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Pile anchors of floating offshore wind farms subjected to lateral cyclic loadings in different directions

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ABSTRACT: This paper presents a numerical study to investigate the behaviour of pile anchors used to support Floating Offshore Wind Turbines (FOWTs). In conventional FOWT farms, each anchor is attached to a single FOWT and thus the anchor is said unshared with the other neighbouring FOWTs and it is subjected to a single unidirectional irregular loading. In order to reduce the high costs of FOWT farms, the behaviour of a shared anchor was recently investigated in literature. Anchor sharing consists of designing a foundation to anchor multiple neighbouring FOWTs organised in an array, rather than designing a set of anchors for each FOWT. Anchor sharing will notably cause irregular cyclic loading on the anchor in different directions. This case corresponds to a global multidirectional irregular loading. This paper presents a numerical study using Abaqus finite element implicit solver to investigate the effect of the global load multi-directionality on the behaviour of pile anchors in sandy soil. Two extreme loading cases among a total of 32 load cases corresponding to a given wind farm layout and a prescribed sea-state were considered in the analysis. Also, two configurations of shared and unshared anchors were investigated for comparison purposes. In the first case, the anchor was subjected to a global irregular lateral load with high amplitude and small directional variation. However, in the second loading case, the anchor was subjected to an irregular global lateral load with a moderate amplitude and a high directional variation. The numerical results have shown that the anchor design is mainly governed by the loading case associated with a high amplitude and small directional variation. The classical unshared anchor design is thus not affected by a possible anchor sharing between multiple FOWTs.

Keywords: Shared pile anchors; Cyclic irregular multidirectional load; Sand; Advanced soil constitutive models; Abaqus.

1. INTRODUCTION

The majority of Offshore Wind Turbines (OWTs) are mounted on bottom-fixed substructures. This type of OWTs is constructed close to the coast in shallow to medium water depths. To increase the benefits of wind resources, wind turbines should be constructed far from the coast in locations with deep water depths where the wind speed is higher and the wind is steadier. However, for these locations, the fixed-bottom offshore wind turbines are not economic or not feasible. In this context, Floating Offshore Wind Turbines (FOWTs) can provide a feasible alternative to the traditional bottom-fixed OWTs.

Floating Offshore Wind Turbines (FOWTs) are supported through mooring lines attached to anchors fixed in the seabed. In conventional usage, unshared anchor system where a single anchor is attached to a single FOWT is used. However; in renewable energy farms involving arrays of floating units, significant cost reduction may be achieved through the use of shared anchors in which each anchor is attached to multiple FOWTs. While significant cost savings might be expected from a reduction of the number of foundations, this results in more complex loading conditions on the anchor, notably causing cyclic irregular loadings in different directions. The

resultant multidirectional cyclic loading case is not fully understood in offshore geotechnics as the majority of researchers focused on piles subjected to unidirectional cyclic loading (Leblanc *et al*. 2009, Abadie *et al*. 2018, Liu *et al*. 2021, among others). To that purpose, this paper presents a numerical study based on the finite element (FE) software Abaqus/standard to investigate the behavior of pile anchors subjected to multidirectional irregular cyclic loading. The work presented here is part of the MUTANC (2024) project by France Energies Marines, which aims to assess the potential of shared anchors based on hydrodynamic, geotechnical and economic analyses.

The pile anchor was embedded in Fontainebleau sand with a submerged unit weight of 10.9kN/m^3 and a relative density of 80%. The Hypoplastic soil constitutive model, originally developed by Wolffersdorff (1996) and later extended to small-strain range by Niemunis and Herle (1997) through the intergranular strain (IS) concept, was used to simulate the sand behavior. This model was shown in literature to be able to accurately capture the accumulated deformation of soil-anchor system due to cyclic loads (cf. Sheil and McCabe, 2016). In this study, the shared anchor is supposed to support three FOWTs through three catenary mooring lines (L_1, L_2 and L_3) separated by a horizontal angle of 120° as shown in Figure 1. The loads time-series through the mooring lines have no vertical components as the catenary mooring has a part of the mooring lines lying down on the seabed.

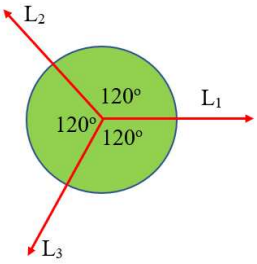

Figure 1. Top view of the shared pile anchor

In the following sections, the numerical FE model is first illustrated. This is followed by a presentation of the loading cases considered in the analysis and ends up with a conclusion of the main findings.

2. THREE-DIMENSIONAL FINITE ELEMENT MODEL

This section aims to present the three-dimensional (3D) FE model used to simulate the behavior of the soil-anchor system under different loading cases. This model is based on the implicit finite element solver "Abaqus/standard". The model consists of three main parts: (i) hollow steel cylindrical anchor, (ii) soil around the anchor and (iii) soil inside the anchor. The anchor is located at the center of a cylindrical soil domain and it was protruded 0.5D_p above the ground surface where D_p is the pile diameter. A pile anchor with an embedded length L_p=20m, a diameter D_p=2.5m and a thickness t_p=0.1m was considered in this study. The associated loading at the head of the pile for an equivalent displacement of 0.1*D is about 12MN (Hr). The thickness of the pile has been chosen in a conservative way and no plastic deformation is allowed in the scope of this study.

Concerning the 3D soil domain, a cylindrical domain with diameter D_s=20D_p and length L_s=1.7L_p was adopted in this study (cf. Figure 2). It was found that these dimensions are sufficient to eliminate the effect of model boundary conditions on the behavior of the soil-anchor system (cf. Alkhoury *et al*., 2022). The outer vertical boundaries of the soil domain were restrained in the lateral directions and allowed to move vertically. However, the soil domain was prevented from moving at its base in both horizontal and vertical directions. An optimal mesh consisting of 15,864 elements and 18,034 nodes was adopted in the analysis (cf. Figure 2). The linear hexahedral solid brick elements C3D8R with reduced integration scheme were adopted for the anchor as well as for the soil elements (e.g. Cheng *et al*., 2023). Concerning the soil-anchor interaction, it was modelled using small sliding, surface-to-surface master/slave contact pair formulation. The anchor, being much stiffer than the soil, was selected as the master surface; while the soil (around and inside the pile) in contact with the anchor was selected as the slave surface.

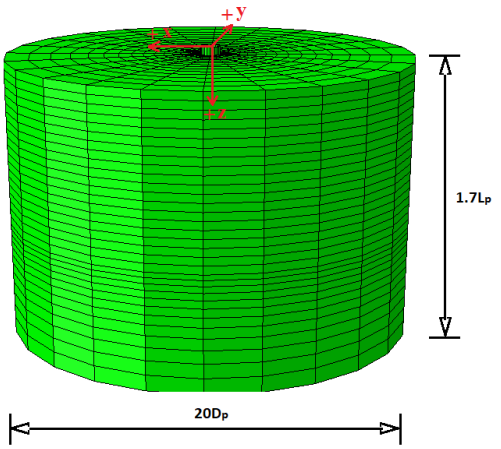

Figure 2. Soil domain and mesh adopted in the analysis.

The steel anchor of unit weight γ_p=78kN/m^3 was considered to follow a linear elastic constitutive model with modulus of elasticity E_p=210GPa and Poisson ratio υ_p=0.2. However, a sophisticated

constitutive model was necessary to simulate the soil behavior. The rate-independent Hypoplastic constitutive model with intergranular strain (IS) concept was used herein to simulate the soil behavior. Due to the high permeability of the sand and low frequency of the external loading, the excess pore pressure in the sand cannot be developed. Therefore, a fully drained condition was assumed in this paper to simulate the sand behavior under long-term time-varying environmental loadings.

The different steps of the finite element simulations may be divided into 3 steps: (i) geostatic stresses are calculated by applying the gravity loading with the soil earth pressure coefficient at rest K_0=0.476 in order to generate the effective stresses developed in the soil due to the soil weight, (ii) the anchor was installed in the soil mass *via* the *wished-in-place* procedure. The aim of this step is to generate the additional effective stresses developed in the soil due to the anchor weight and (iii) the anchor was loaded using the force-control method. The aim of this step is to calculate the deformation of the soil-anchor system due to the applied loads.

3. LOADING CASES

Within the MUTANC project, the wind turbine considered in the wind farm is the IEA-15MW (NREL 2020). It was combined with the VolturnUS-S semi-submersible floater suggested by Christopher et al. (2020). This paper focuses on a water depth of 80m and considers three catenary chain mooring lines for each FOWT. In this case, the loads transmitted to the anchors do not include vertical components.

A regular layout of the wind farm with a turbine spacing equal to $7D_{\text{Rotor}}$ = 1680 m and a 120° spreading angle between the mooring lines was considered in this project (see Figure 3).

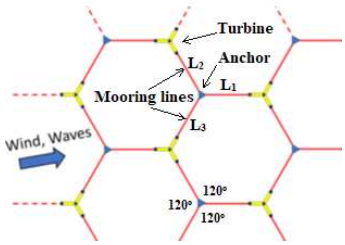

Figure 3. Layout of the wind farm.

Shared and unshared anchor configurations are studied in this paper for comparison purposes. A shared anchor configuration implies that the anchor is connected to three mooring lines L_1, L_2 and L_3 (as shown in Figure 1) and therefore to three different FOWTs. However, in the case of an unshared anchor, the anchor is supposed to be connected to only a single mooring line (L_1 or L_2 or L_3) and thus to a single FOWT. The farm layout and anchor disposition are kept the same when studying the shared and unshared anchors in this paper.

In order to calculate the loads that may be applied to the different pile anchors of a floating offshore wind farm, a comprehensive numerical study was performed using a hydro-aero-servo-elastic model developed within the SIMA workbench. To reduce the calculation time, only one FOWT together with its three mooring lines fixed at mudline were modelled within MUTANC project. The effect of not modeling multiple FOWTs is considered negligible, as supported by previous studies (C. Fontana, 2018).Three hours (3h) numerical simulations were carried out following the DNV guidelines [DNV 2021 and DNV-GL 2016]. An Ultimate Limit State approach considering extreme Met-Ocean events with a return period of about 50 years was adopted in the analysis. The established model was carefully benchmarked with the data provided by Christopher *et al*. (2020) and produces expected performances (see Lovera *et al*. 2025).

Shared and unshared loadings were obtained by combining different stochastic realizations of the same environmental conditions on a FOWT, ensuring that no repetition was performed with each realization to obtain uncorrelated loadings. The combination method to obtain the design anchor load is presented in more details in Lovera *et al*. (2025). This load resulted from the combination of six stochastic realizations of a sea state as applied to one single FOWT. To avoid coherence effects, the combinations are done with six different realizations at each mooring line thus leading to 120 possible time-series. The selected time-series is the one for which the peak load is the closest to the mean of the peak loads over the 120 time-series. Similarly, for the unshared loading case, the selected time-series is the one (among the three mooring lines) for which the peak load is the closest to the mean of the peak loads obtained from the different realizations, avoiding outliers and ensuring a fair estimate while preventing overestimation for consistent and reliable comparisons between cases. In the MUTANC project, 32 load cases were studied, with variations in alignment and intensity of wind, wave and current conditions. Here, two extreme cases among all the studied cases were selected as they were deemed to present the most important loading amplitude (LC1) and the most important loading direction variation (LC2). These loading cases correspond to an environmental scenario with a significant wave height of 11m, a peak period of 13 sec, a 10-minute

average wind speed at 10m height of 40m/sec and a current velocity of 1m/sec. In each load case, both shared and unshared anchors were considered. For the shared anchor case, when the direction of the wind, wave and current is 'in-line' as shown in Figure (4), a high tensile load was found to develop in the mooring line L_1 with respect to the two other mooring lines (L_2 and L_3) leading to a quasi-unidirectional global irregular cyclic load in the direction of L_1. However, when the direction of the wind, wave and current is 'in-between' as shown in Figure (4), high tensile loads were observed in the mooring lines L_2 and L_3 as compared to that developed in the mooring line L_1. This leads to a highly multidirectional global irregular cyclic load.

Notice that in the first loading case (LC1), the global lateral load has a high amplitude of about 14MN (see Figure 5.a), i.e. 1.17*Hr, and a small variation in the load direction of less than 10° (see Figure 5.b). In the second loading case (LC2), the lateral load has a moderate amplitude of about 8MN (see Figure 6.a), i.e. 0.67*Hr, but a high variation of the load direction of about 90° (see Figure 6.b).

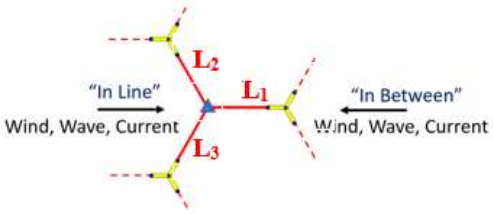

Figure 4. Environment loads orientations

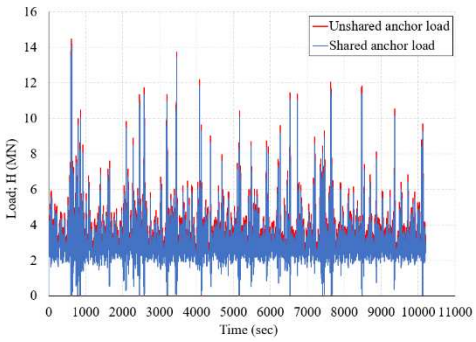

Figure 5.a. Lateral load time-series for LC1

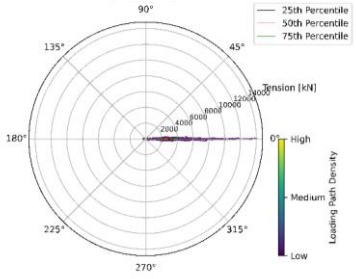

Figure 5.b. Lateral load direction of the shared anchor for the loading cases LC1

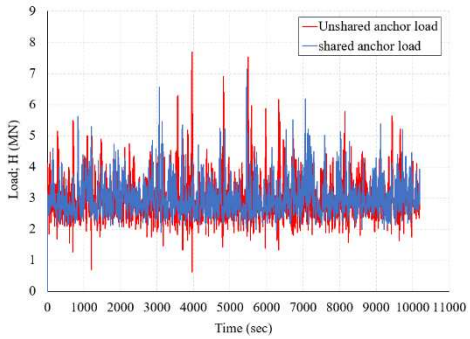

Figure 6.a. Lateral load time-series for LC2

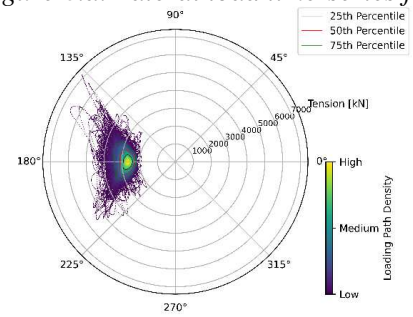

Figure 6.b. Lateral load direction of the shared anchor for the loading cases LC2

4. NUMERICAL RESULTS

In this section, the numerical results obtained from the numerical simulations are presented and discussed. The parameters of the Hypoplastic model with IS for Fontainebleau NE34 sand are firstly calibrated based on independent laboratory tests (Li *et al*. 2016) and then finely tuned for a cyclic multi-amplitude unidirectional loading case by comparing the numerical results with the centrifuge test results performed in the framework of MUTANC project (results not shown here). The calibrated parameters are provided in Table (1). These parameters were used in all the numerical simulations performed in this paper.

Table 1. Calibrated parameters of Hypoplastic constitutive model for Fontainebleau sand

Parameter	value
φ_c	31.6°
p_t	0.001
h_s	4.8GPa
n	0.29
e_{d0}	0.37
e_{c0}	0.88
e_{i0}	0.99
α	0.24
β	1.70
M_R	4.00
M_T	2.00
R	0.00015
β_r	0.40
χ	6.00

Figure (7) shows the evolution of the normalized resultant lateral displacement at the ground level v_G/D_p for the unshared and shared pile anchors for the loading case LC1. This figure shows a sudden increase in the lateral displacement at time t=631 sec. This phenomenon can be explained by the sudden increase of the lateral load applied to the pile anchor as may be seen in Figure (5.a) where the load increases from 0.075MN to 14.17MN in a short time period (from t=623.1 sec to t=631.6 sec). Figure (7) also shows that after the sudden increase in pile displacement, this pile displacement remains almost constant and does not exceed its value at t=631.6 sec. This is because the load does not exceed its maximum value after t=631.6 sec. This means that the displacement is very sensitive to the maximum load that the pile has previously experienced in its life time. From Figure (7), it can be observed that the final displacement of the unshared pile anchor (31.7cm) where v_G/D_p=0.127 is larger than that of the shared pile anchor (24.4cm) where v_G/D_p=0.1, the final displacement of the unshared pile anchor being 30% larger than that of the shared pile anchor.

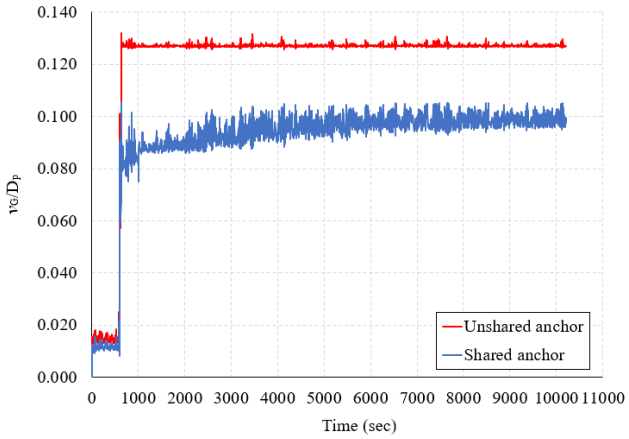

Figure 7. Anchor normalized lateral displacement under LC1 for unshared and shared pile anchors

Figure (8) shows the evolution of the normalized resultant lateral displacement at the ground level for the unshared and shared pile anchors for loading case LC2. These figures indicate that contrary to the load case LC1, for LC2 the lateral displacement of the shared pile anchor (11.5cm) where v_G/D_p=0.05 is greater than that of the unshared pile anchor (6 cm) where v_G/D_p=0.02. This may be explained by the high variation of the load inclination angle in the horizontal plan where the load is highly multidirectional. It is worth to mention herein that the greater displacement of the shared anchor under LC2 is much lower than that of the unshared anchor under LC1. This means that the displacement of the unshared pile anchor under LC1 governs the design and thus, the classical unshared pile design is not affected by a possible anchor sharing between multiple FOWTs.

Figures (9.a) and (9.b) show the time variation of the angles α and β, α and β being respectively the inclination angles (with respect to the direction of mooring line L_1) of the applied load and the resultant displacement for the shared pile anchor under LC2. From these figures, one can observe that the resultant load inclination angle α varies between -45° and 45° with respect to the direction of the mooring line L_1; however, the displacement inclination angle β varies between -30° and 16° with respect to this direction. This means that the resultant displacement direction does not follow the applied load direction. The displacement direction varies in a narrower sector with respect to the resultant load direction.

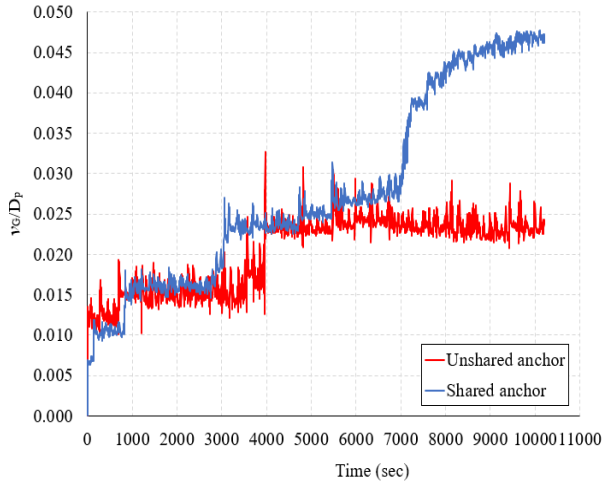

Figure 8. Anchor normalized displacement under the LC2 for unshared and shared pile anchors

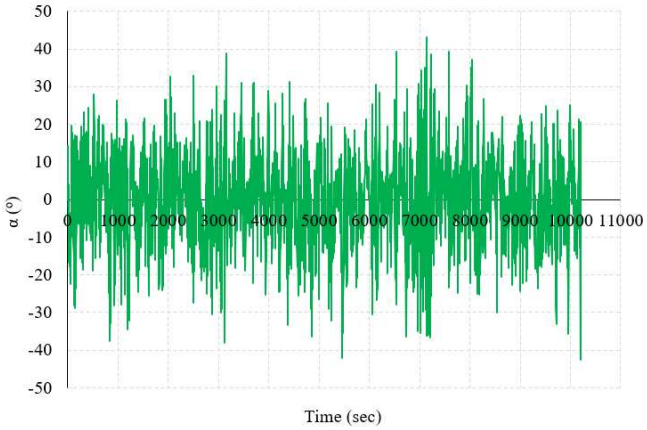

Figure 9.a. Variation of the inclination angle α of the resultant load under the loading case LC2

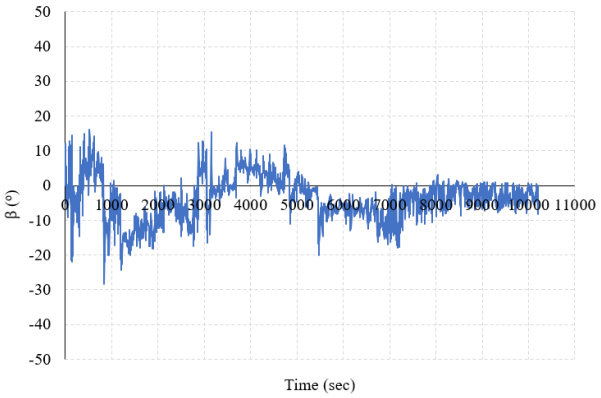

Figure 9.b Variation of the inclination angle β of the lateral displacement under the loading case LC2

CONCLUSIONS

In this paper, a numerical study of a pile anchor subjected to a cyclic irregular multidirectional lateral loading was performed. The objective is to test the performance of shared anchors as compared to unshared ones within a floating wind farm. The numerical model used to simulate the behaviour of the soil-anchor system was based on the commercial software Abaqus. The advanced Hypoplastic constitutive model with intergranular strain was used to simulate the soil behaviour. Two extremes time-series were considered in this paper among a total of 32 load cases provided in the framework of MUTANC project by France Energies Marines. In the first time-series LC1, the applied load has a high amplitude but is quasi-unidirectional. However, in the second time-series LC2, the applied load has a moderate amplitude but it is highly multidirectional. Also, both configurations of shared and unshared anchors were considered for the two load cases for comparison purposes. The numerical results have shown that for the sea state considered in this paper, the classical unshared pile design is not affected by a possible anchor sharing between multiple FOWTs. This observation needs to be validated over a large number of sea states involving misalignment between wind, wave and current.

AUTHOR CONTRIBUTION STATEMENT

A. Ahmed: Formal Analysis, Writing- Original draft, Reviewing and Editing. **Ph. Alkhoury**: Writing, Methodology, Reviewing and Editing. **Z. Li**: Methodology, Reviewing and Editing. **T. Coquio**: Supervision, Reviewing and Editing, Funding acquisition. **A-H. Soubra**: Supervision, Methodology.

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