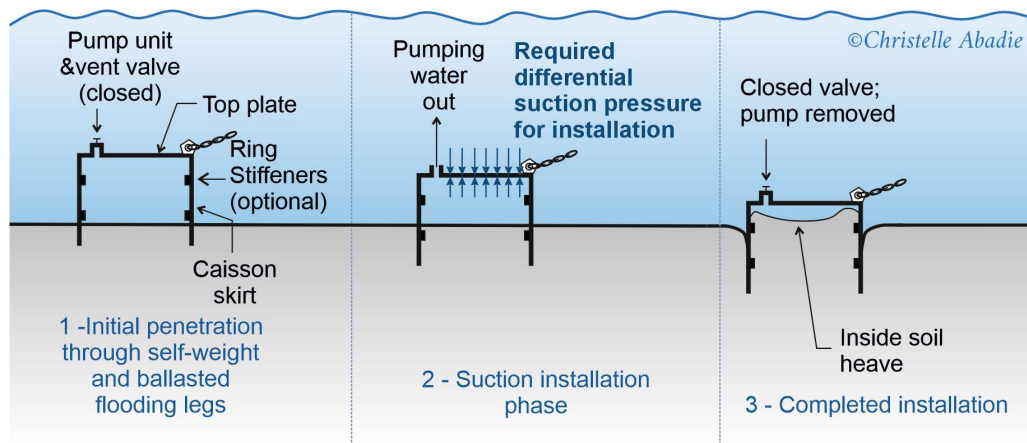


Figure 7: Definition and stages of installation of a suction caisson

Suction caisson design is structured around three critical phases:

1. **Installation**, including site preparation, such as levelling, and ensuring proper skirt penetration. Installation feasibility is a primary challenge and is as vital as the caisson's in-place capacity.
2. **Capacity** This phase evaluates the caisson's performance under operational loads—vertical, horizontal, and moment (VHM)—including uplift and cyclic loading.
3. **Serviceability** Here, short- and long-term displacements are assessed, accounting for the effects of cyclic loading. The design verifies the required settlement to fully mobilise the caisson's capacity.

Installation is highly sensitive to ground conditions, and their design typically demands more time and effort compared to monopile foundations. While comprehensive design guidelines for suction anchors are still under development, significant progress toward standardisation has been made. Notable contributions include the frameworks proposed by the Carbon Trust (2019) and CFMS (2024).

4.5. Innovative Anchoring Solutions for Deep-Water Applications

The complexity and cost of installing traditional anchors in deep waters are driving the development of simpler, more efficient alternatives (Figure 6), currently being tested in laboratories. These innovative designs prioritise ease of installation while maintaining robust performance:

- **Helical Piles**, or screw piles, consist of cylindrical steel shafts fitted with helical blades at the base. These blades enable the pile to be screwed directly into the seabed, simplifying installation and enhancing load-bearing capacity.
- **Winged Piles and Dynamically Penetrating Anchors (DPA)** are piles or cone-tipped piles with winged welded plates along their shaft, enhancing their pull-out holding capacity. They can be designed for free-fall penetration in ultra-deep waters, embedding to depths two to three times their length. Their holding capacity—estimated at three to six times their weight—makes them cost-effective despite lower efficiency.
- **Dynamically Embedded Plate Anchors (DEPLA)** combine the installation efficiency of DPAs with the capacity advantages of vertical plate anchors.
- **Suction Embedded Plate Anchors (SEPLA)** integrate the reliability of suction caissons with the efficiency of plate anchors.

- **Ring Anchors**, such as the Multiline Ring Anchor (MRA) (USA Patent No. US 2020/0407021 A1, 2020), are hollow, open-ended cylinders with external padeyes, ideal for multiline shared anchoring.
- **Micropile and Helical Pile Groups** are small-diameter, grouted steel piles drilled 10–15m into the seabed, stabilising soil like plant roots. Effective in rocky conditions and for shared anchoring.

5. Shared Mooring

Shared mooring configurations (e.g., Figure 3 and Figure 4) for Floating Offshore Wind Turbines (FOWTs) offer significant advantages, including potential cost savings for large-scale projects, along with reduced seabed footprint, faster installation, and lower environmental impact. However, this approach introduces new risks: increased anchor loading, complex anchor–seabed interactions, and complex soil responses to multi-directional cyclic stresses. These factors heighten the potential for progressive, cascading failures, which could compromise the structural integrity of the entire wind farm.

As of 2024, Hywind Tampen remains the only commercial floating wind farm using shared anchors (Frossard et al., 2025), with ongoing pilot projects and research aimed at validating their feasibility. Ensuring safe implementation requires accurate prediction of anchor capacity and strict control of displacement under operational loads. **Ratcheting deformation** is a critical concern, referring to the progressive accumulation of permanent anchor displacement under long-term, multi-directional cyclic loading. Such ratcheting can incrementally degrade soil strength, reduce holding capacity, and alter load distribution, thereby threatening the integrity of the mooring system. To mitigate this risk, anchor movement is generally limited to less than 10% of the anchor diameter, and long-term cyclic performance must be verified through analysis or testing.

Pile-type anchors are often preferred for shared-anchor systems because of their vertical symmetry (Cerfontaine et al., 2023), although they remain sensitive to cyclic inclined loading. Understanding pile response to multi-directional cyclic loading is critical for assessing the behaviour of embedded anchors, including suction anchors, and for advancing emerging anchor concepts (**Error! Reference source not found.**), that currently lack formal design guidance. Given the limited commercial experience, significant uncertainties persist, highlighting the need for further research into the long-term behaviour of shared anchors under multi-directional cyclic loads, as well as ongoing monitoring of demonstration projects such as Hywind Tampen, in operation since 2023.

5.1. Effects of multi-directional cyclic loads

5.1.1. *Experimental observations on pile anchors*

Research by Richards (2019) and Richards et al. (2020), building on Rudolph et al. (2014), reveals ratcheting of piles under multi-directional cyclic loads of varying loading spread angles and load magnitude and displacement increased by 18% compared to uni-directional cyclic loading. Recent experimental studies (e.g., Abadie, 2025, Zabatta et al., 2024, 2025; Chalhoub et al., 2024, 2025a,b) have deepened the understanding of pile behaviour under complex loading.

For offshore foundations, the primary load sequence is the ‘Cross’ test (Figure 8), which combines constant load in one direction with two-way cyclic loading in another. This scenario mirrors offshore wind

conditions, where steady wind loads align with wave-induced cyclic loads from a different direction, known as static-cyclic load misalignment (Figure 3).

Figure 8 presents laboratory results from carefully scaled shared-anchor pile models tested under cross-loading, at a low load level corresponding to operational load (in blue), followed by a higher load level (in orange) corresponding to a storm. The tests were performed within the MUTANC (Zabatta et al., 2024, 2025) and GEOLAB (Chalhoub et al., 2024) projects. These results show that cross-type loading induces substantially greater permanent deformation along the constant load axis. While the deformation spread angle is reduced relative to the load spread angle, the residual displacement remains substantial. These are very recent initial results presented by Abadie (2025), Zabatta et al. (2025) and Chalhoub et al. (2025) and further research is needed to quantify deformation accumulation over cycles and clarify the impact of load angles on ratcheting behaviour, supporting the development of practical design methods. Although similar results are expected on other embedded anchors, the research also needs to be extended to other embedded anchor geometries for design applications.

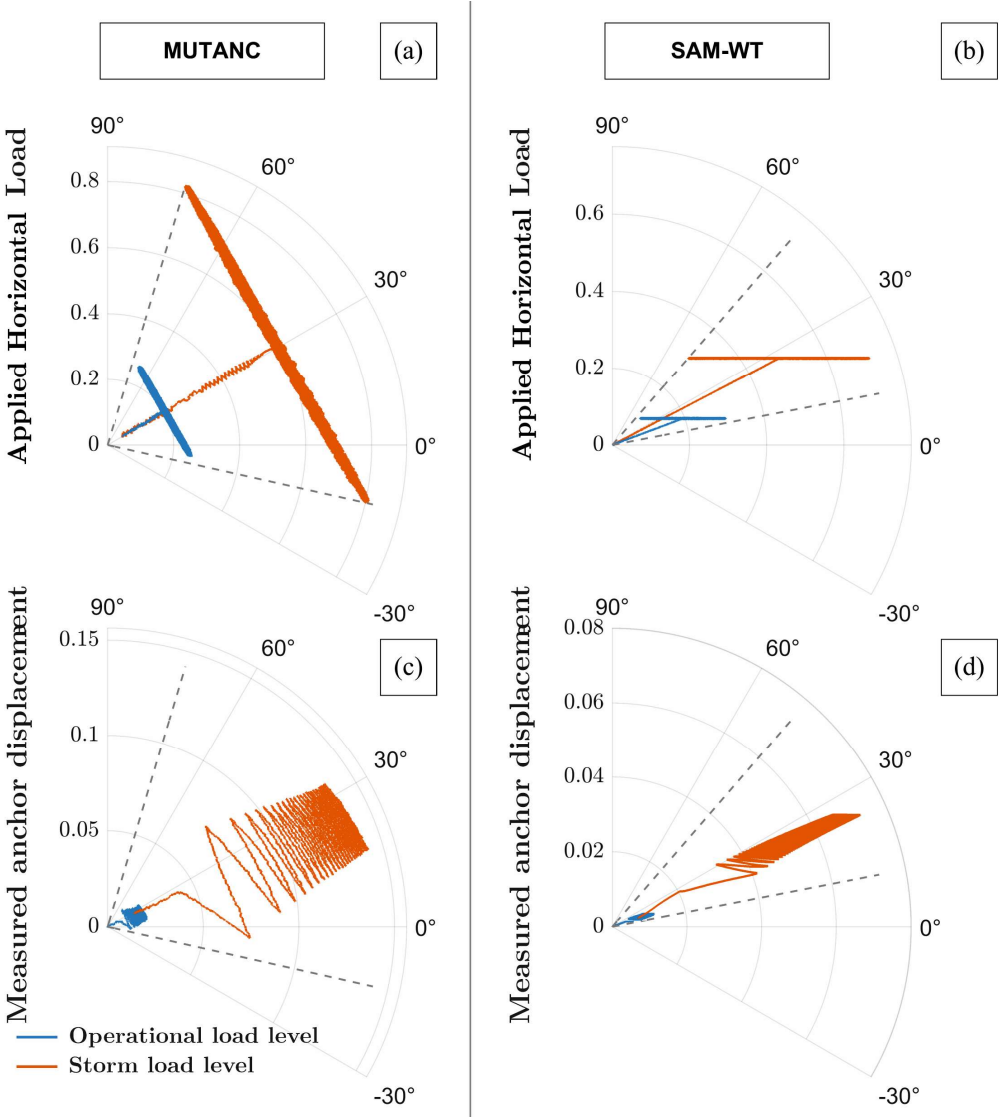


Figure 8: Experimental rose response to multi-directional cyclic Cross load from the MUTANC and SAM-WT projects (Abadie, 2025): (a,b) input load, (c,d) pile displacement response

5.1.2. The case of shallow foundations

While different soil response mechanisms are mobilised during multi-directional cyclic loading of shallow foundations, similar results have been observed with regard to the accumulation of permanent deformation (Figure 9), showing the need for a comprehensive understanding across all anchor types.

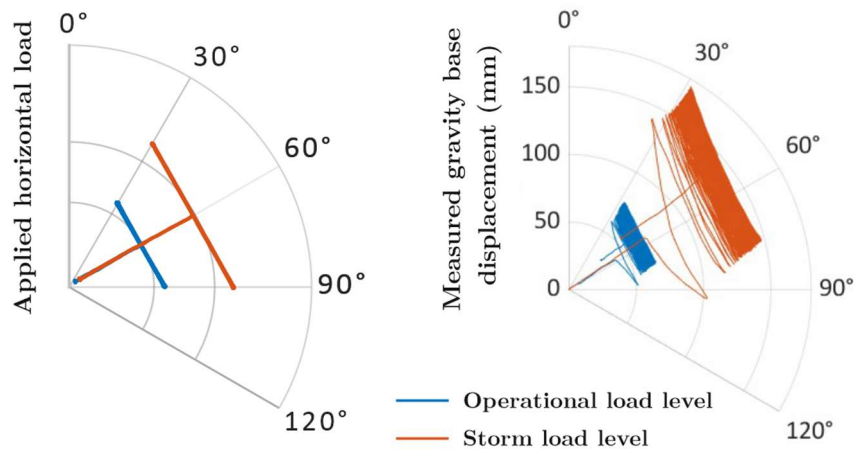


Figure 9: Experimental response to multi-directional cyclic cross load on a gravity base (Ifeobu et al., 2025)

5.1.3. Modelling and design methods

Methods for Modelling Pile Response to Lateral Loads typically include:

- **Degradation Factors:** Fast and widely used in industry, but empirical and dependent on extensive benchmark data.
- **Simplified 0-D Macro-Element Model:** Efficient for cyclic loading but lacks explicit pile modelling and may overlook depth-dependent soil changes.
- **Simplified 1-D Models (e.g., PISA, p-y curves):** Effective for monotonic loading but computationally intensive for long-term cyclic analysis (Abadie et al., 2023).
- **Advanced 3-D FE Models:** Highly accurate but time-consuming and impractical for cyclic scenarios.

However, none of these methods have yet been adapted to long-term multi-directional cyclic loads, and guidelines will need to be developed in the future to permit cost-effective design of shared anchor piles across a wind farm site. Several initiatives are taking place in this direction. Notably, CLAP (Cyclic Loading Analysis of Piles) is a novel framework by Abadie and Page (2025) that permits the simulation of long-term multi-directional cyclic loading. It captures coupled horizontal forces and moments (H_x , H_y , M_x , M_y) using a multi-surface kinematic hardening (MSKH) framework, and permits to capture ratcheting over large cycle number. The model is under development but shows promise for enhancing 0-D and 1-D pile models, particularly for static-cyclic misalignment loading (Figure 10). The model is well-suited for integration into standard structural analysis software (Page et al., 2018, 2019) and enables efficient computation of pile responses under very large numbers of load cycles (Abadie, 2015; Abadie et al., 2023). Such modelling approaches are therefore essential for advancing both the understanding of shared anchor behaviour and the development of design methods tailored to industry practice.

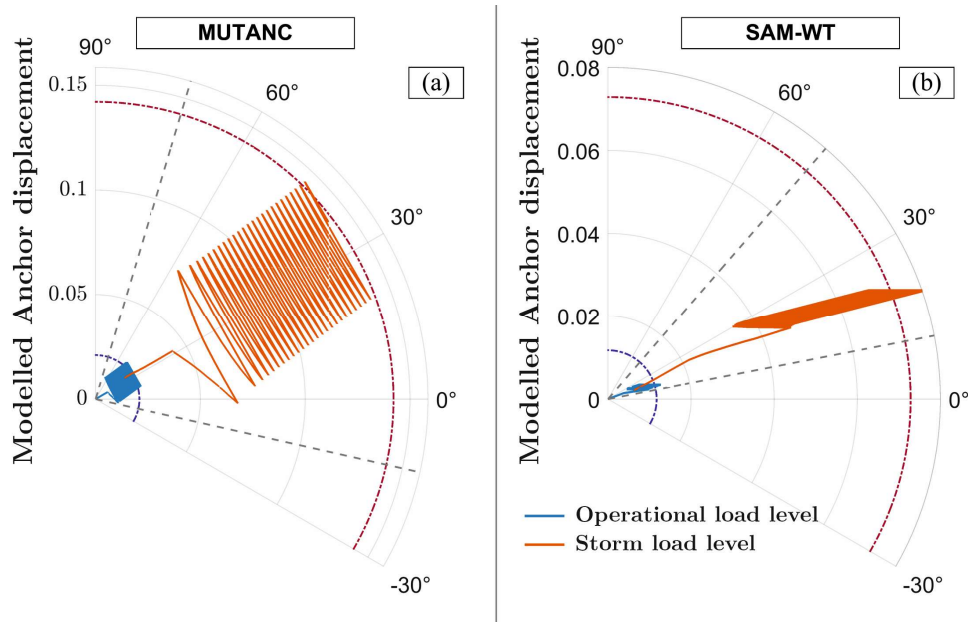


Figure 10: Predicted numerical CLAP response for (a) MUTANC and (b) SAM-WT Cross tests. The dash-dotted coloured lines indicate maximum experimental displacement for each load packet (Figure 8); The grey dashed lines indicate the magnitude of the cross-load angle (Abadie, 2025)

5.1.4. Implications for design

The design of anchor piles under multi-directional cyclic lateral loading remains an emerging and non-standardised field (Herduin, 2019). Larger deformations from multi-directional cyclic loading can significantly affect the long-term structural integrity of offshore foundations in several ways:

► Progressive Capacity Change

- Change in Holding Capacity: Accumulated deformations (ratcheting) can change the properties of the soil around the foundation, changing its lateral and vertical resistance over time.
- Soil Softening: Repeated cyclic loading may cause soil remoulding or strength loss, particularly in clay or loose sand, further changing stability.

► Fatigue and Material Damage

- Structural Fatigue: Increased deformations lead to higher stress cycles in the foundation material (e.g., steel piles), accelerating fatigue crack growth and potentially causing premature failure.
- Connection Failures: Excessive movement can stress welds, bolts, or grouted connections, increasing the risk of joint failures or leaks in sealed systems.

► Operational Risks

- Misalignment and Overloading: Deformations may alter the load distribution across the foundation, leading to uneven stress concentrations and localised overloading.
- Cascading Effects: In shared mooring systems (e.g., floating wind farms), progressive deformation in one anchor can redistribute loads unpredictably, increasing the risk of system-wide instability or collapse.

► Serviceability Issues

- Excessive Displacement: Large deformations can cause permanent tilting or settlement, compromising the alignment and performance of turbines, platforms, or subsea infrastructure.

- Increased Maintenance Costs: Foundations experiencing significant deformation may require more frequent inspections, repairs, or even replacement, raising long-term operational costs.

➤ **Environmental and Regulatory Concerns**

- Seabed Disturbance: Repeated movement can disrupt marine ecosystems or violate environmental permits, especially in sensitive areas.
- Compliance Risks: If deformations exceed design limits or industry standards (e.g., ISO, DNV), projects may face regulatory penalties or insurance complications.

Larger deformations, therefore, compromise safety, durability, and cost-efficiency. Addressing them requires a combination of resilient design, proactive monitoring, and adaptive maintenance to ensure long-term integrity.

Critical factors—such as spread angle, load angle variations, and magnitude—depend heavily on the specific loading regime. MUTANC, SAM-WT and the findings in this paper highlight that loading patterns (e.g., Cross-type loads) significantly influence ratcheting behaviour. Notably, some multi-directional loading scenarios may pose design risks. To unlock future cost savings, reduce environmental impact, and advance the field, experimental and numerical models must capture the coupled effects of multi-directional cyclic loading. Validated tools such as CLAP provide calibration benchmarks for various pile geometries and loading scenarios, enabling conservative and reliable design in the future.

6. Optimising Anchor Performance: Padeye Depth and Soil-Chain Interaction

In mooring systems—whether catenary or semi-taut—using anchor piles, suction caissons, or drag anchors, the optimal chain attachment point is typically below the mudline. For piles and suction caissons, positioning the padeye deeper boosts resistance to horizontal loads. The ideal depth is achieved when the anchor moves through the soil without rotating, found by iteratively balancing forces above and below the padeye. Here, the chain adopts an inverse catenary profile, with soil friction easing tension at the attachment point, or padeye (Figure 11). This tension reduction enables more efficient anchor sizing.

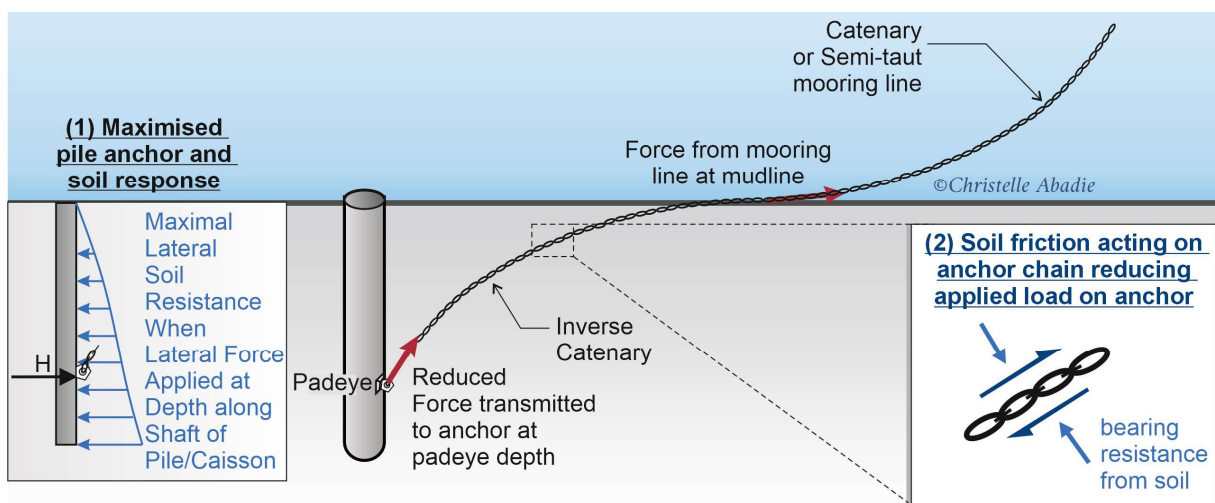


Figure 11: Configuration of loads transmitted by a catenary or semi-taut mooring line to an anchor

Evaluating how the chain interacts with the soil is critical: it defines the loading angle and force on the anchor, generating an uplift component that directly influences design. The equilibrium of an embedded anchor line, accounting for soil friction and bearing capacity, determines both the line's angle and tension at the padeye. Randolph and Gouvernec (2011) provide a simplified analytical approach, while Neubecker and Randolph (1995) offer a more detailed method, both for clayey soils. For sandy soils, Kwa et al. (2025) propose a theoretical model calibrated against experiments and using cone penetration test data as input to predict embedded line shape and tensioning response.

7. Conclusion

Floating offshore wind technology is essential for unlocking the vast deep-water wind resources, offering a technical potential far exceeding that of fixed-bottom systems. However, its widespread adoption is hindered by high capital costs, particularly for foundation and mooring systems, which can account for up to 20% of total project expenses. The design of anchoring systems is critical, as they must withstand complex, long-term cyclic loads from wind, waves, and currents, while accommodating the unique challenges of large-scale, standardised deployment.

Current anchoring solutions—ranging from traditional gravity, drag, and pile anchors to innovative suction caissons and shared systems—each present trade-offs in cost, reliability, and environmental impact. Shared anchoring, while promising significant cost savings and reduced seabed footprint, introduces risks such as cascading failures and increased reliability concerns due to multi-directional cyclic loading. Experimental and numerical studies highlight the need for improved modelling of ratcheting effects and soil-anchor interactions, particularly under static-cyclic misalignment, to ensure long-term structural integrity. Future research must focus on standardising design guidelines for multi-directional cyclic loading, advancing predictive models, and validating emerging anchor technologies. Addressing these challenges will be pivotal in reducing uncertainty, optimising costs, and enabling the safe, large-scale deployment of floating offshore wind farms.

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9. On the author

Dr. Christelle Abadie graduated in 2011 with a double degree from ENSTA Paris and an MSc in Advanced Structural Design. She pursued her PhD at the University of Oxford, developing a novel model for monopile foundations under cyclic lateral loading in offshore geotechnics. She subsequently served as lead PDRA on the design of monopiles to ultimate limit state design through the PISA2 project at Oxford. In 2018, Dr. Abadie became an Assistant Professor at the University of Cambridge, becoming the youngest member of the permanent Engineering faculty and the first female fellow in Engineering at Fitzwilliam College. In 2023, she joined the University Gustave Eiffel, focusing on next-generation offshore wind turbine foundations through geotechnical centrifuge testing and simplified models for industry application. Dr Abadie received the Bright Spark Lecture award at the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG, 2025) for her work on multi-directional cyclic loading of piles. She has served as academic representative for the British Offshore Engineering Society, UK representative for the European Large Geotechnical Institutes Platform, member of TC209, and lead editor and co-general secretary of ISFOG 2025. She collaborates with leading offshore wind companies and authored the foundation chapter for the ICE book on civil engineering aspects of offshore wind farms to be published in 2026.



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