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# Specificities of floating offshore wind turbines for risk and safety evaluation of anchoring systems

## Spécificités des éoliennes flottantes pour l'évaluation du risque et de la sécurité de leurs systems d'ancrages

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**ABSTRACT:** Floating offshore wind turbines (FWT) are still in their infancy and represent only 0.2% of currently installed commercial offshore wind capacity (193 MW of 65 GW) but will be critical to achieve net-zero objectives by 2050. The design of mooring systems and anchors for FWTs relies heavily on established Oil and Gas (O&G) practice, although governed by different design requirements. Reassessment and refinement of anchor system design methods and practices is necessary, recognising the different risks from FWT failure and the imperative for mass-production within the next 25 years. This paper identifies first the main differences between floating O&G and FWT and the associated geotechnical challenges and risks; then four key developments relevant to industry needs are selected and the solutions to reduce risk and uncertainty are then detailed: (i) Shared anchors; (ii) Farm-wide reliability assessment; (iii) Whole-life geotechnical design; and (iv) Screw pile installation. These examples show how physical, numerical and theoretical modelling can compensate for the current lack of FWT field experience to reduce design risk and raise project viability. Finally, technical project-wide risk is put into perspective by a comparison with the planet-wide risk resulting from delayed offshore wind farm installation.

**RÉSUMÉ**: Les éoliennes flottantes en mer (EFM) ne représentent que 0,2 % de la capacité éolienne offshore commerciale disponible (193 MW sur 65 GW), mais seront essentielles pour atteindre les objectifs de zéro émission nette d'ici 2050. Une réévaluation et un raffinement des méthodes de conception des systèmes d'amarrage et des ancres pour les EFM, basée sur les pratiques et l'expérience de l'industrie pétrolière, sont nécessaires pour prendre en compte leurs spécificités (e.g. conséquences limitées d'une défaillance) et la nécessité de les produire en masse dans les 25 prochaines années. Cet article identifie les principales différences entre les technologies flottantes pétrolières et éoliennes, ainsi que les défis et les risques géotechniques associés. Quatre développements clés pertinents pour l'industrie sont ensuite sélectionnés, et les solutions pour réduire les risques et les incertitudes sont ensuite détaillées : (i) Ancres partagées ; (ii) Évaluation de la fiabilité à l'échelle du parc ; (iii) Conception géotechnique tout au long de la vie ; et (iv) Installation de pieux vissés. Ces exemples montrent comment la modélisation physique, numérique et théorique peut compenser le manque d'expérience de terrain avec les EFM afin de réduire les risques de conception et d'accroître la viabilité des projets. Enfin, le risque technique à l'échelle du projet est mis en perspective avec le risque planétaire résultant du retard de l'installation de parcs éoliens offshore.

**Keywords:** Offshore geotechnics; anchoring; risk and reliability; physical modelling; numerical modelling

# 1 INTRODUCTION

## 1.1 Decarbonisation and offshore wind

Weaning society off fossil energy sources is an urgent challenge to limit the impact of future climate change (IPCC, 2021). Among the multiple solutions that must be deployed, the development of offshore wind energy sources is key to achieve climate neutrality, i.e. 'net zero', across Europe and worldwide. The Global Offshore Wind Energy Compact (IRENA et al., 2021) sets a global ambition of 380 GW of offshore wind capacity by 2030 and 2000 GW by 2050 to meet the aims of the Paris Agreement.

Europe and the UK have led in offshore wind installation over the last twenty years, almost entirely in shallow waters where bottom-fixed foundations, such as monopiles, are cost-effective. However, Floating Wind Turbines (FWT) are needed to unlock more than 70% of the offshore wind potential in the European Economic Area, where floating structures are required in water deeper than 50 m (International Energy Agency, 2019). FWT will also unlock areas further away from shore, where stronger and more consistent winds can be harnessed to generate more energy. The pace and scale of necessary offshore wind development, in conjunction with the development of new technologies introduces new geotechnical risk and safety challenges to be evaluated and overcome.

## 1.2 Floating offshore wind

Floating offshore wind is a nascent technology, comprising < 0.2% of total global offshore wind capacity at the close of 2023 (GWEC, 2022).

Currently, only four commercial floating offshore wind farms, totalling 24 FWTs, have been installed – all across Europe, located in Scotland (Hywind Scotland – 30 MW, Kincardine 50MW), Norway (Hywind Tampen – 88MW) and Portugal (WindFloat Atlantic – 25MW). The high scenario 2050 projections for UK offshore wind alone involve between 5,000 and 20,000 FWTs, which must be built in the next two decades (Putuhena et al., 2023). By comparison, there are currently 25 floating Oil & Gas (O&G) production facilities operating in the North Sea and East Atlantic (Gourvenec et al., 2022) – a population that will soon be eclipsed by floating offshore wind platforms.

Multiple concepts of FWT platforms exist and are still under development (Figure 1), but all need at least three mooring lines to stabilise and maintain the platform in position. Catenary mooring, formed of heavy metal chains, are the currently favoured configuration, but taut and semi-taut mooring concepts are under development for FWTs.

Mooring lines are anchored to the seabed by a diverse range of anchor technologies (Cerfontaine et al., 2023b), many of which have been used for decades for O&G platforms. However, the scale and pace of FWT development will put the existing supply chain under considerable strain, from vessel availability (site investigation and installation) to lab testing facilities, raw materials and anchor manufacture capability. Therefore, a reassessment of anchor design and the associated risk, built on previous O&G experience, is necessary to reflect specificities of FWT and unlock their large-scale deployment.

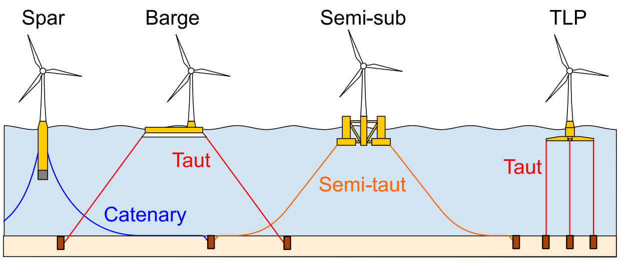


*Figure 1. Different types of floating offshore wind platforms (Spar, Barge, Semi-submersible and Tension Leg Platform) and mooring systems (Catenary, Semi-taut and Taut). Various mooring systems are suitable for different platforms with exception of TLP. Drawing not to scale.*

## 1.3 Risk and reliability evidence from O&G

The O&G industry has operated floating structures of comparable size to a floating wind turbine for around 50 years (Randolph et al., 2011; Ronalds, 2005). Ship-shaped, spar-shaped or semi-submersible floating O&G production systems are typically moored by 6-12 mooring lines designed for an operating life of 20-30 years, and have been used across a range of water depths to more than 3000 m (e.g. Moore et al., 2017).

The population of floating O&G platforms is relatively small, compared with the >3000 fixed platforms installed in the Gulf of Mexico, which provide a statistically-significant population to assess their reliability. However, recent pan-industry projects have examined the reliability of floating O&G platform moorings and anchors (Horte et al., 2017), based on failure data from operating facilities and from probabilistic analysis using existing design methods.

A mooring system reliability of $2 \times 10^{-4}$/annum is often targeted, although this is linked to the consequences of failure associated with the release of hydrocarbons (Goodwin et al., 2000). For the mooring lines, observed failures lead to an estimated average failure rate of $3 \times 10^{-3}$/annum (Ma et al., 2013). For the anchoring system, designed to a target $4 \times 10^{-4}$/annum (Gilbert et al., 2005), there are insufficient case studies of failures to develop a corresponding average observed failure rate. This suggests an inconsistency between design practice for moorings lines and anchors since the anchors are in practice more reliable than mooring lines, which represent the station-keeping 'weak link'.

Insights from these experiences can provide lessons learnt for FWT and have 3 key implications:

1. Current design practice for anchors is leading to a higher anchor reliability than the attached mooring line based on target reliabilities and practical observations.
2. Adjusted design approaches for FWT need to be calibrated against different target reliability, because failure consequences of FWT do no entail the same environmental and human risk.
3. 'Unrecognised' components of anchor capacity (such as consolidation-driven whole-life response, or inertial effects for very fast loading), which require quantification and adoption in design methods.

## 1.4 Reliability-based design for FWT

Reliability-based design optimisation of offshore renewable energy structures (Clark et al., 2018) can contribute to the reduction in design conservatism and cost, adapted to the specificities of FWT detailed in the next section. Probabilistic approaches for the design of bottom-fixed offshore wind turbines have been introduced (Charlton et al., 2022; Shittu et al., 2021; Zhang et al., 2023), but fewer studies exist for FWT (Devin et al., 2021; Hallowell et al., 2018).

While thousands of bottom-fixed structures have already been installed and provide a statistically-significant population to assess existing design practice, the several tens of installed FWT provide only limited ability to assess their reliability (Kolios et al., 2009; Li et al., 2022) and identifying critical modes of failure. This is even more prevalent for anchors, although advances in anchoring design will be supported by a rapid growth in performance data as new FWTs are deployed. For example, at a nominal failure rate of 2 × $10^{-4}$/annum, across a population of 10,000 FWTs, each with 3 mooring lines and anchors, 6 failures per year might be expected.

Geotechnical aspects are often neglected or oversimplified in reliability-based approaches, due to the inherently high geotechnical uncertainties, either epistemic (i.e., uncertainty on predictive models) or aleatoric (i.e., uncertainty on design variables). It is more complex to measure, quantify and predict soil properties and soil-foundation responses, than for human-made materials or structures.

The goal of this Paper is to review geotechnical challenges and risks induced by the specificities of FWT, and to demonstrate how physical, numerical and theoretical approaches can be leveraged to reduce both epistemic and aleatoric uncertainty, by identifying new modes of failure, by developing new predictive models or by enhancing soil characterisation.

## 2 SPECIFICITIES OF FLOATING OFFSHORE WIND

In the following section, the specific challenges and opportunities of FWT are detailed, and compared with current floating O&G (Figure 2) and bottom-fixed wind practice. The consequences for the anchor design and risk analysis are highlighted in each case.

### 2.1 Generalities

*Consequence of failure:* Failure of a FWT represents only a minimal risk to human life or the environment, as structures are uncrewed and do not lead to hydrocarbon release, unlike hydrocarbon drilling or production platforms. Without these hazards, a higher probability of failure (i.e. lower reliability) may be acceptable and need only be weighed against economic considerations.

*How deep is deep?* Bottom-fixed O&G have been built up to 535m water depth (Petronius Platform), while bottom-fixed wind becomes impractical and uneconomical beyond 60m water depth. This is due partly to technical consideration, e.g. the need to limit riser movement for O&G (Randolph et al., 2011), and partly to different business models, which makes gigantic fixed structures unaffordable for wind.

*Development size:* While O&G platforms are built across a limited number of isolated sites, tens of thousands of FWT will be built in farms of hundreds of structures, over hundreds or thousands of km$^2$. The scale and pace of this deployment will put additional constraints on the supply chain. The industry has to move from the O&G template of bespoke anchor design and production to mass-production, which requires greater understanding of anchor and mooring performance and enhanced guidelines for engineers.

### 2.2 New technologies

*Reducing size of mooring line systems:* New technologies offer potential to increase efficiency of mooring lines and anchors. Efficiency in mooring lines can be achieved by (i) reducing the number of lines, at

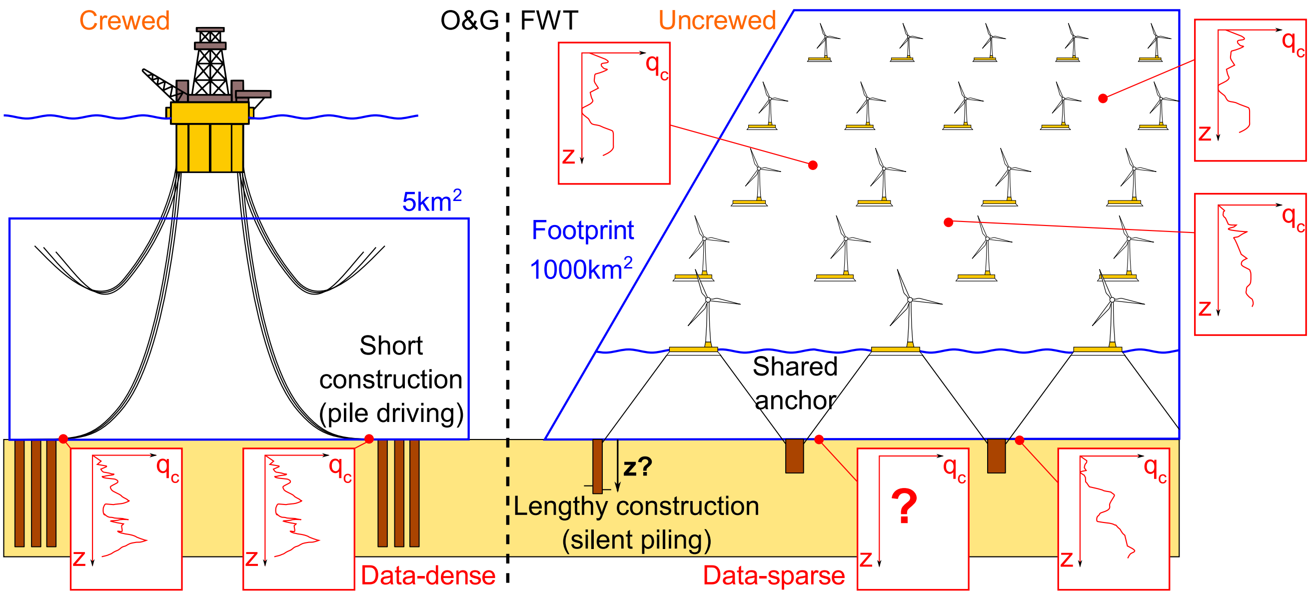


*Figure 2. Comparison of floating Oil and Gas (O&G) and Floating Wind Turbine (FWT) farm.*

the expense of a lower system resilience (Fontana et al., 2018); and (ii) reducing the length of lines with taut or semi-taut synthetic mooring configurations. The latter solution improves platform compliance in relatively shallow water, reduces steel consumption and FWT footprint. However, those two solutions impose greater magnitude of loads and greater vertical uplift component of loads to anchors increasing the challenge of geotechnical anchor design (Huang et al., 2020), even if load-reduction devices can mitigate load increase (e.g. Festa et al., 2024).

*Reducing number of anchors:* The number of anchors required across a FWT farm can be reduced by linking multiple lines from different FWT to a common "shared" anchor (Fontana et al., 2018). This can reduce the number of anchors by up to 60%, but also introduces complexity of loading onto the anchor, which could be detrimental to its cyclic performance (Herduin, 2019) and induce strength degradation risk in the longer term.

*Silent anchor installation:* New environmental restrictions aim at reducing underwater noise, which makes pile driving either impossible or more expensive. This has led to development of new installation methods, such as vibro-piling (Kementzetzidis et al., 2022), or new anchor types, such as screw piles (Cerfontaine et al., 2022). Existing uncertainties due to the lack of field experience are being progressively reduced through field, laboratory and numerical studies.

## 2.3 New ground modelling approaches

*Different sizes:* The design of floating wind farms face greater uncertainties in ground conditions than O&G or even bottom-fixed wind farms, due to their scale and the need for at least 3 anchors per turbine. For example, the recently-installed Seagreen wind farm located offshore Scotland covers an area comparable to the city of Lisbon, extending from the Vasco de Gama bridge out to the Atlantic Ocean (Figure 3). By comparison, the footprint of a single O&G platform or development is a few 100s of $m^2$ to a few $km^2$ (Randolph et al., 2011).

Uncertainties in ground conditions increase risk in both predicting installation refusal and holding capacity of anchors. Ground conditions can vary considerably across a site and a thorough soil investigation at all potential anchor points, including along the installation path for drag anchors, may be too expensive and time consuming (Jenner et al., 2002).

*Site investigation approach:* Early assessments of the right strategy for site investigation across offshore wind farms advocated for greater geophysical-geotechnical data integration to estimate engineering parameters, to reduce uncertainties in ground models (Sauvin et al., 2019; Vardy et al., 2017) and to speed up the site investigation process. Developing anchor technologies and design methods resilient to uncertainties in ground conditions is a key pathway to reduce the risk.

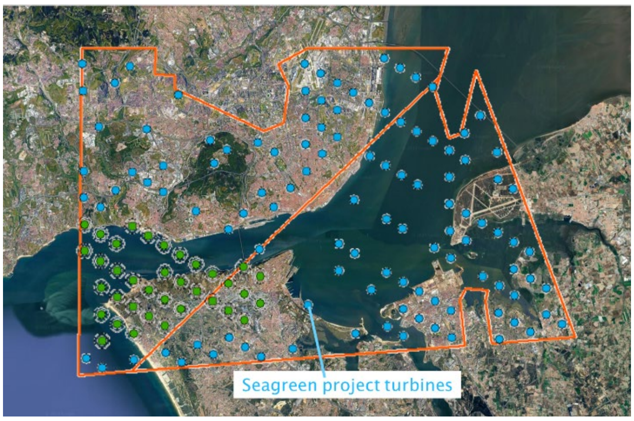


*Figure 3. Footprint of a typical offshore wind farm (Seagreen).*

*Farm-wide assessment:* Another consequence of the large population of structures in a wind farm is that the design must consider the likelihood of multiple failures. Although a design storm event may impose the same sea state throughout a farm, this will not exert the same maximum load on all turbines. Assessments of reliability therefore are more realistically performed considering the full farm-wide population.

## 2.4 New design philosophies

Traditional geotechnical design of anchors compares the maximum peak static load sustained by the anchor to its minimum drained or undrained capacity. Reduced soil strength due to cyclic loading from wave and wind effects on the soil properties, is typically considered by a quasi-static approach, and is accounted for by a degradation factor on the static properties (Jostad et al., 2014).

*Whole-life design:* A more realistic and less conservative design approach should account for the through-life variation in soil strength, by capturing the complex, physical mechanisms taking place into the soil, beyond the drained/undrained dichotomy. For instance, consolidation episodes (pore water pressure dissipation) in between storm events (pore water pressure accumulation) lead to soft clay densification and to a progressive increase of its undrained strength with time (Laham et al., 2021). This effect is encapsulated into a "whole-life geotechnical design" philosophy and has implications for anchor design, life extension and decommissioning (Gourvenec, 2022).

*Rate effects:* Loads induced by wind and wave action usually have a period ranging from 5s to 15s. At this loading rate, some anchor will experience partial drainage (Cerfontaine et al., 2023b), which can unlock significant temporary uplift resistance when compared to a purely drained loading, as demonstrated for plates (Chow et al., 2020) and suction caissons (Cerfontaine et al., 2016). In addition, FWT systems are dynamic in essence, and the highest loads often happen at a fast loading rate, e.g. due to mooring line snatch loading. Considering inertial effects into the ground can also unlock additional anchor resistance (Kwa et al., 2021).

## 3 KEY FOCUS TOPICS

To illustrate how the aforementioned challenges are being addressed, four key focus topics have been selected for more detailed discussion, as topics of high importance for the industry. These are (i) Shared anchors, (ii) Farm-wide design for reliability and risk, (iii) Whole-life geotechnical design approach, and (iv) Installation of screw piles. It is shown below how adequate physical, numerical and theoretical modelling can reveal new modes of failure and eventually reduce their associated design risk.

### 3.1 Shared anchors

Shared anchors can experience a reduction in peak lateral load between 30% and 50% (Fontana et al., 2018; Pillai et al., 2022) with respect to unidirectionally loaded anchors, as mooring lines are pulling in opposite directions, as shown in Figure 4. However, the angle of the resulting load to the horizontal direction is always greater than the angle of the mooring line itself, as horizontal components of each line oppose each other, but vertical components add up. This effect will be reinforced for taut mooring lines, which should become more common with the development of synthetic mooring systems but can also be true for catenary mooring lines if the anchor padeye is below ground level.

Pile type anchors are the most adapted to anchor sharing, due to their vertical symmetry (Cerfontaine et al., 2023), but can be vulnerable to cyclic inclined loading. Indeed, it was shown by Huang et al. (2020) that such loading had a positive impact on the lateral resistance, but a detrimental impact on the vertical resistance. The risk associated with shared anchors is increased by the lack of data and prior experience with this technology. A single commercial floating wind farm (Hywind Tampen) is secured by shared anchors and has been fully in operation since the summer 2023. Observations from real-life case studies should give more confidence in their use in the future.

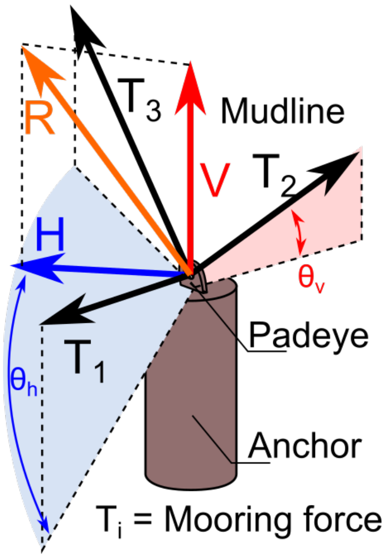


*Figure 4. Simplified representation on the loads applied to a shared anchor by three mooring lines (Ti=1,2,3), vertical (V) and horizontal (H) components of the resulting load (R), $\theta_v$ is the inclination of any force to the horizontal direction, $\theta_h$ is the position of the resulting load in plane with respect to a reference direction.*

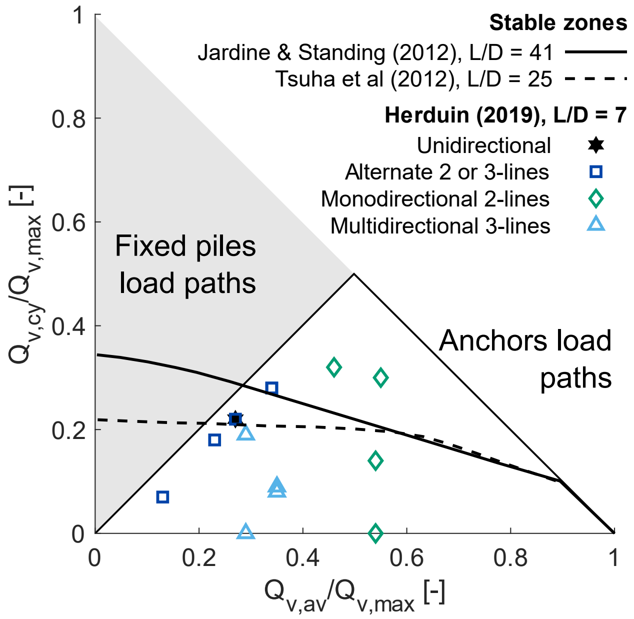


*Figure 5. Stability diagrams for piles cyclically loaded axially, after (Herduin, 2019; Jardine et al., 2012; Tsuha et al., 2012). Dots indicate loading configurations that led to failure of the anchor, from Herduin (2019). Mooring lines were inclined of 40° to the horizontal. ($Q_{v,av}$, $Q_{v,cy}$, $Q_{v,mon}$) are the average and cyclic applied vertical loads, and monotonic vertical resistance of the pile.*

The epistemic uncertainty associated with the behaviour of shared anchors can be reduced by careful experiments, such as centrifuge testing. The most comprehensive set of tests was undertaken by Herduin (2019) on relatively short and rigid piles for mooring lines inclined of 40° to the horizontal and embedded in sand. However, no framework for shared anchor design exists to date.

Results can be represented by using the stability diagram framework, which depicts stable combinations of purely vertical average and cyclic amplitude loads normalised by the maximum vertical resistance, e.g. the combinations that lead to a vertical displacement lower than 0.1D after 1000 cycles. For comparison, stable zones identified by previous researchers are depicted in Figure 5, (Jardine et al., 2012; Tsuha et al., 2012), for relatively long piles with L/D in the range 25-41.

Results from centrifuge tests of an anchor under shared loading conditions (Herduin 2019) were analysed in the stability diagram framework, by considering the projected vertical components of the applied load. Each test also had a horizontal component, which was either fixed in direction (unidirectional, $\theta_h = cst$), took different discrete directions (alternate, $\theta_h = \theta_{h1}$ or $\theta_{h2}$), had a narrow range of variation (monodirectional $15° < \theta_h < 75°$) or was changing continuously in multiple directions (multidirectional $0° < \theta_h < 360°$). The most detrimental loading paths were those involving large variation in the horizontal load components, as they led to an unstable response for vertical loads much lower than previously identified for purely vertical loading. However, mooring lines in the research were inclined of 40° to the horizontal, representative of mooring systems for wave energy converters. More research is needed to cover lower mooring line angles ($\theta_v < 20°$), more representative of realistic conditions for floating wind turbines.

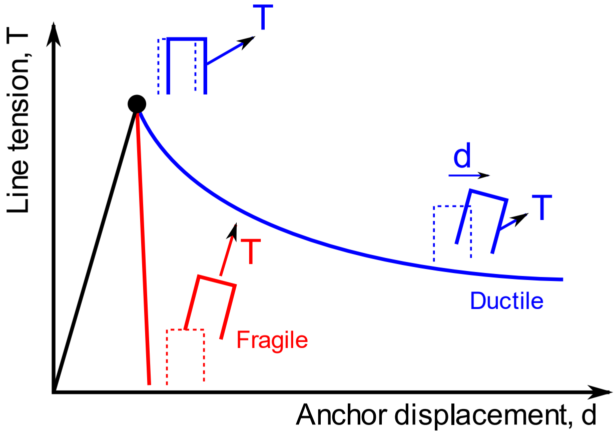


*Figure 6. Anchor ductility for load reduction and resilience.*

A higher reliability and resilience can be unlocked by using anchoring technologies with enhanced resilience and ductility, as shown in Figure 6. While vertical anchor resistance is often fragile and drops fast post-peak (e.g. for a pile), lateral resistance is more ductile and exhibits residual resistance. Therefore, a "failed" anchor laterally loaded can still mobilise some resistance, while the induced anchor movement can reduce the load applied by the mooring line (reduced pre-tension for taut mooring lines).

This resilience can be particularly critical for shared anchors, where the failure of one anchor or mooring line can lead to a cascading effect and progressive failure of more anchors, thus reducing the reliability of the system with respect to a non-shared configuration (Hallowell et al., 2018).

## 3.2 Farm-wide design for reliability and risk

The difference in failure consequences for FWT compared to O&G structures justifies a revisiting of load and resistance partial factors where these have been inherited from O&G design practice and should prompt wider adoption of probabilistic methods to meet a target reliability identify the optimum design approach from both a cost and safety perspective.

A benefit of assessing design reliability using a probabilistic approach is that uncertainties and variations can be readily incorporated allowing 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 (see Section 3.3).

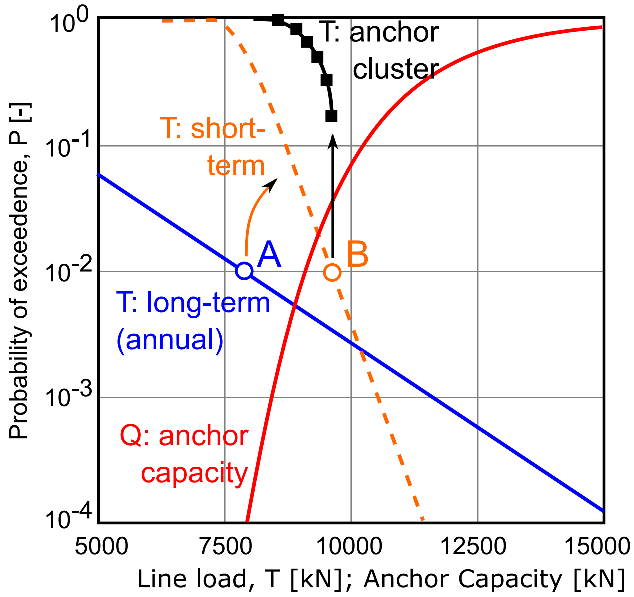


*Figure 7. Wind farm-wide load (T) and resistance (Q) variations, based on analysis in Stanisic et al. (2019).*

This farm-wide approach is illustrated here by considering a farm-wide analysis of mooring line loads and anchor resistances during a design event. Figure 7 illustrates the complexity of assessing farm-wide uncertainty in load and resistance for a wind farm comprising many turbines, each with multiple mooring lines and anchors. This example is based on the floating system reported by Stanisic et al. (2019), which analysed a floating barge structure stabilised by four clusters of 6 mooring lines and anchors.

Considering first the design loading actions, the characteristic annual maximum mooring line load – termed the most probable maximum, MPM, Stanisic et al. (2018) is assigned a distribution, usually developed from time domain simulations, which is referred to as the long term variability (blue solid curve in Figure 7). In this example, the distribution of the MPM mooring load for multiple floating units in the same sea state for which the long term MPM is $T$ = 7800 kN, and has a 1% chance of annual exceedence ($P$ = 0.01, point A).

If the same floating unit is exposed to a given sea state for different periods of time, or on different occasions, the actual maximum load will differ – this is referred to as short term variablity. The short term variability associated with a long-term (annual) maximum marked as A ($P$ = 0.01) is shown as the orange dashed curve in Figure 7. Due to this short term variability, given the occurance of a sea state that causes A ($P$ = 0.01), there is a 1% probability ($P$ = 0.01) of $T$ = 9600 kN. That is, among an array of 100 floating units, for a long term MPM of 7800 kN, one unit would be expected to see 9600 kN. This defines the variation in loads across an array of floating units when the farm is subjected to the same sea state. It therefore controls the potential for multiple failures.

In addition, there is a further variability to consider within the maximum loads among multiple anchors in the same cluster of mooring lines/anchors. In Figure 7, Point B shows an illustrative MPM anchor load from short and long term variablity. The neighbouring anchors in the 6-anchor cluster are exposed to loads that are lower, but within 11% of this maximum (as indicated by the black markers). This in-cluster variation in loading influences the potential for a single line failure to cascade into a full loss of station-keeping (Stanisic et al., 2019).

The geotechnical anchor capacity is always uncertain due to (i) uncertainty in the ground properties and (ii) uncertainty in the model used to assess the anchor capacity from the ground properties, and is represented by a fragility curve in reliability-based design. In Figure 7 an example fragility curve is shown (Q, red solid line in), which is based on the typical uncertainty in foundation capacity envelopes presented by Shen et al., (2023) using random fields analysis. Their analyses capture the variation in capacity for a foundation placed at random locations on ground with known mean and coefficient of variation in undrained shear strength.

Usually the long term and short term variabilities are combined in the assessment of a design load distribution (e.g. Stanisic et al. 2019). However, it is useful to decouple these effects for farm-wide design because this allows the farm-scale spatial variation in loading to be estimated. This can be achieved by sampling the design loads across the array using the short term variability superimposed on a single representative case from the long term variability.

When combined with the spatial variability in geotechnical capacity, this approach allows the probability of failure of multiple structures within a farm to be quantified, incorporating the correlation between the design loads and resistances across different turbines within a farm.

## 3.3 Whole-life geotechnical design approach

Accumulated soft soil strength degradation, i.e. softening, over the life of an offshore foundation or anchor is typically captured by so called 'SN' curves, to account for the reduced strength (S) due to undrained cyclic loading over a number of cycles (N) for the design life (Andersen, 2015). However, in reality, stormy weather periods (high load amplitude), typically winters, alternate with quiet weather periods (low load amplitude), during which accumulated pore water pressures, that have led to softening, dissipate, leading to a recovery and even enhancement of the soil strength in normally and lightly overconsolidated clays (Gourvenec, 2020, 2022; Kwa et al., 2023c). Therefore, considering only strength degradation in soft soils is often overly conservative.

The "whole-life" geotechnical design approach applied to soft soils explicitly includes the effect of consolidation periods throughout the life of an anchor or foundation. The approach is exemplified in Figure 8, which represents the theoretical state of a representative soil element close to an anchor over 3 years of operation, divided in 3 winters and 3 summers. Significant storms are assumed to occur during winter time, and lead to the accumulation of pore water pressure (u, in Figure 8b) and a reduction in the current undrained strength ($s_u$, in Figure 8b).

Each storm takes place in undrained conditions, hence at constant void ratio, depicted by a horizontal line in Figure 8a. Dissipation of pore water pressure and subsequent consolidation occur in between storm events and mostly during summer time, leading to a soil densification (reduction in e in Figure 8a).

The time necessary to fully dissipate pore water pressures depends on material, geometric properties and load applied (Kwa et al., 2023b), so the consolidation process is not complete after every summer, but the undrained strength still progressively increases beyond its initial value ($\Delta s_u > 0$ in Figure 8b). Similarly, the potential rise in $s_u$ depends on the initial over-consolidation ratio of the soil (Gourvenec et al., 2014).

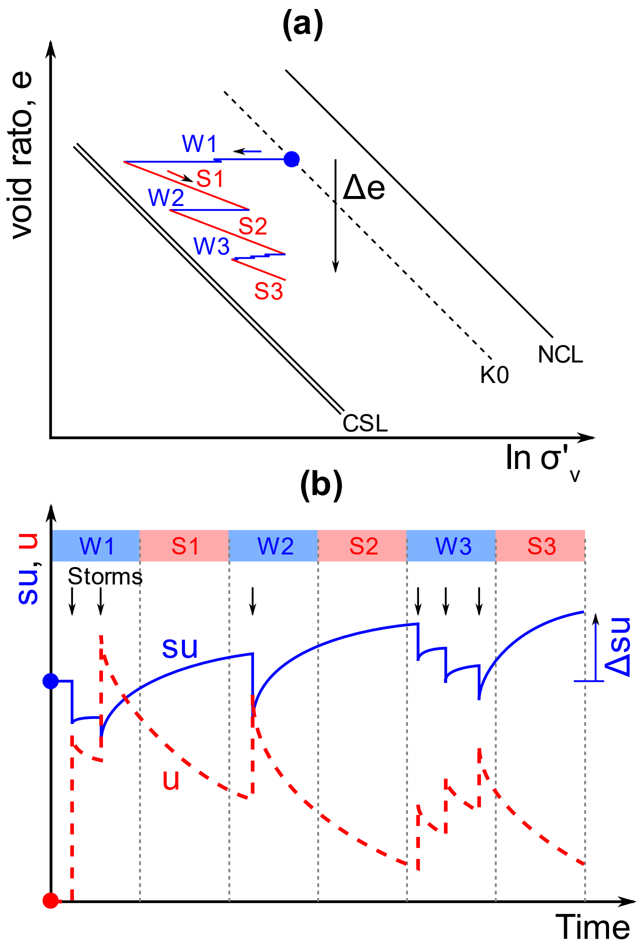


*Figure 8. (a) Changes in void ratio and effective vertical stress of an element of soil close to an anchor due to episodes of cyclic loading during winters (W) and summer (S) periods. (b) Change in pore water pressure (u) and mobilizable undrained strength in the soil element (su) with time. Schematic representation of whole-life effect, not to scale. Based on (Laham et al., 2021).*

The whole-life approach illustrates that the drained/undrained dichotomy is insufficient for modern design. It is possible to unlock additional anchor resistance, if a more complex physics is taken into account, and if probabilistic design is adopted, as the soil strength increase depends on its loading history. 10,000 3-year long histories representative of a wave energy converter attached to a plate anchor have been considered in combination with an anchor macro-element, capable of tracking average undrained strength degradation and pore water pressure dissipation (Kwa et al. 2023a). The anchor diameter necessary to limit the probability of failure to $10^{-3}$ was extrapolated from those results and ranges between 5 and 6m across different coefficients of consolidation (Figure 9). By comparison, a diameter of 7.5m would have been necessary if only undrained strength degradation had been considered, without any consolidation.

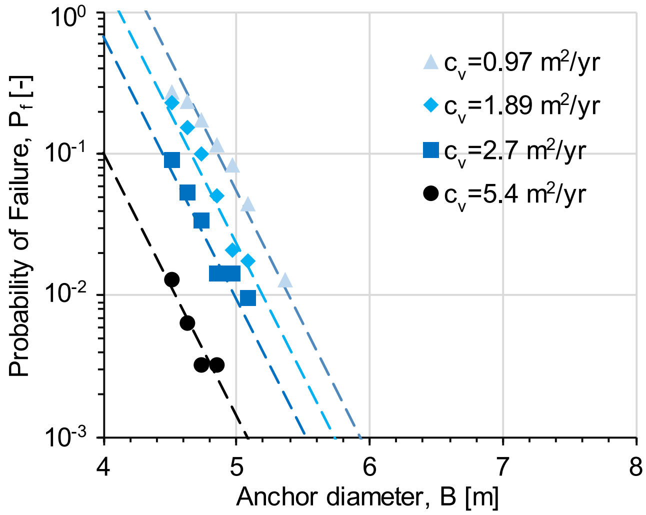


*Figure 9. Probability of failures for a given anchor diameters as a function of the coefficient of consolidation ($c_v$), calculated based on 10,000 load history simulations, (Kwa et al., 2023).*

A similar approach has been adopted coupling the anchor macro model with hydrodynamic mooring line analyses for floating wind, predicting minimum plate anchor areas of half that from traditional design by considering whole-life soil response and load reduction devices (Kwa et al., 2023a).

## 3.4 Installation of screw piles

Screw piles are composed of one or several helices attached to a steel shaft (see Figure 10), which are very efficient to sustain axial uplift loading and can be "silently" installed by applying axial force and torque at their head to screw them into the ground (Cerfontaine et al., 2023a). Screw piles have been


*Figure 10. Sketch of a screw pile (rotated 90°). $D_h$ and $p_h$ are the helix diameter and pitch and $D_s$ is the shaft diameter.*

widely used onshore, but their use offshore requires a significant upscaling in their dimensions and the development of bespoke installation tools (Cerfontaine et al., 2020).

So far, the risk of refusal during installation due to insufficient force and torque capabilities has impeded their adoption, despite a continuously growing interest. Indeed, the magnitude of the vertical reaction (crowd) force required to install large-scale screw piles according to onshore guidelines ranges from 10-20MN, which cannot be sustained by current installation vessels. Those guidelines require a pitch-matched installation, which means that the helix will advance axially by one helix pitch per rotation of the helix, and is often referred to as perfect installation.

Geotechnical centrifuge modelling and DEM simulations were used to prove the feasibility of large screw pile installation in sand (Cerfontaine et al., 2021) with limited reaction force, thus reducing the perceived installation risk. It was shown that a change in installation parameter (AR = advancement ratio) below the range allowed by the design guidelines (0.8 ≤ AR ≤ 1.2), could lead to a significant reduction in the measured crowd force (Figure 11). The AR is the ratio of the vertical displacement of the pile for each pile revolution. It is equal to 1 in pitch-matched conditions and lower than 1 during overflighting.

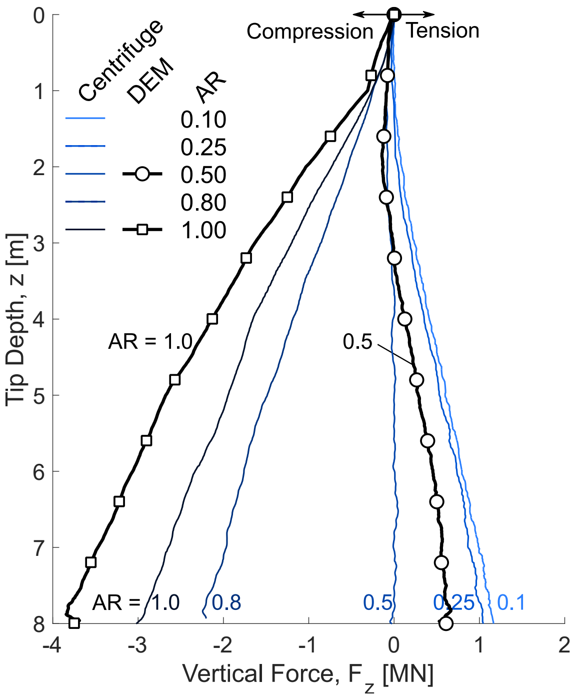


*Figure 11. Vertical (crowd) force measured in centrifuge and DEM modelling of single-helix screw pile installation in a medium-dense sand at fixed ARs. AR = advancement ratio, = 1 for pitch-matched and <1 for overflighted piles. After Cerfontaine et al. (2021).*

The overflighting physical mechanism was revealed by DEM simulations. During pile overflighting, the helix edge picks up some soil and forces it to move upwards, which is constrained by the existing soil acting as a non-linear spring. The resistance of the upper soil to this imposed movement creates a reaction force acting on the helix and oriented downwards. The lower the imposed AR, the more the resulting force is reduced, and a tensile force was eventually measured. This means that the pile pulls itself into the ground. It was also shown that the tensile resistance was enhanced by the installation, which created some preloading of the ground.

The installation in the field is not AR-controlled as per the experiment, but is undertaken at constant resulting force. The sum of reaction forces acting on the shaft, helix and tip is equal to the screw pile and installation tool weight. The AR of a given pile would then vary during installation to adapt to ground conditions, with a lower AR expected in a denser sand. A pile could then overcome undetected harder soil layers, which de-risks the installation, though some research on overflighting in clay and boulder effects still has to be undertaken. A significant torque still has to be provided during installation, which can reach tens of MNm, but was deemed less of an issue than the required reaction force by contractors.

The powerful combination of physical and numerical modelling, enabled a mechanism-based theoretical framework to be developed, leading to further pile geometry optimisation to further reduce installation requirements and reduce risk (Cerfontaine et al., 2022).

## 4 RISK – A WIDER PERSPECTIVE

### 4.1 Project-wide and planet-wide perspectives

It is useful to close this review of risk and safety evaluation of floating offshore wind by considering the wider risk perspective, including the impact of climate change (Figure 12).

So far, this paper has focused on a *project-wide* (or company-wide) perspective, which considers the risk and safety associated with company personnel and the general public who are exposed directly to hazards during the project operations. The environmental impact assessment, or other activities required to meet regulatory requirements, widen this scope by ensuring that nearby ecosystems remain safe from harm.

On the other hand, the perspective that an individual may have, or that society collectively has is called here a *planet-wide* perspective. It is not unique, as different social groups, nationalities and regional populations will have varying views on the relative importance of wider risks. However, there is an international consensus that global warming must be kept below 1.5° and we must develop offshore renewable energy sources to reach carbon neutrality by 2050. Therefore, the *planet-wide* perspective on offshore renewables includes the climate-related risk from *not* developing a project – or delaying the construction and development process – as well as the risks associated with going ahead (Figure 12).

Any delay to the growth of offshore renewable energy (ORE) raises the risk of not reaching climate neutrality by 2050 and causes harm through the climate impacts from that prolonged fossil fuel use. This harm reaches the same individuals as the project-based risk field of view, but it also has the potential to affect the entire global population, due to the distributed impact of carbon emissions.

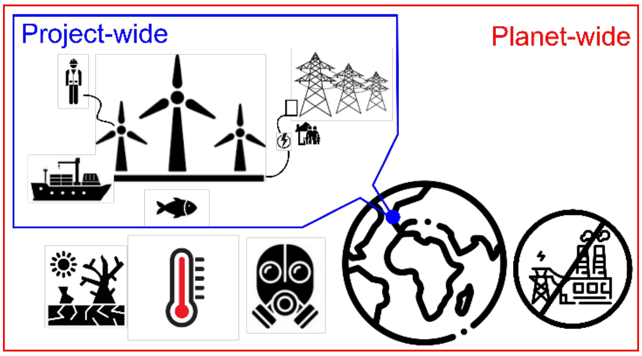


*Figure 12. Risk views: project-wide vs planet-wide.*

## 4.2 Human risk linked to carbon emissions

The consequences on human health (heat/cold, air pollution, loss of habitable areas…) of carbon emissions occur through the many cascading impacts outlined in the major national and international reports produced by organisations such as the Intergovernmental Panel on Climate Change (IPCC).

The simplest approach to quantify these *planet-wide* impacts so they can be weighed against *project-wide* risks, is to use the mortality cost of carbon. That is, the estimated cost, in human lives, per unit of additional carbon emissions. Bressler (2021) describe an analysis of more than 100 studies into the human risk from climate change across a wide range of impact. It is concluded that 4,400 tonnes of carbon emitted in 2020 is expected to cause one excess (i.e. additional) death during the period 2020-2100.

## 4.3 *Planet-wide* human risk linked to Offshore Renewable Energy

Using the metrics from Section 4.2, it is simple to assess the difference in human risk from the *project-wide* and *planet-wide* perspectives given in Figure 12. For instance, It was estimated by The Crown Estate (2022) that an additional 17Mt of $CO_2$ would have been produced in 2022 if the 45 TWh offshore wind energy had been produced by fossil fuel-based energy. Therefore, each TWh of UK offshore wind currently saves 86.5 lives globally over this century. The 2022 UK offshore wind production will have saved 3900 lives by 2100 and these outcomes will grow and accumulate with each future year of offshore wind production.

The same logic can be applied to a future offshore wind farm that is currently being proposed and designed. A 2 GW capacity floating wind farm operating at a typical capacity factor of 50% will produce 260 TWh of electricity over a 30-year operating life. Based on the fossil fuel abatement and carbon mortality rates above, this wind farm will save 22,700 lives that would otherwise be lost as excess deaths due to climate change impacts from fossil fuel burning.

This saving of $>10^4$ lives by mitigating climate risk far exceeds the human risk seen in the *project-wide* perspective. Figures for industrial injuries and deaths show that the wind, solar and nuclear industries are safer than coal and fossil fuel production, on a global average, although high regional variations are present. The wind power industry has a death rate estimated to be 0.04 deaths/TWh production (Ritchie, 2020), or 10 deaths over the operating life of a 2 GW wind farm.

These simplified comparisons illustrate the increasing importance of a holistic perspective on risk, and the need for carbon and risk literacy among practising engineers. A holistic perspective, understood and acknowledged by all stakeholders, will ensure that the planning and development of energy systems including ORE will maximise the societal benefits and minimise overall human risk, not only the risk to those directly involved in projects.

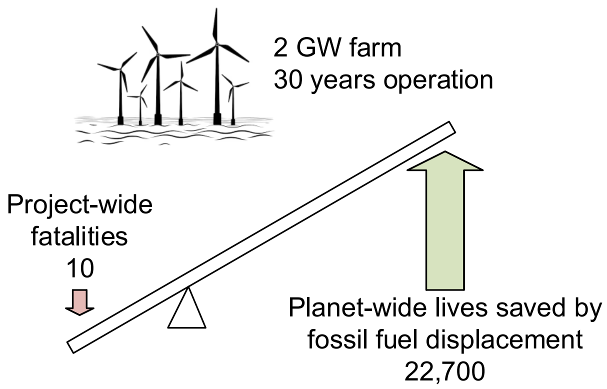


*Figure 13. Human mortality from an offshore wind farm.*

# 5 CONCLUSIONS

The design of floating offshore wind turbines (FWT) has so far been based on the experience accumulated by the Oil and Gas (O&G) industry. However, the scale and pace of floating offshore wind developments to reach net-zero by 2050 is such that new design practices, technologies and guidelines must be developed to better suit FWT specificities and reduce their associated risk. By comparison with O&G, floating wind farms extend over a much greater area, are expected to be more than 100 times more numerous and their failure have a much lower impact.

Among various enhancement possibilities, two new design approaches (e.g. "whole-life" design or farm-scale reliability assessment) and two new technologies (e.g. shared anchors or "silently" installed screw piles) were discussed in this paper. The perceived risk associated to each innovation is magnified by the lack of field experience, which does not allow for a real-life estimation of their reliability. In each case, it is shown how physical, numerical and theoretical modelling can be combined to identify to new failure modes or provide sound evidence to reduce their associated risk.

Finally, it is argued that the *project-wide* risk related to those innovations should be put into perspective with the *planet-wide* risk associated with the delayed operation of new offshore wind units and prolonged operation of fossil-fuel energy systems. A holistic approach is necessary to encompass risk at different scales and maximise the benefits to society at wide.

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