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The performance of shared suction caisson anchors in sand for FOWT with taut mooring

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ABSTRACT: Floating offshore wind (FOW) arrays installed with shared anchors have been proposed as a cost reduction strategy for energy production. However, the ability of shared anchors to maintain station keeping under multidirectional cyclic loading remains uncertain, leading to over-conservative design. This study investigates the performance of a shared suction caisson anchor for a FOW array subjected to multidirectional cyclic loading. Mooring loads were derived from aero–hydrodynamic modelling of the IEA 15MW turbine and VolturnUS-S reference platform in an extreme sea state, with taut mooring in different water depths. A fully-coupled nonlinear dynamic finite element (FE) analysis of the anchor was carried out using the advanced Sanisand-MS constitutive model, and the performance of the shared anchor was explored. The results show that shared suction caisson anchors, when installed within a sand deposit and subjected to taut mooring loads, can maintain performance during peak 50-year return period environmental loading events. The shared anchor appears to provide a sufficient vertical tensile capacity under drained conditions. While progressive upward ratcheting behaviour of the caisson, sufficient to deteriorate anchor performance, is considered unlikely over the service lifetime of the anchor, further investigation is required. Mooring design to reduce the load inclination angle on the anchor could help alleviate this potential risk.

Keywords: Floating offshore wind; shared anchor; finite element; cyclic loading; sand.

1 INTRODUCTION

Floating offshore wind (FOW) turbines (FOWTs) enable wind farms to be developed in deeper waters, where the potential for wind energy generation is greater. However, gigawatt (GW)-scale projects required for full industrialisation of the technology remains challenging due to performance uncertainty and the levelised cost of energy (LCOE), which is still much higher than that of traditional fixed-bottom foundations.

To reduce the LCOE of FOW, shared anchors, first adopted in the pre-commercial FOW array Hywind Tampen, provide a promising cost-reduction solution. However, their ability to maintain station-keeping under multidirectional cyclic loading remains uncertain, leading to over-conservative design. Until recently, there has been little requirement to investigate multidirectional loading of axisymmetric anchors, such as suction anchors or piles, for floating structures. Research carried out to date has included geotechnical centrifuge modelling in clay (Chung, 2012) and in sand (Herduin, 2019)

The aero-hydrodynamic behaviour of FOWTs utilising shared anchors has been previously investigated to demonstrate feasibility (e.g. Pillai et al., 2022). However, to date, no investigations have incorporated the cyclic mooring loads generated through these aero-hydrodynamic analyses of the FOWT into an advanced fully-coupled dynamic analysis of the anchor.

Some studies have suggested that the cost benefit of anchor sharing may be enhanced in deeper waters, as turbine spacing requirements and economics may favour a centrally shared anchor point (Catapult, 2024). Beyond depths of around 200m, the weight and cost of the mooring chain in a catenary configuration is higher, and synthetic taut mooring lines are being considered as an alternative. The novelty of this study is to assess the geotechnical performance of a shared anchor with taut mooring in different water depths. The investigation uses a coupled aero-hydrodynamic analysis of FOWTs to generate mooring loads, which are implemented in a fully-coupled nonlinear dynamic FE analysis of the shared anchor. To this end, mooring loads were obtained through the coupled aero-hydrodynamic modelling of the IEA 15MW turbine and VolturnUS-S reference platform subjected to a single extreme sea state with colinear environmental loading. Polyester taut moorings were adopted with water depths of 300m, 500m and 1000m. The performance of the shared anchor was subsequently evaluated through a fully-coupled dynamic FE analysis using the advanced Sanisand-MS constitutive model implemented in the OpenSees platform.

2 FOWT CASE STUDY

2.1 FOWT definition

Coupled aero-hydrodynamic simulations of a FOWT were conducted using OrcaFlex (Orcina, 2022). The chosen floater was the UMaine VolturnUS-S Reference Platform (Allen et al., 2020), a semisubmersible platform designed to support the IEA Wind 15-Megawatt Offshore Reference Wind Turbine (Gaertner et al., 2020), as shown in Figure 1.

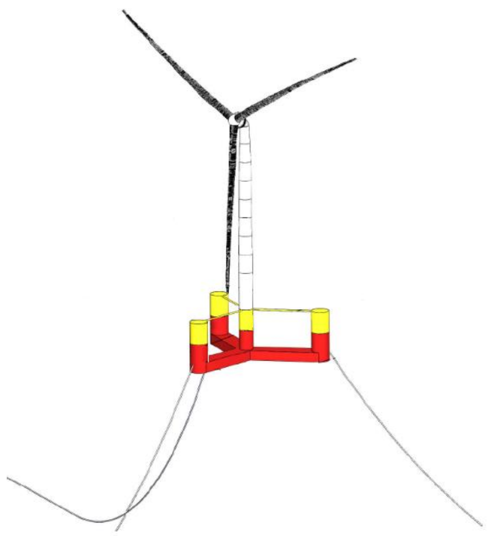

Figure 1. UMaine VolturnUS-S FOWT (Allen et al., 2020)

Details of the taut mooring for water depths 300m, 500m and 1000m are provided in Table 1. Each mooring line was designed to ensure that the peak tension in a 50-year storm does not exceed 40% of the breaking load.

Table 1. Taut mooring properties

Section	Material	Thickness (mm)	Length (m)
1	Studless chain	90	30 (fairlead length)
2	Polyester	210	1090 (300m depth) 1157 (500m depth) 1907 (1000m depth)
3	Studless chain	90	40 (anchor length)

2.2 Array configuration

Three FOWTs are positioned as shown in Figure 2.

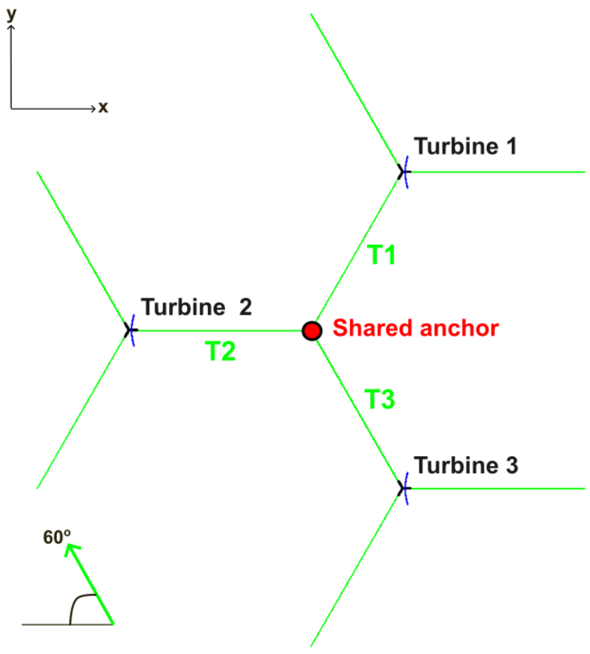

Figure 2. Wind turbine layout: T1, T2 and T3 are the mooring lines connected to the associated turbine.

For all water depths, the wind turbines are positioned 9 times the rotor diameter apart (2.1km), except for the 1000m water depth case, where the FOWTs are positioned 3.1km apart. This is to allow for a more optimal design by reducing mooring line inclination.

2.3 Environmental load cases

The IEC 61400-1 (IEC, 2019) Design Load Case (DLC) 6.1, as shown in Table 2, was applied for each water depth. In DLC 6.1, the turbine rotor is in a parked position, and the global extreme environmental action comprises a combination of site-specific extreme wind and waves with a 50-year return period. A colinear heading of 60° was chosen, as shown in Figure 2.

Table 2. Design load case

DLC	Heading (°)	Hs (m)	Tp(s)	Current (m/s)	Wind speed (m/s)
6.1	60	14.7	15	0.45	33

Figure 3 shows the taut mooring line tension for Turbine 1 (T1), Turbine 2 (T2) and Turbine 3 (T3) under DLC 6.1 with 60° heading, for water depths of 300m, 500m, and 1000m. In this heading, both T1 and T2 are under tension, providing multidirectional cyclic loading to the shared anchor. Under tension, increasing water depth increases the inclination of the mooring line measured from the seabed (angle provided in figure legend). The extracted mooring loads used in the FE analysis of the shared anchor were selected from the time period between 1450 and 2050s, as also indicated in Figure 3.

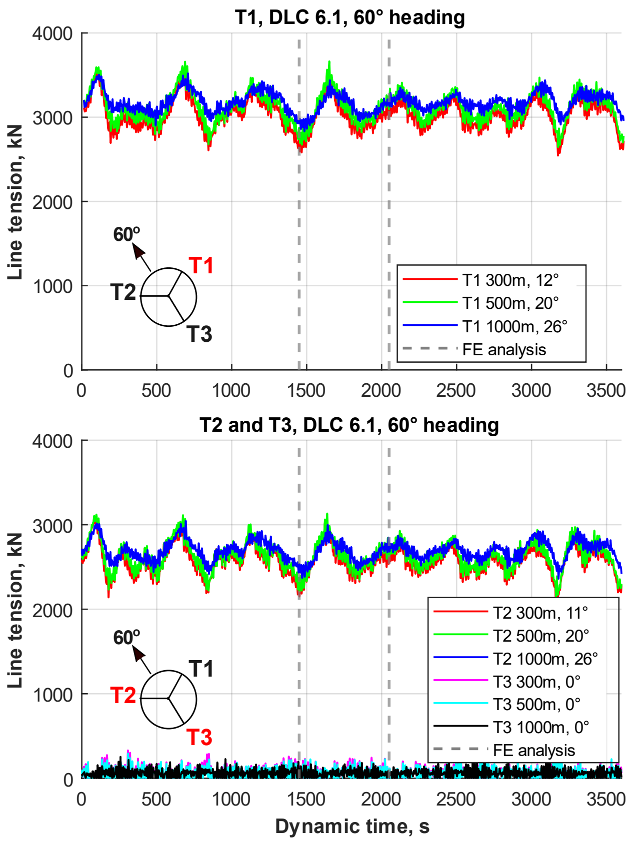

Figure 3. Line tension for taut mooring cases, DLC 6.1 60° heading

3 FE MODELLING OF SHARED ANCHOR

3.1 FE model

The numerical modelling was conducted using the OpenSees simulation platform (McKenna, 1997). The model comprises a suction caisson anchor with a diameter =10m and length=10m, as shown in Figure 4. The model dimensions of 80m (x), 80m (y) and 30m (z), were sufficiently large to avoid boundary effects. The base of the model was fully fixed, while the lateral boundaries were allowed to move in the z-direction.

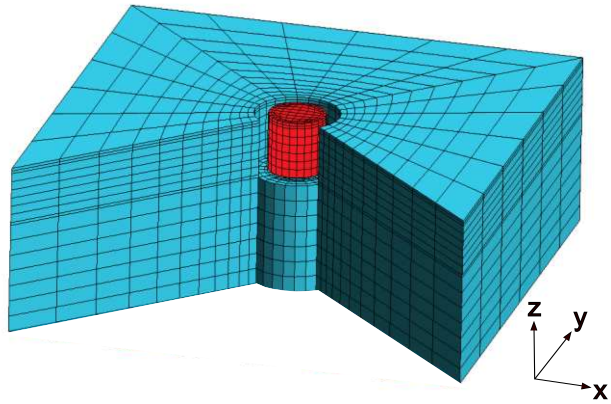

Figure 4. Sliced FE model showing anchor (centre - red) and extent of the soil domain. The model is 80m × 80m × 30m.

The anchor was modelled using eight-node stabilized single-point (SSP) brick elements with a thickness of 0.5m. The anchor was assigned elastic properties of $E = 210$ GPa, $\nu = 0.3$, and a reduced steel density of 2.509 Mg/m^3, to account for the modelled anchor thickness.

The soil was modelled using fully-coupled SSPbrickUP elements, which employ a mixed displacement-pressure (u-p) formulation. To model the soil-structure interaction, a 0.5m thick interface layer of SSPbrickUP elements was placed around the caisson, with a reduced dimensionless shear modulus, $G_0 = 0.72$, and critical stress ratio, $M_c = 0.83$. ZeroLengthContact3D node-to-node frictional contact elements were also inserted to model the interaction between the SSPBrick elements of the anchor and the SSPBrickUP elements of the soil-interface. The soil domain was modelled as a homogeneous sand layer with an initial void ratio of 0.72 and a saturated unit weight of 1.932 Mg/m^3.

To simulate the padeye connections on the shared anchor, mooring line tensions were assigned to three nodes located at 120° intervals around the caisson diameter, at a depth of 5.5m below the lid.

3.2 Constitutive model

The Sanisand-MS model (Liu et al, 2019) was selected to simulate the constitutive behaviour of the soil. This model can capture the ratcheting effects that occur in sands during high-cyclic loading, particularly in the presence of a static stress field or in the case of asymmetric loading. The model is a bounding surface plasticity model with a yield, memory and bounding surfaces that updates the original SANISAND04 (Dafalias and Manzari, 2004) framework by introducing a hardening memory surface concept. The model parameters calibrated by Liu et al., (2019) for quartz sand were adopted for this analysis, as shown in Table 3. The permeability of the soil was initially set to 1.0×10^{-4}m/s.

Table 3. Sanisand-MS parameters from Liu et al. 2019

Elasticity		Critical state				
G_0	ν	M	c	λ_c	e_0	ξ
110	0.05	1.27	0.712	0.049	0.845	0.27

Plastic modulus			Dilatancy		Memory surface		
h_0	c_h	n^b	A_0	n^d	μ_0	ζ	β
5.95	1.01	2.0	1.06	1.17	260	0.0005	1

3.3 Validation

Vertical tensile pull-out tests were conducted in the FE model to validate the caisson's capacity and refine interface parameters. These tests were conducted at a slow rate to avoid the generation of significant negative excess pore pressures underneath the caisson lid or skirt tip. A drained capacity of around 6.5MN was determined which compared well with hand calculations (Houlsby et al., 2005). To check the practical relevance of the drained capacity of the caisson for design purposes, the maximum contribution to pull-out force (in the positive *z* direction) from the three mooring lines T1, T2 and T3 was identified. For the loading with the highest vertical component (2.8MN at 1000m depth), the capacity was sufficient to meet the ultimate limit state (ULS) of combined vertical actions, with a global design safety factor of 2 for axially loaded suction piles, as given in ISO 19901-7 (ISO, 2017).

4 RESULTS

4.1 Caisson displacement

The displacement of the shared anchor was measured by tracking a node located at the centre of the caisson lid. The displacement in the *x*, *y* and *z*- directions at 300m, 500m and 1000m water depths under DLC 6.1 with 60º heading are shown in Figure 5. The results show that, when T1 and T2 are loaded, the greatest displacement occurs when the highest loading is applied in the time series, at about 1650s (full timeseries) or 200s (extracted for FE analysis). At a water depth of 1000m, the anchor experienced the most uplift with a vertical pull-out of around 0.006m recorded over the 600s period. The pull-out, for the 500m and 300m water depths reduced to ~0.004m then ~0.002m, respectively. This suggests that, under similar cyclic loading regimes, which is the case for the 300m, 500m and 1000m water depths (see Figure 3), the increasing mooring line angle with water depths, that increases the vertical component of the tensile mooring loads, resulted in a greater caisson pull-out, as shown for the 1000m water depth.

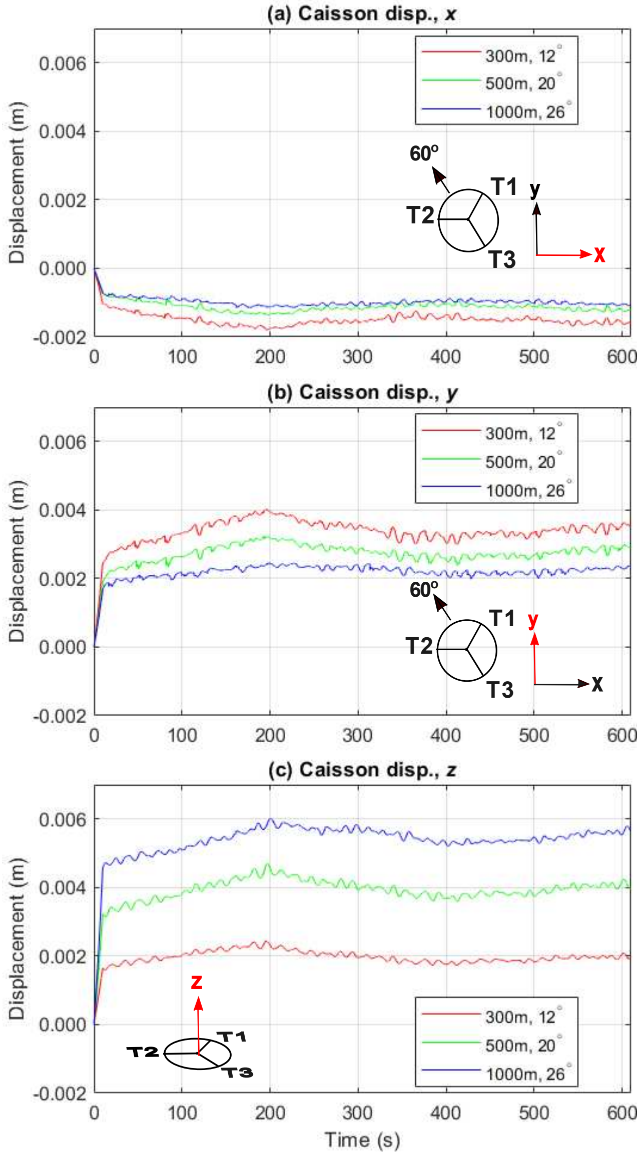

Figure 5. Caisson displacement, DLC 6.1 60º heading

Minor lateral displacement occurs in the negative *x*-direction and positive *y*-direction due to the horizontal load components of both T1 and T2. The most lateral displacement is generated at 300m water depth, where the load inclination angle is lower. Such magnitudes of displacement are well within permissible serviceability limits and would not affect the short-term ability of the caisson to maintain station-keeping during a peak environmental loading event. However, it is feasible that the performance of the caisson under longer-term multidirectional cyclic loading could deteriorate if upwards displacement of the shared anchor accumulates permanently following repeated storm cycles. This upwards ratcheting of the caisson could lead to a loss of capacity, a risk which might be further exacerbated by local and global scouring of the foundation or trenching around mooring lines.

4.2 Caisson capacity

To determine the threshold at which the loading on the shared anchor in the DLC 6.1 60º heading case would generate a pull-out (in the *z*-direction) sufficient to exceed serviceability criteria, the simulation at 1000m water depth was repeated with scaled mooring loads. These results are shown in Figure 6a, where "1.0, 2.0, 2.3, 2.4" are the factors applied to the mooring loads and "1.0×10^{-4} m/s" is the modelled permeability.

The results show that over the 600s monitoring period, pull-out (vertical displacement) increased with the scaling of the mooring loads. It was observed pull-out failure commenced when the mooring line loads were scaled by a factor greater than 2.4. This would correspond to a total applied vertical tensile load (*z*-component) of 6.72MN, which slightly exceeds the drained vertical tensile capacity of the caisson (~6.5MN).

4.3 Pore pressure evolution

Pore pressures measured underneath the caisson lid, skirt toe and in front of the skirt between the T1 and T2 padeyes are shown in Figure 6b, c and d for the 1000m water depth while increasing mooring line loads. These results show that, with an assigned permeability of 1.0×10^{-4}m/s, no significant excess pore pressures were generated within or adjacent to the caisson, suggesting predominantly drained conditions under this permeability and loading. The sustained cyclic loading regimes generated by the taut moorings, with high mean load and small amplitude, do not provide sufficient amplitude or frequency to have a significant effect on excess pore pressure accumulation. This is consistent with the assumption that for a generally clean sand, the behaviour is likely to be drained.

To determine if excess pore pressures around the caisson could be developed, an additional simulation was conducted with the permeability reduced to 1.0×10^{-6}m/s, which is more typical of a finer or silty sand, and the applied loads increased by 2. Transient large reductions under the caisson skirt toe (Figure 6c) and increases in pore pressure on the caisson skirt between the T2 and T1 padeye (Figure 6d) were observed as loading commenced. These pressures stabilised as the analysis continued, suggesting initially undrained then transition toward more partially drained conditions.

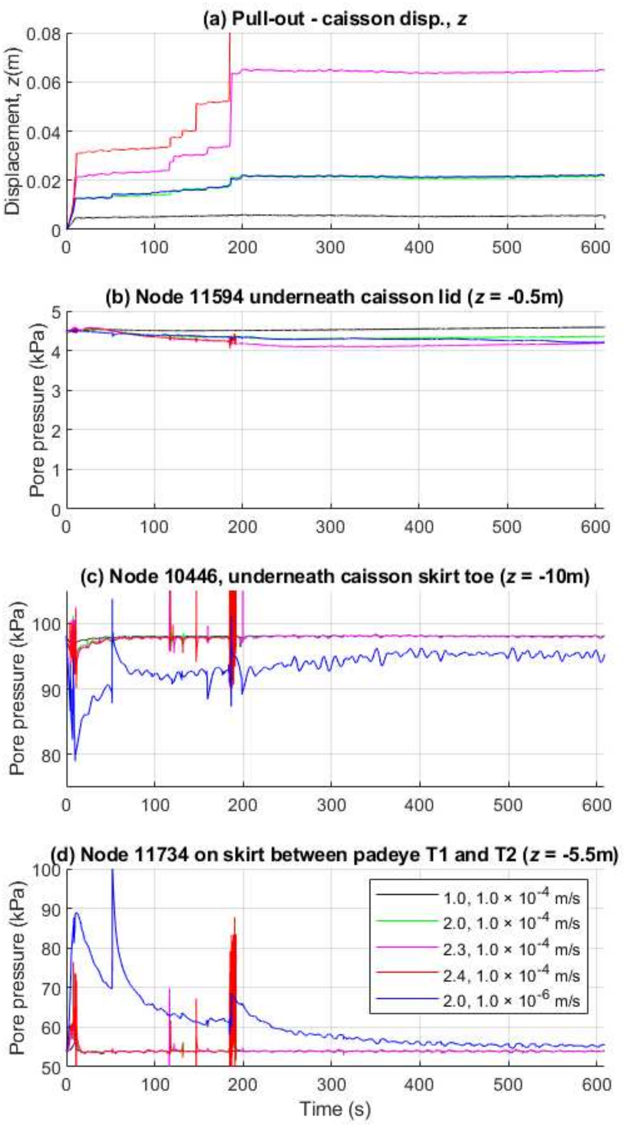

Figure 6. Taut mooring 1000m, DLC 6.1 60º with increasing mooring loads: (a) caisson displacement and (b, c and d) pore pressures

5 CONCLUSIONS

This paper investigated the performance of a shared suction caisson anchor installed in sand for FOWTs with taut mooring in water depths of 300m, 500m and 1000m. The investigation employed a fully-coupled dynamic FE analysis of the anchor, using mooring loads obtained from a coupled aero-hydrodynamic simulation of the FOWTs. An extreme sea state (DLC 6.1) and 60° heading was considered for the environmental loading, resulting in sustained high cyclic loading on two (T1 and T2) of the three mooring lines attached to the shared anchor.

The capacity of the shared anchor was shown to be sufficient to withstand 50-year storm loading, with only minor displacements observed, which are not considered to affect short-term performance. Anchor uplift was greatest in the 1000m water depth, corresponding to the highest mooring line load inclination angle.

Taut mooring loads for the 1000m water depth case were increased until anchor pull-out, and were identified to be close to the drained vertical tensile capacity. Pore pressure generation, measured around the caisson structure, also indicated a predominantly drained soil response under the applied loads. The findings suggest that suction caissons installed in sand may be suitable shared anchors for FOW arrays with taut mooring using polyester (or other synthetic) lines, providing their design include a sufficient drained capacity. While the potential for upward ratcheting of the shared anchor exists, it is likely that performance of the anchor would not deteriorate significantly over its service lifetime.

Further analysis should focus on determining upward ratcheting behaviour under repeated storm cycles with varying intensity, applying additional environmental loading conditions and orientations, and considering potential scour effects. Vertical tensile pull-out, under drained conditions, appears to be the critical failure mechanism that should govern design of shared anchors installed in sand with taut moorings.

AUTHOR CONTRIBUTION STATEMENT

First Author: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualisation, Writing- Original draft. **Second Author**: Conceptualization, Methodology, Software, Visualisation, Writing- Original draft **Additional Authors**: Funding acquisition, Methodology, Supervision, Writing – review and editing. **Last Author**: Funding acquisition, Writing – review and editing.

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