The influence of ground conditions on the performance of shared anchor systems for floating offshore wind

H. Dingle & T. Gordelier
Arup, Bristol, UK

A.C. Pillai
Renewable Energy Group, College of Engineering, Mathematics and Physical Sciences, University of Exeter

ABSTRACT: Significant growth of the floating offshore wind sector is anticipated over the next decade as developers target increasingly deeper sites. The efficient design of mooring systems and innovative anchor layouts will be critical in driving down the cost of this technology. Sharing anchors would lead to a reduction in total number of components to be fabricated and installed. It is also perceived that shared anchors may be smaller, facilitating installation by more readily available and cheaper vessels. These shared anchors must, however, be designed to withstand loading from multiple directions and for an increased number of fatigue load cycles. The efficiencies that can be gained from anchor sharing will vary depending on anchor type, mooring line type, applied loading, and ground conditions. This paper presents a study of the anchor types that would typically be considered for three representative sites with a common water depth, but varying ground conditions to include soft clays, dense sands, and shallow bedrock. The suitability of each anchor type for use in a shared anchor system is evaluated for the representative sites, and the anchor performance is compared across the different soil types.

1 **Introduction**

1.1 *The growth of floating offshore wind*

Significant growth of the floating offshore wind sector is anticipated over the next decade as developers target increasingly deeper sites. In the UK alone, the government is targeting the deployment of 5GW of floating offshore wind by 2030 (UK Government, 2022).

The vast majority of offshore wind farms deployed to date have used fixed foundations and the technical and economic challenges with the mass fabrication, installation and operation of the main foundation types (predominantly monopiles and jacket structures) are relatively well understood. In contrast, deployment of floating technology has been largely limited to individual prototype substructures and demonstration farms, with only a handful of commercial wind farms in operation (such as Hywind Scotland and Kincardine).

The key components of the foundations for a floating offshore wind turbine comprise the substructure (also referred to as ‘hull’ or ‘platform’), the moorings and the anchors. Much focus of research and development to date has been on the optimisation of the substructure and to a lesser extent the moorings, with little specific research dedicated to anchoring systems.

Anchoring systems are required to maintain station keeping and ensure survivability under extreme environmental events. They must be designed and optimised for given specific site conditions including water depth and environmental conditions, and also the seabed morphology and underlying ground conditions (Pillai et al., 2022).

Anchor technology is well established from decades of use in the oil and gas industry. However, with the need for serial production and rapid deployment for floating offshore wind, there is a need to critically review anchor types and layouts to understand possible efficiencies.

1.2 *Shared mooring and anchor systems*

Shared mooring and anchor systems provide an opportunity for the total number of components associated with a floating offshore wind turbine (FOWT) to be reduced. In addition to reducing costs associated with fabrication, transportation and installation of the anchors, this has the potential to significantly decrease the site investigation requirements by reducing the number of positions requiring characterisation.

Shared anchor technology is currently being trialed at the Hywind Tampen site, currently under construction. This site utilises 19 suction anchors for 11 wind turbines (ReNews, 2022), in comparison to the previous Hywind Scotland project that had 3 anchors per turbine. It has been estimated that on a wind turbine site of 100 turbines, shared anchor systems could reduce mooring costs by up to 20% (Ford, 2020).

Given that shared anchors are connected to multiple lines, and the turbines at the end of these lines can be several wavelengths apart, the loads can be phased, leading to a shared anchor experiencing more load cycles, and greater variation in direction that these loads are experienced (Lozon and Hall, 2023). Shared anchors must, therefore, be designed to withstand loading from multiple directions and for an increased number of fatigue load cycles. Some of the lower cost, simpler anchor types (for example drag anchors) suitable for station keeping under single mooring lines will not be suitable for multi-directional loading without modification. The efficiencies that can be gained from anchor sharing will vary depending on anchor type, mooring line type, applied loading, and ground conditions.

1.3 *Focus of current study*

This paper focusses on the influence of ground conditions on the potential reduction in anchor sizes that could be realised between single anchors and shared anchors. A case study site is considered with a water depth of 70 m and single set of metocean conditions representative of a site in the Celtic Sea. A short list of common anchor types is considered, and the suitability of each anchor type for use in a shared anchoring system is discussed.

Preliminary calculations are presented to provide an indication of the potential reduction in size of individual anchors in a shared anchor system compared to a single anchor for the case of a 15 MW turbine, on a semi-submersible platform, with a catenary mooring system for each soil type considered.

This purpose of this study is to review the potential relative reduction in size of a shared anchor compared to a single anchor. An in-depth review of absolute anchor costs and savings is outside the scope of the current study. The reduced number of anchors in a shared anchor configuration across a wind farm is not considered in the savings presented.

2 **Background**

2.1 *Overview of anchor technologies*

Common anchor types that may be suitable for FOWT can broadly be broadly divided into the following categories (based on Diaz et al., 2016) and illustrated in Figure 1:

- piled anchors (installed by free fall, driving, drilling and grouting or suction);
- direct embedment plate anchors (including dynamically loading plate anchors (DEPLA), suction embedded plate anchors (SEPLA), and pile driven plate anchors (PDPAs));
- gravity anchors; and
- drag embedment anchors.

A comprehensive description of these common anchor types is provided in several references including Diaz et al. (2016), Vryhof (2018) and ABS (2013).

There are a range of factors to consider in anchor selection for a given site. These include but are not limited to the soil conditions and seabed morphology, fabrication and installation cost, performance under sustained and cyclic loading, the direction of loading (dictated by mooring type) and the magnitude of loading. In general, this latter factor will be driven by the turbine size, metocean conditions, water depth, substructure type and choice of mooring.

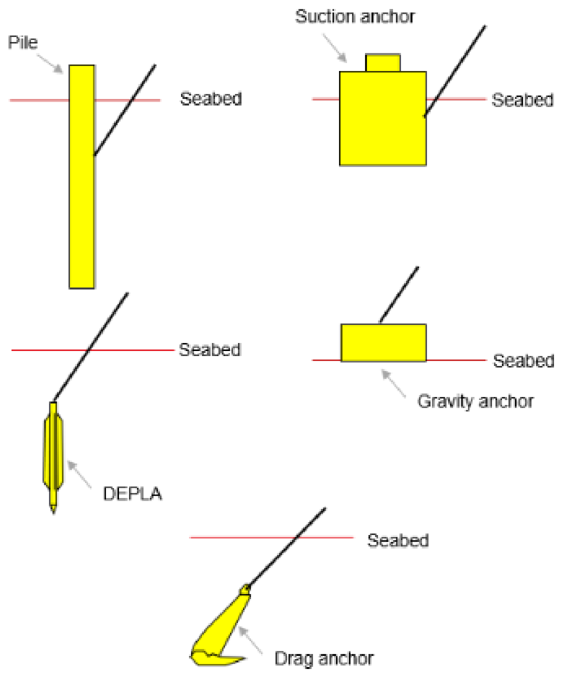


Figure 1. Common anchor types suitable for FOWT (based on information provided in Vryhof, 2018).

2.2 *Key considerations for shared anchor systems*

2.2.1 *General*

The following section presents some of the key considerations for selection of technologies for a shared anchor system, which differ from those for a single anchor. Particular attention is given to (a) the ability of the anchor to resist multi-directional loads; (b) the relative importance of horizontal and vertical resistance mechanisms; (c) the effects of cyclic loading and (d) the potential impact of increased seabed disturbance due to multiple moorings and attachment points (padeyes).

2.2.2 *Resisting multi-directional loading*

Adapting anchor types with a vertical axis of symmetry for a shared anchor system is a relatively straightforward matter of attaching additional padeyes (connections to the mooring lines) around the circumference of the anchor (Diaz et al., 2016). This includes both pile and gravity anchor types.

Plate anchor types with a primary direction of resistance are less readily adapted for shared anchor systems. This may be overcome by attaching a series of mooring lines to an intermediary load ring which then transmits the load to individual anchors (Lee et al., 2016), although the simplicity of the single anchor solution is reduced in this scenario.

The impact of multi-directional loading on anchor performance is not addressed in current design practice. The results of centrifuge modelling on shared anchors under inclined loading in sand presented by Herduin (2019) indicate that multi-directional loading can significantly reduce pile and suction anchor capacity. In this modelling, the dominant failure model for a shared anchor was always vertical, reflecting the larger vertical component of load due to the addition of the taut mooring lines (see Section 2.2.3). The impact of multi-directional loads on a shared anchor under primarily horizontal load from a catenary mooring system is less clear, but it is anticipated this will be lower than for anchors under taut line loading.

2.2.3 *Changes in horizontal and vertical loading*

Shared anchors must be designed to withstand loading from multiple directions. While the resolved horizontal loads acting on a shared anchor may be lower than for an individual anchor due to opposing forces in different mooring lines, there is likely to be an increase in net uplift due to the additive effect of the vertical loads from multiple turbines (Pillai et al., 2022).

The relative importance of the changes in vertical and horizontal loading regime will depend on both the mooring configuration, the anchor selection and the performance of the specific soil conditions under sustained and cyclic loads. For example, the design of anchors supporting a catenary mooring system is likely to be governed by the horizontal anchor capacity, with relatively low applied vertical forces. The benefit from the reduction in net horizontal forces in a shared anchor system is likely to outweigh the negative impact of increased vertical loading, provided the selected anchor type can withstand some degree of vertical loading. Conversely, for steeply inclined taut mooring line arrangements, vertical capacity is likely to be more critical and the net increase in uplift will require careful consideration in ULS (ultimate limit state) design.

2.2.4 *Effects of cyclic loading*

Shared anchors must be designed to withstand an increased number of in-service loading cycles, in multiple directions, compared to individual anchors. Inadequate design of shared anchors to resist cyclic loading may result in loss of station keeping.

The effects of cyclic loading on shared anchor performance are complex. The load rate, magnitude of cycles and direction of cycling (one way versus two way) can all affect the degree of cyclic degradation. Shared anchors can expect to undergo two-way cyclic loading which is expected to result in a less favourable combined result of cyclic degradation and rate effect than anchors attached to a single mooring line (DNV, 2019).

Calculation of the reduction in anchor capacity due to cyclic loading from waves relies on assessment of the accumulation of pore water pressures and strains throughout a storm event, in combination with consideration of partial drainage conditions. Such calculations can make use of the ‘contour diagram concept’, as presented in Andersen (2015) and recommended in DNV-RP-C212 (DNV, 2019) to assess the cyclic degradation of a soil following a design storm.

A detailed review of the performance of anchor types under cyclic loading is not included within the current study. However, with respect to consideration of the influence of ground conditions on shared anchor suitability, it is noted that soil and rock types with a lower susceptibility to cyclic loading (e.g. dense sands) are anticipated to outperform those soil types that will experience significant degradation in strength and stiffness (e.g. soft clays).

2.2.5 *Risk of trenching*

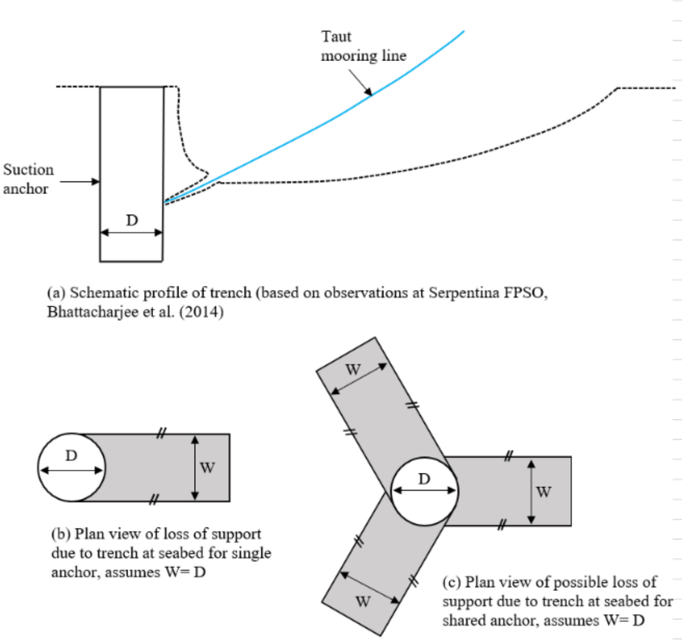
For piled anchors resisting horizontal loads, the optimal positioning of padeyes is typically between 50% and 70% down the length of the pile (ABS, 2013). Application of loading at this depth mobilises the higher resistance of a translational rather than rotational failure mode.

The soil disturbance associated with the protruding padeye and trailing chains can significantly reduce the skin friction above the padeye depth. Further, in certain soil types, scour trenches may occur around anchor lines, compromising both ultimate vertical and lateral capacity. While this concern may be manageable for anchors with a single mooring line attachment, the potential for scour to occur around the entire circumference of the pile or caisson is a more serious issue (Diaz et al., 2016). This is illustrated in Figure 2.

Observations of open trenches in the soft clay around the chains for the suction anchors for the Serpentina Floating Production Storage and offloading system (FPSO) offshore Equatorial Guinea are reported by Bhattacharjee et al. (2014). The formation of these trenches ultimately led to the need to replace the suction anchors and moorings to address the loss of integrity of the mooring system.

Observations on the mechanisms of trench formation, supported by the results of centrifuge testing, are presented by Sassi et al. (2017). Trench formation is thought to be initiated by the continuous cyclic chain movement through the soil in response to varying metocean conditions. As a result, the development of trenching appears to be a more significant issue for taut mooring line systems compared to catenary moorings. Further, the relative likelihood of trenching in different soil types will depend on both the susceptibility to scouring and the ability to support deep open trenches (Diaz et al., 2016).

Positioning padeyes at the top of the anchors would reduce the risk of loss of anchor holding capacity due to trenching. However, this would result in a significant reduction in the efficiency of the anchor design due to mobilization of a non-optimal failure mechanism. Numerical analysis reported by Feng et al. (2019) to investigate this topic concluded that improvement in geotechnical capacity by changing the padeye position to reduce trench depth was negligible because gains in capacity from a reduced trench depth were offset by reduction in capacity due to transition to a rotational mechanism.



(a) Schematic profile of trench (based on observations at Serpentina FPSO, Bhattacharjee et al. (2014)

(b) Plan view of loss of support due to trench at seabed for single anchor, assumes W= D

(c) Plan view of possible loss of support due to trench at seabed for shared anchor, assumes W= D

Figure 2. Loss of soil support due to seabed trenching for both a single and shared anchor arrangement

2.2.6 *Mooring line failure*

The design of shared anchors needs to consider the impact of failure of a single mooring line on the remaining anchor points. Failure of one mooring line may cause one FOWT to move out of position, which changes the load pattern on the remaining anchor points. These anchor points may support other floating wind turbines which are still operating (DNV, 2021a).

This accidental limit state (ALS) condition is not considered further in this study. However, depending on the FOWT system (turbine, sub-structure and moorings), this may become a critical design scenario for the anchors.

3 **Study inputs**

3.1 *Anchor types*

3.1.1 *Overview*

This study focuses on the performance of the following anchor types in a shared anchor system:

- driven piles;
- suction anchors; and
- gravity anchors.

These technologies have been selected as those relatively well understood by the industry and widely adopted for both fixed and floating offshore structure foundations.

All these anchor types can be designed to resist both vertical and horizontal loading, making them suitable for both catenary and taut mooring line configurations. Additionally, they could all be easily adapted to multi-line mooring installations.

Specific considerations of each anchor type in a shared anchor system for a range of soil conditions is provided in the following section.

3.1.2 *Driven anchors piles*

Driven piles can be installed in a wide range of soils and weak rocks, including layered soils.

For this study, driven pile anchors are assumed to be installed in suitable soils with mooring lines attached via padeyes positioned at an optimal depth of approximately 50% of anchor length below seabed, following the guidance in ABS (2013). This makes the anchors potentially susceptible to loss of resistance above pad eye depth due to the formation of trenches in certain soil types, refer to Section 2.2.5.

3.1.3 *Suction anchors*

Suction anchors are traditionally considered most suited for installation in homogeneous deposits of sands and clays. However, as demonstrated by the trial installations at the Seagreen 1 offshore wind farm, suction caisson installation may be feasible in a wide range of ground conditions including high strength clays and layered profiles (Jones and Harding, 2020).

Suction anchors are more susceptible to scour than driven piles due to their lower embedded length to diameter (L/D) ratio. Similarly, suction anchors will be less suitable for sites with any significant seabed gradient than driven piles.

For this study, suction anchors are assumed to be installed in suitable soils with mooring lines attached via padeyes positioned at an optimal depth of approximately 70% of anchor length below seabed (ABS, 2013). Again, this makes the anchors potentially susceptible to loss of resistance above padeye depth due to the formation of trenches in certain soil types.

3.1.4 *Gravity anchors*

Gravity anchors are suitable for installation at sites with low seabed slopes, with shallow bedrock or high strength surface soils with suitable bearing capacity (e.g. dense sands and stiff over-consolidated clays).

The susceptibility of gravity anchors installed on non-cohesive sediments to scour will become significantly more pronounced with the addition of multiple padeyes and mooring line attachments associated with a shared anchor system.

3.2 *Case study site*

The site selected for this study is assumed to have the same water depth and metocean conditions as presented by Pillai et al. (2022) in their assessment of anchor loads for single and shared anchor systems for a shallow water mooring of a 15 MW FOWT on a semi-submersible platform, moored with a large spread catenary arrangement in the Celtic Sea. The key parameters associated with this study are summarised in Table 1.

Table 1. Summary of environmental conditions at case study site (from Pillai et al. (2022)

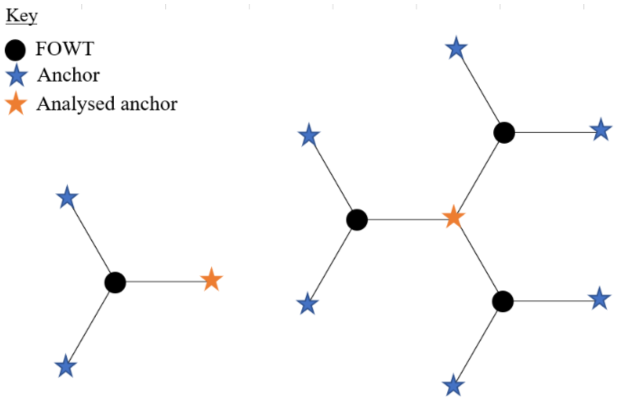
Reference	Value
Water depth (m)	70.0
Wind speed (m/s) *	33.0
Significant wave height, H_s (m)*	14.4
Mean zero-crossing wave period, T_z (s) *	14.1

*Corresponding to the extreme seastate in design load case (DLC) 6.1, as defined in IEC 61400-3-2 (IEC, 2019).

3.3 *Anchor configuration and loading*

This study considers the loading applied to single and shared anchors providing the station keeping for a 15 MW IEA-15-240 RWT turbine (Bredmose et al., 2022) supported on the VolturnUS-S semi-submersible platform (Allen et al., 2020) with large spread chain catenary moorings, as presented by Pillai et al. (2022). The shared anchor configuration considered in the study is as shown in Figure 3.

As described in detail in Pillai et al. (2022), these loads have been derived from an aerodynamic-hydrodynamic coupled dynamic analysis of the turbine, substructure and mooring system. For the purpose of this study, the peak anchor loads calculated for the extreme seastate (DLC 6.1) will be considered, as summarised in Table 2.



(a) Single anchor configuration considered in study

(b) Shared anchor configuration considered in study

Figure 3. Single and shared anchor arrangements considered in study (based on Pillai et al., 2022)

Table 2. Peak vertical and horizontal anchor loads for case study site, corresponding to DLC 6.1 (from Pillai et al., 2022)

Load direction	Single anchor (kN)	Shared anchor (kN)	Shared anchor load/single anchor load (%)
Vertical	121	219	181
Horizontal	4844	1597	33

3.4 *Ground conditions*

Preliminary calculations have been undertaken to assess the potential savings in anchor mass for an individual shared anchor compared to a single anchor for uniform profiles of soft clay, dense sand and weak rock. Typical geotechnical parameters have been adopted for each profile, as summarised in Table 3.

Table 3. Typical geotechnical parameters adopted for the study

Type	γ' (kN/m^3)	s_u (kN/m^2)	c' (kN/m^2)	ϕ' (°)	UCS (MPa)
Soft clay	7	25	-	-	-
Dense sand	11.75	-	-	38	-
Weak rock	12.0	-	25	40	2.0

4 **Methodology**

4.1 *Overview*

Preliminary calculations have been performed for initial sizing of anchors to resist the peak horizonal and vertical loads presented in Table 2 for both single anchor and shared anchor configurations. The aim of these calculations is to demonstrate the relative potential saving in individual anchor mass between a shared anchor and a single anchor for different soil types. The reduction in total number of anchors across the wind farm is not included in the potential savings presented. As the focus is not on the absolute anchor sizes, the study has adopted the loads presented in Table 2 as design loads, with no further partial load factors applied.

Calculations have been performed only for combinations of anchor and soil types assumed at this stage to be technically feasible, refer to Table 4. Analysis has been completed using in-house scripts and the software Oasys ALP as noted in the following section.

Table 4. Combinations of anchor and soil types considered.

Anchor type	Soft clay	Dense Sand	Weak rock
Driven piles	✓	✓	✗
Suction anchors	✓	✓	✗
Gravity anchor	✗	✓	✓

4.2 *Method by anchor type*

Preliminary calculations have been undertaken in accordance with the general principles of DNV-ST-0119 (DNV, 2021a). Material partial factors have been adopted from DNV-ST-0119.

There are multiple anchor geometries (combination of wall thickness, diameter and length) that will satisfy the design requirements. It is not always intuitive which combination will result in the lowest anchor mass (e.g. a larger diameter and shorter pile versus a small diameter and longer pile). To address this, a parametric study has been performed to identify the anchor geometry with the lowest mass by performing multiple calculations that sweep through a range of appropriate diameters and lengths.

4.2.1 *Driven piles*

The lateral response of driven pile anchors has been calculated using the software Oasys ALP. In ALP, the pile is modelled as a series of elastic beam elements, with the soil modelled as a series of non-interactive, non-linear Winkler springs. For this analysis, lateral p-y springs have been calculated using the API methodology (API, 2011) for sands and clays under cyclic loading conditions. It is noted that a limitation of this study is that these p-y curves are not validated for multi-directional loading.

The anchor piles have been designed to the following design criteria: (a) the theoretical design total lateral pile resistance is not exceeded (DNV, 2021b); (b) peak lateral displacements of the anchors are less than 10% of the pile diameter and (c) structural capacity of the pile in bending and shear is not exceeded.

4.2.2 *Suction anchors*

The horizontal capacity of suction anchors has been calculated using the principles outlined in DNV (2021b), DNV (2017) and the simplified capacity methods presented by the Carbon Trust (2019).

A ratio of anchor diameter to wall thickness (D/t) of 100 has been assumed based on previous experience. A limiting slenderness ratio (L/D) of 8 for clay and 1 for sand has been assumed to avoid soil plug instability during installation.

4.2.3 *Gravity anchors*

The gravity anchors are assumed to be constructed from concrete and positioned directly on the seabed. Horizontal resistance is estimated from the available frictional resistance between the underside of the foundation and the seabed, based on the methodologies for gravity bases presented in DNV (2021b).

5 Results

The anchor mass calculated for each design scenario is summarised on Figure 4. Figure 5 focuses on the non-gravity anchor types given the very large difference in mass between these and the gravity anchors. Further detail in the anchor sizing is presented in Table 5.

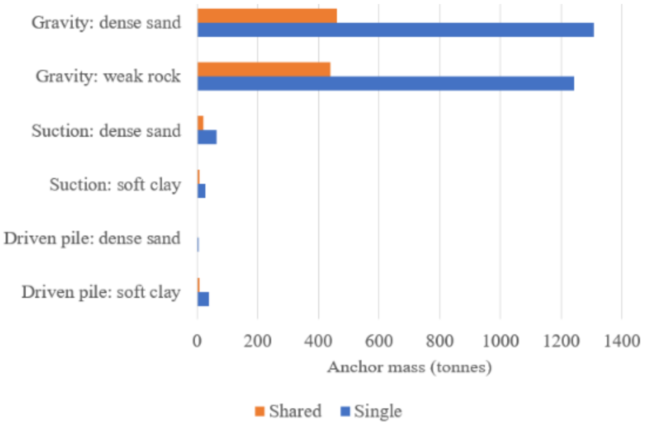


Figure 4. Preliminary assessment of single and shared anchor mass for design scenarios considered in this study (with gravity anchors)

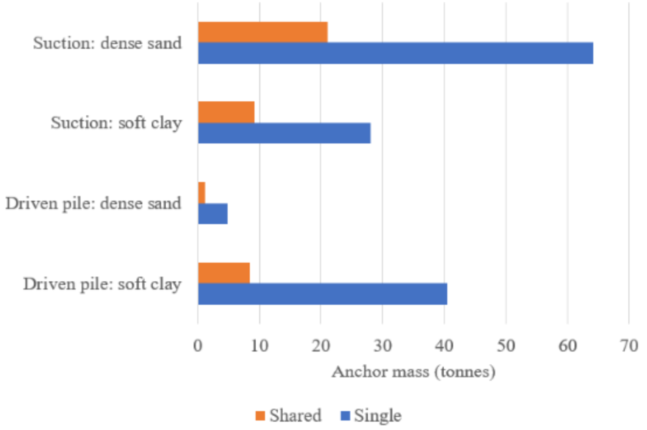


Figure 5. Preliminary assessment of single and shared anchor mass for design scenarios considered in this study (without gravity anchors)

Table 5. Summary of preliminary results

Anchor type	Soil type	Dimensions of shared anchor as percentage of equivalent single anchor (%)		
		Diameter	Embedded length	Mass
Driven pile	Soft clay	50	68	21
	Sand	50	67	24
Suction	Soft clay	67	67	33
	Sand	65	65	33
Gravity	Weak rock	71		35
	Sand	71		35

The following is noted with respect to these results and with reference to the difference in horizontal loads for the single and shared anchors in Table 2:

- for driven anchor piles in both soft clay and sand, the ratio of the mass of the shared anchor to the single anchor is lower than the ratio of the applied horizontal loads;
- the drivers for the optimal anchor geometry (i.e. lowest mass) for the driven anchor piles vary by soil type. For the anchor pile in clay, the single anchor geometry is governed by overall lateral stability whereas the shared anchor geometry is governed by the structural capacity of the pile section. The wall thickness for the single anchor geometry is limited by the imposed minimum thickness for installation but is under utilised with respect to moment capacity under the extreme loads. For the driven anchor pile in sand, the converse applies: the single anchor is relatively optimised with respect to both lateral stability and structural capacity whereas the shared anchor is under utilised with respect to moment;
- for suction anchors in both soft clay and sand, the ratio of the mass of the shared anchor to the single anchor is close to the ratio of the applied horizontal loads. Based on the results of the parametric sweep performed for this study, more slender anchor designs (i.e. highest L/D) provide the lowest mass solutions. This reflects the non-linear relationship between passive resistance and embedded length and the positive contribution of increased overburden to base shear; and
- for gravity anchors on both sand and weak rock, the ratio of the mass of the shared anchor to the single anchor is approximately equal to the ratio of the applied horizontal loads.

6 Discussion

These preliminary results indicate the potential for savings in the mass of individual anchors through adopting shared anchor systems (instead of single anchor systems) for a FOWT with a large spread chain catenary mooring.

It is noted that the current study does not explicitly consider the impact of multi-directional cyclic loading on anchor capacity which is anticipated to reduce the magnitude of the savings presented (see Section 2.2.2), which is a topic of future research.

The smaller resolved horizontal load acting on the shared driven anchor piles facilitates both a reduction in the embedded length required for lateral stability and the steel section size required to resist the applied structural forces. The magnitude of saving in anchor mass is influenced by changes in the governing failure mechanism between the shared and single anchor systems for the lowest mass anchor geometry, which is anticipated to account for the small differences in savings seen between soil types. Once the effects of cyclic loading are considered, it is expected that the savings for the anchor piles in soft clay will be reduced more than other soil types due to the increased susceptibility to degradation under cyclic loads.

The potential savings for suction anchors are slightly lower than for the driven anchor piles, at 12% and 9% less for the clay and sand respectively. The stresses in the walls of the caissons during operation are generally low and hence the anchors derive less benefit from a reduction in section size due to the lower applied loads compared to the driven anchor piles. The current study does not consider the optimal caisson geometry required to satisfy installation conditions, which may alter this conclusion. Again, once the effects of cyclic loading are considered, it is also expected that the savings for the suction anchors in soft clay will be reduced.

As discussed in Section 2.3.2, suction anchors and driven pile anchors with padeye attachments at depth may have reduced capacity due to trenching around the mooring lines. This is an area of ongoing work for the authors. This could be another factor influencing the potential efficiencies of shared anchors piles in soft clay, in combination with the increased susceptibility to degradation under cyclic loads.

Gravity anchors can struggle to compete with alternative anchor types in single anchor systems due to their high mass. However, a significant saving in the mass of an individual anchor can be expected in a shared anchor configuration. The magnitude of the saving is as expected as the base friction providing the horizontal resistance will be roughly proportional to the mass of the anchor.

The current calculations for gravity anchors neglect the effects of cyclic loading, which will be more significant for the two-way loading of a shared anchor system than for the one-way loading of a single anchor. In soil types susceptible to cyclic loading, this will reduce the relative savings.

A further consideration for shared gravity anchors is the loss of support due to scour and seabed disturbance around multiple catenary moorings, which may also contribute to a reduction in savings.

It is noted that the anchor loads utilised in this example are specific to the selected mooring design. Minor mooring design changes could increase the loads e.g. a reduction in mooring footprint.

Additionally, future work should consider ALS conditions with one failed mooring line. This will further influence anchor holding capacity, particularly in shared anchor scenarios.

7 **Conclusions**

Shared mooring and anchor systems offer an opportunity for significant efficiencies in the design of a floating offshore wind farm due to both a reduction in the total number of components and the size of individual anchors. Shared anchor solutions are already being installed in commercial floating wind farms.

This paper presents a study of the possible shared anchor types suitable for installation in soft clays, sands and shallow bedrock with a catenary mooring system. Preliminary sizing calculations have been performed for the different anchor types under representative extreme loads for single and shared anchors supporting a 15 MW turbine on a semi-submersible platform, with a large spread chain catenary mooring, in a site with 70 m water depth.

Based on this preliminary assessment, potential savings in the mass of individual anchors in a shared anchor system are indicated for all soil and anchor types considered. It is anticipated that once the effects of multi-directional cyclic loading and seabed trenching are considered, the relative savings will be reduced for susceptible soil types.

This study has considered the reduction in mass of an individual anchors in a shared system compared to a single anchor system. However, multiplied up to a wind farm scale the potential benefits are clear. Further work will consider the influence of both trenching and multi-directional cyclic loading on shared anchors.

8 **References**

Allen C, Viselli A, Dagher H, Goupee A, Gaertner E, Abbas N, Hall M, Barter G. (2020). Definition of the UMaine VolturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine. Technical Report, NREL and IEA Wind.

American Petroleum Institute. (2011). Recommended Practice 2GEO Geotechnical and foundation design considerations.

American Bureau of Shipping (ABS). (2013). Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines. Technical Report.

Andersen KH. (2015). Cyclic soil parameters for offshore foundation design. Proceedings of the International Symposium on Frontiers in Offshore Geotechnics ISFOG15, Oslo, Taylor & Francis Group, London, 5-82.

Bhattacharjee S, Majhi S, Smith D and Garrity R. (2014) Serpentina FPSO mooring integrity issues and system replacement: unique fast track approach. Paper 25449, OTC, Houston.

Bredmose H, Rinker J, Skrzypinski W, Zahle F, Meng F, Dykes K, Gaertner E, Barter G, Bertolotti P, Sethuraman L and Shields M. (2020). Definition of the 15MW Reference Wind Turbine, Technical Report, Corewind (EU H2020).

Diaz BD, Rasulo M, Aubeny CP, Fontana CM, Arwade SR, DeGroot DJ and Landon M. (2016). Multiline Anchors for Floating Offshore Wind Towers. OCEANS 2016 MTS/IEEE Monterey, Monterey, CA, USA, 2016, pp. 1-9.

DNV. (2021a). Floating wind turbine structures. Standard DNV-ST-0119.

DNV. (2021b). Support structures for wind turbines. Standard DNV-ST-126.

DNV. (2019). Offshore soil mechanics and geotechnical engineering. Recommended Practice DNV-RP-C212.

DNV. (2017). Geotechnical design and installation of suction anchors in clay. Recommended Practice DNV-RP-E303.

Feng X, Gourvenec S and White DJ. (2019). Load capacity of caisson anchors exposed to seabed trenching. Ocean Engineering 171 (2019) 181-192.

Ford (2020). Shared anchors slice cost of floating wind parts, vessels. Reuters Events, Renewables, Online 21/10/2020.

Herduin M. (2019). Multi-directional loading on shared anchors for offshore renewable energy: definition and preliminary investigation into soil behaviour and anchor performance. PhD Thesis, University of Western Australia.

IEC (2019). IEC 61400-3-2: Wind energy generation systems part 3-2: design requirements for floating offshore wind turbines.

Jones L and Harding A. (2020). Experience from full-scale caisson trial installations at the Seagreen Offshore Wind Farm. Proceedings of the International Symposium on Frontiers in Offshore Geotechnics ISFOG20, Austin, Texas.

Lee J, Hong J, Aubeny CP, Arwade S, Degroot D, Martinez A, Beemer R, Balakrishnan K and Nam Y. (2021). Installability of a Multiline Ring Anchor System in a Seabed under Severe Environmental Conditions. OCEANS 2021: San Diego – Porto, San Diego, CA, USA, 2021, pp. 1-9

Lozon E and Hall M. (2023). Coupled loads analysis of a novel shared-mooring floating wind farm, Applied Energy, vol. 332.

Pillai AC, Gordelier TJ, Thies PR, Dormenval C, Wray B, Parkinson R and Johanning L. (2022) Anchor loads for shallow water moorings of a 15MW floating wind turbine – Part 1: Chain catenary moorings for single and shared anchor scenarios. Ocean Engineering 266 (2022) 111816.

ReNews (2022). Suction anchors installed at Hywind Tampen. Online 20/05/2022.

Sassi K, Kuo MY-H, Versteele H, Cathie DN, Zehzouh S. (2017). Insights into the mechnisms of anchor chain trench formation. Proceedings of the 8th Offshore Site Investigations and Geotechnics Conference, Society for Underwater Technology, London, UK.

The Carbon Trust (2019). Offshore Wind Accelerator - Suction Installed Caisson Foundations for Offshore Wind: Design Guidelines.

UK Government (2022). Policy Paper: British energy security strategy. Updated 07/04/2022.

Vryhof. (2018). Vryhof Manual: The Guide to Anchoring.