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Finite Element Analysis of Shared Suction Anchor Capacity Including Effects of Trenching

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ABSTRACT: This article presents results from a feasibility study investigating trenching effects for the anchors of a floating offshore wind farm located in the North Sea. A semi-taut mooring concept with suction anchors with 1, 2 and 3 mooring lines has been assessed. Soil conditions are representative of Norwegian Continental Shelf (NCS) conditions consisting of homogeneous very soft to medium clay in upper 20-30 m. Projects in comparable soil conditions have demonstrated significant trenching, especially for taut mooring floaters in the oil and gas industry. Since trenching might be a plausible scenario, there is a need in the industry to quantify its impact on the anchor design. A literature review on trench formation and trench susceptibility in soft clays has been performed to establish trenching geometries. To quantify the impact of trenching on the anchor capacity, base case calculations with and without trench formations have been conducted. The loading effect of one or more mooring lines has also been quantified, and failure modes such as torsional loading in case mooring line failure have been analysed. This paper presents a practical engineering approach to account for a combination of the complex geometry of several mooring line trenches and different suction anchor geometries in 3D FEA to perform early-stage anchor design optimization. Structural considerations of the suction anchor layout are discussed on a high-level.

Keywords: Suction anchor; Trenching; Shared anchors; Soft clay, FEA

1 INTRODUCTION

Mooring systems in very soft to soft clays have in several cases shown significant amount of trenching due to the movement of the mooring lines. For the development of floating wind, shared anchors can be an attractive solution. However, the potential effect of trenching may be more severe, with up to one trench formation for each mooring line connected to the anchor. This article presents results from a feasibility study investigating trenching effects for a floating offshore wind farm with a shared anchor configuration located in the North Sea.

A brief literature review is presented in chapter 2 and the basis for analysis is presented in chapter 3. The further structure of this article in broad terms follows the structure of a feasibility study conducted on Equinor's behalf. In chapter 4 an initial screening is presented. Chapter 5 presents details on the workflow in the 3D Finite Element Analysis (FEA) with focus on scripting, whilst chapter 6 presents some example findings from the 3D FEA calculations. The focus has been on investigating different effects on holding capacity. In chapter 7 some results of the anchor sizing optimization are given. Chapter 8 describes some recommendations for further work, before conclusions are included in chapter 9.

2 LITERATURE REVIEW - TRENCHING

Several cases of trench formation for taut or semi-taut moorings in the oil and gas industry have been reported. A literature review was conducted to understand how trenches from the mooring lines may develop and how the design typically is performed to cope with or mitigate trench formation. Experiences of trenching are found from suction anchor projects in very soft to soft clays as described by Bhattacharjee et al. (2014), Arslan et al. (2015), Alderlieste et al. (2016), and Colliat et al. (2018). The trench development is in several cases observed to form horizontally from around the padeye depth, often with a back wall close to the suction anchor and relatively steep side walls with V-shape. Initiation of the trench is thought at the mooring line dip-down point and the trench is thought progressively developed towards the suction anchor as the mooring line dynamics also may be affected by the shape of the inverse catenary. See e.g. Randolph et al. (2020) and Wang et al. (2020) for further description of the mechanism.

The literature review conducted suggests that the experience of trench formation is for clay sites with undrained shear strength s_u of about 20 kPa or less.

Analysis approaches to cope with trenching effects shows that the trenching effect is dependent on both mooring line dynamics and soil strength. Relevant references are e.g. Wang et al. (2020) and Rui et al. (2023). Rui et al. (2023) presents numerical simulations of the complex 3D dynamics of the mooring response. It is noted that this article has not considered such a complex numerical approach. In the performed study we have adopted the gathered experience and developed a practical approach to investigate effects of up to 3 trenches on the suction anchor capacity (Figure 3, right).

3 BASIS OF ANALYSIS

A semi-taut mooring concept with suction anchors with 1, 2 and 3 mooring lines has been assessed for the station keeping of a floating wind turbine (Figure 1). The mooring spread is planned in a honeycomb pattern, see Figure 2 where the normal operating conditions (NOC) are illustrated.

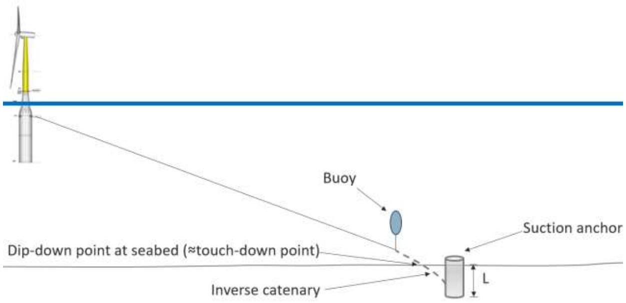

Figure 1. Sketch of semi taut mooring system for a 1-line anchor (not to scale)

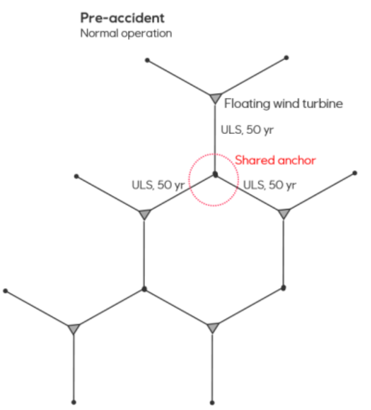

Figure 2. Sketch of honeycomb floating wind turbine pattern in NOC with loads according to DNV (2021)

3.1 Soil conditions

Soil conditions are representative of NCS conditions and consists of homogeneous very soft to medium clay in upper 30 m. Representative soil parameters are listed in Table 1. This is a slight simplification of the actual soil layering. s_{uC} refers to the monotonic undrained shear strength in compression from CAUC tests.

Table 1. Representative soil parameters.

Depth, z [m]	Plasticity index I_p [%]	Effective unit weight [kN/m^3]	s_{uC} [kPa]
0-30	50-35	7.5	1.7+2.33 z

Anisotropy factors for the undrained shear strength used in the calculations are given as s_{uD}/s_{uC}=0.75 and s_{uE}/s_{uC}=0.55.

Cyclic strength is assessed based on site specific cyclic laboratory program. High-level assessment of storm load amplitude history has been made and experience from previous projects for similar loading conditions is drawn upon. A net positive cyclic shear strength increase is found relevant for the study for a representative 50-year return period North Sea storm composition.

3.2 Trench geometry

As mentioned, the observations from industry cases of trenching suggest that trenches tend to form horizontally from around the padeye depth, often with a back wall close to the suction anchor and relatively steep side walls with V-shape. The shape of the trenches is closely related to the lateral movement of the mooring lines. A detailed description of the mechanism can be found in Rui et al. (2023). For engineering applications, Rui et al. (2023) suggests applying a simplified trench profile in a triangular prism shape that is relatively similar to what has been adopted in our study. All 3D analyses were performed with the following premises about the trench geometry:

- depth equal to padeye elevation or a relevant cut-off depth when the trench is stable.
- width at the bottom trench of 1 m to avoid numerical challenges in 3D calculations.
- no back-wall.
- one trench formation per line.

For the initial anchor sizing assessment (chapter 4), the trench top width was assumed to be equal to the anchor diameter. PLAXIS 2D (Bentley Systems Inc., 2022a) slope stability calculations were later performed to support the experience from the literature. Based on undrained and drained slope stability analysis, it was concluded that a trench of about 7 m depth with slope inclination 1:0.6 (59°) and V-shape was stable in the long-term conditions for the relevant soil conditions as shown in Figure 3. Note that the soil has cohesion also for drained conditions.

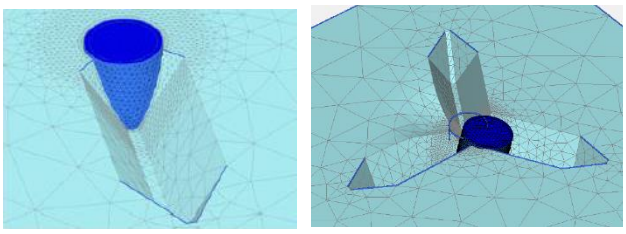

Figure 3. Trench geometry for 1-line configuration (left) and 3-line configuration (right)

It is noted that the width of the trench will be of influence on the suction anchor capacity. Rui et al. (2023) describes that the soil removal process adjacent to the anchor is most related to soil collapse, while the soil removal process further away from the anchor is more related to the lateral chain dynamics. Furthermore, the article indicates that soil collapse "*… have significant reduction when the soil strength gradient increases to k = 2 kPa/m*". The assumptions with regards to the trench geometry made in this article fit reasonably well with these observations.

3.3 Loads and safety philosophy

Table 2 summarizes the four design cases considered for the analysis and design of 1-line and 3-lines anchors. β refers to the out-of-plane load angle giving a global torsional load on the suction anchor. See definition in Figure 4. The dip-down angle of the mooring line chosen is modest, with a relatively low amplitude in angle.

Table 2 Factored loads at dip-down point for normal operation conditions (NOC) and accidental conditions (AC). Loads in bold are considered accidental loads.

Case #	Anchor	Design condition	Line	Load [MN]	β [°]
1	1-line	NOC	L1	10.6	0
2	1-line	AC	**L1**	**6.4**	**60**
3	3-lines	NOC	L1	10.6	0
			L2	4.4*	0
			L3	4.0*	0
4	3-lines	AC	**L1**	**6.4**	**60**
			L2	4.4*	0
			L3	7.7*	0

*Note that pretension on the downwind lines in the analysis of the holding capacity for case #3 and #4 is used.

According to DNV-ST-0119 (2021), for design of shared anchors, load contribution from all mooring lines shall be accounted for. With reference to the left illustration in Figure 4, failure of one mooring line may cause one floating wind turbine to move out of position, while the anchor may support other wind turbines which are still operating. This scenario, triggered by a damaged line, shall be defined as an accidental scenario. As the shared anchor is supporting operating wind turbines, the soil material factor used for the anchor is 1.2, while the mooring loads are a combination of ALS and ULS loads (see also Table 2, load case #4). Note that the soil material factor is equal to the minimum Factor of Safety (FoS) in the geotechnical analysis. This scenario introduces a significant global torsion on the anchor.

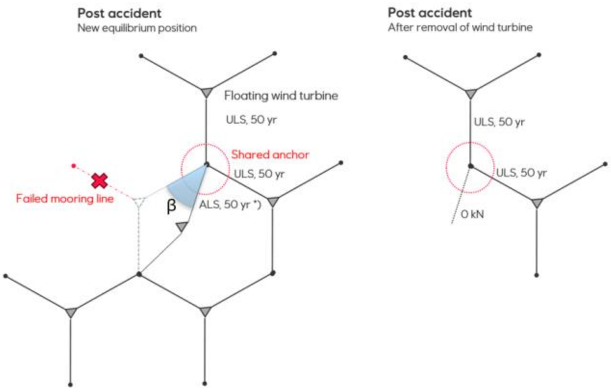

Figure 4. Sketch of honeycomb floating wind turbine pattern in accidental condition with loads (DNV, 2021)

It should be noted that the loading condition on a shared anchor configuration in a wind farm is complex. In the current work, a simplified approach has been used to the define the anchor loads.

4 SCREENING OF ANCHOR SIZE

An initial screening assessment was performed using the CAISSON software (S. Kay Consultant, 2018) to establish a starting geometry given a set of design mooring loads. See also Kay (2015).

The calculations in CAISSON could not consider the effect of trenching nor torsional resistance enhancement, which was later addressed using PLAXIS 3D (Bentley Systems Inc., 2022b) analyses. CAISSON analyses were performed for different anchor length (L) to diameter (D) ratios and padeye locations to establish capacity trend lines as function of geometry and padeye location focusing on a 1-line anchor in intact condition (ULS) (see also Table 2, load case #1). The results showed that an anchor diameter of 6-8 m was feasible and practical as a starting point for further analyses. The aspect ratio

(L/D) was approximately 2.0 and the padeye location close to 2/3L elevation below seabed. This geometry is in line with experience from similar projects. Note that in subsequent sections, padeye elevation refers to the padeye depth relative to seabed as a function of the anchor length (L).

5 FEA WORKFLOW

The simultaneous complexity of loading conditions when sharing anchors and of the failure mechanism when considering trenching necessitated the use of 3D FEA at an early stage of the calculation process. It was essential to investigate a variety of variables. Consequently, it was decided to automate most of the modeling and calculation process using Python to control the workflow in the FEA software PLAXIS 3D.

A key element when using Python to construct geometry in PLAXIS 3D was ensuring a satisfactory mesh for all calculations. Therefore, a significant part of the scripting process involved correctly and automatically handling the intersection of different geometries and the deletion of redundant geometries.

Using the intersection command in PLAXIS on two surfaces rendered the original Python mapping of the surfaces redundant as new surfaces were created. Consequently, new surfaces needed to be sorted after the intersection command was used. To achieve this effectively, the “center of gravity” command was extensively used to map the locations of the new surfaces. Surfaces were then deleted or retained based on their positioning after intersections. Additionally, volumes were used to control the mesh in different regions.

The script was also designed to be as general as possible, so that all variables could be examined if needed.

Through this process, each model achieved a similar mesh quality regardless of the input variables. However, it remained crucial to address and quantify the overshoot in calculated capacity to optimize calculation time. Generally, all FE calculations are susceptible to overshoot in capacity calculations due to discretization errors. This issue is particularly significant for PLAXIS 3D, which utilizes 6-noded elements. The overshoot was estimated by performing mesh convergence tests on selected models including benchmarking against CAISSON without trenches. Different load conditions also affected the overshoot. In general, an overshoot between 10-15% was estimated for models with around 100k elements under ULS conditions. Local refinement of the mesh was implemented considering the failure modes.

The constitutive model adopted in the FEA calculations was the NGI ADP soil model. The caisson was modeled with shell elements with interface elements applied.

6 PARAMETRIC ASSESSMENT

To benchmark the effect of trenching, suction anchors with diameter 6, 7 and 8 meters were sized with and without trenches in PLAXIS 3D for the soil conditions, trench geometry, and load cases defined in chapter 3. To cope with the significant global torsional loading in accidental state, external fins to enhance the torsional resistance were considered (section 6.3). This concept that has been used successfully for design of subsea suction bucket foundations in the oil and gas industry according to the authors knowledge, at least since 2004-2005. Such fins are hereinafter referred to as external fins.

Some isolated effects are described in the following sub-sections.

6.1 Trenching effects on anchor capacity

The effect of trenching was studied for both 1-line and 3-lines configurations for NOC and modelling the trench down to padeye level. The results presented in Table 3 are showing the percentage reduction in the targeted FoS relative to FoS achieved by the anchor design from the initial anchor sizing analysed in PLAXIS 3D. The results show a relative reduction of FoS from 35-43% when trenching effects are accounted for in this example. With reference to Alderlieste (2016), reductions of 20% for pure lateral translation to 32% for a situation where the suction anchor is free to rotate, were reported for a 1-line configuration. It is noted that in the results shown in Table 3, the padeye placement has not been optimized and therefore give high values of reduction in FoS. Sizing optimization is described further in chapter 7.

Table 3 Example of trenching effect on suction anchor in-place capacity, relative reduction on FoS for a trenched profile relative to no trenching.

Load case	D [m]	Type	Padeye elevation [-]	Reduction of FoS [%]
#1	6.0	1-line	2/3L	35
#3	6.0	3-lines	2/3L	43

6.2 Optimum padeye placement

The effect of different padeye elevations, namely above (1/2L) and below (2.5/3L) the so-called “optimum” level at 2/3L - which is traditionally used in suction anchor design - were studied for 1-line anchor for NOC and modelling the trench down to padeye level. When running the initial analyses, it became clear that the optimum padeye elevation had to be slightly shifted downwards when trenching effects are accounted for, in order to avoid an overturning failure with forward rotation – and hence increasing the risk of active gap formation which consequently could reduce the suction anchor capacity significantly. Moving the padeye elevation from 2/3L to 2.5/3L ensured a more lateral translation failure, see Figure 5. This is also in agreement with previous findings in the literature, as indicated by Alderlieste (2016) who concludes that the padeye level should be shifted somewhat below "optimum" (2/3L) level to maximize the holding capacity when accounting for trenching effects. In addition, Alderlieste (2016) concludes that a padeye at the top of the suction anchor (close to seabed) is inefficient. Note that the comparison in Figure 5 is for different depth of trenches, here it was assumed that the trench was progressing down to the padeye level.

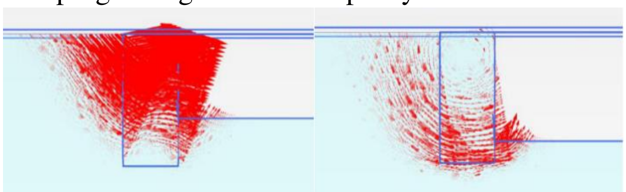

Figure 5. Failure mode for pad-eye at 2/3L (left) and 2.5/3L (right). Cross section through 3D FEA model.

Our results are presented in Table 4, showing the percentage reduction in the targeted FoS relative to FoS achieved by the anchor design from the initial anchor sizing analysed in PLAXIS 3D. Subsequent analyses were therefore performed with an optimized padeye elevation of 0.7L.

Table 4 Example effect of different padeye placement on suction anchor in-place capacity, relative reduction on FoS for a trenched profile relative to no trenching.

Load case [-]	D [m]	Padeye elevation [-]	FoS no trench [-]	FoS with trench [-]	Reduction of FoS relative to base case [%]
#1	6.0	2/3L	1.24 (base case)	0.81	35
#1	6.0	1/2L	0.90	0.62	50
#1	6.0	2.5/3L	1.14	0.85	31

6.3 Global torsion

The effects of trenching were studied for both 1-line and 3-lines configurations for accidental conditions (load case #2 and #4) and modelling a 7 m deep trench. Initial results when implementing global torsional loads in PLAXIS 3D showed that the accidental loads became governing for the design of the suction anchors. External fins were introduced as a mitigation measure to further optimize the design. References to some recent articles on the topic are Fu et al. (2021, 2024), which demonstrates that fins are shown to increase the torsional capacities of the suction anchor. In our assessment we have included such anti-rotation fins towards the bottom of the suction anchors, where the soil shear strength is highest and where trench formation is less likely to progress towards the fins.

Results shown on Table 5 show that the skirt length can be reduced by approximately 7 m when using external fins to increase the anchor torsional capacity, leading to an estimated weight reduction of 25%. Note that this example does not include structural modeling, which was further optimized, as shown in chapter 7.

Table 5 Suction anchor geometry based on different configurations, with and without external fins.

D [m]	Type [-]	Padeye elevation [-]	External fins [-]	Trench depth [m]	L [m]
7.0	3-line	0.7L	No	7	21
7.0	3-line	0.7L	Yes	7	14

Regarding overshoot in 3D FEA, it is important to recognize that for an anchor without fins the calculations resulted in a small overshoot, while introducing fins significantly increased the overshoot. This was due to the need for a finer mesh around the fins to capture the complex failure mechanism, whereas without external fins, the failure was at the soil-wall interface where the soil plug also failed in torsion. Extensive efforts were made to provide a high-quality mesh around the external fins.

7 ANCHOR SIZING OPTIMIZATION

A suction anchor diameter of 7 m was selected for further structural assessment and modelling, adopting padeye placement of 0.7L which was determined as an optimum placement considering a maximum assumed trench depth of 7 m. On a general basis, slender suction anchors would be beneficial from a cost perspective. Aspect ratios may typically be in the range 2-5 for such soil conditions. A simplified screening tool was developed to estimate the weight of different anchor configurations. This was based on experience from previous detailed design of suction anchors, considering aspects such as lid layout, shell buckling capacity, padeye- and internal stiffener arrangement. Internal stiffeners are needed for structural considerations. The layout of the internal stiffeners will enhance the torsional capacity. However, only up to the base shear capacity. To enhance the torsional capacity of the suction anchor further, the external fins are included at the bottom of the anchor. See Figure 6 for an illustration of the preliminary design from the feasibility study. It is noted that no detailed optimization of the external fin layout was carried out in this study.

Table 6 provides a summary of the optimized anchor geometries that were compared with such screening tool. The results are showing that, when accounting for a reasonable trench geometry, a reduction of about 25-30% in steel weight can be achieved for an anchor with 3-lines for an optimized padeye at 0.7L, compared to the case of having the padeye at the top of the anchor. Having the padeye at the top of the anchor is in general an inefficient design, as it results in larger anchors and hence more steel, even if it eliminates the risk of trenching. Placement of the padeye at the top of the anchor might offer some additional benefits in terms of marine operations execution and environmental impact. Those may be further investigated using a cost/benefit analysis. Further, the results from the screening tool are showing an additional reduction of weight of approximately 10% when external fins are introduced.

Finally, effects on anchor capacity due to trenching were also estimated for the optimized anchor geometry. A maximum reduction of suction anchor holding capacity of about 16-23% was estimated depending on the load case and associated failure mode for an anchor with 3-lines and padeye at 0.7L, for a reasonable trench geometry.

Table 6 Optimized suction anchor geometry based on different configurations, with and without external fins. Net positive cyclic shear strength increase included.

D [m]	Type [-]	Padeye elevation [-]	External fins [-]	Trench depth [m]	L [m]
7.0	3-line	Top	No	0	25
7.0	3-line	0.7L	No	7	16
7.0	3-line	0.7L	Yes	7	14.5

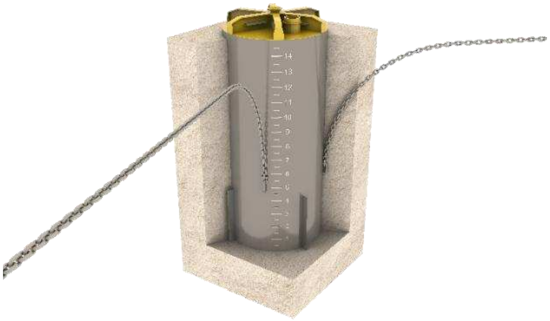

Figure 6. Artistic view of suction anchor in soil.

As part of the feasibility study, different approaches to cope with the issue of trench formation were discussed. The *emperical/analytical approach* used in this study can be used as a starting point and if found relevant in engineering practice, followed by an *advanced analysis approach* in detailed engineering, looking further into the line dynamics with advanced trenching mechanism incorporated or model testing, or a combination of both. It is noted that the trench mechanism is highly complex, with effects such as effective stress relief, interaction between different trenches, water entrainment in soil and complex fluid dynamics interaction with chain and very soft/ soft clay. Any detailed study of the mechanism should carefully consider relevant uncertainties.

For either approach chosen, one may consider an *inspection and mitigation approach*, looking into e.g. gravel or rock installation of trenches in case these develop to a predetermined level. In this regard, a cost benefit analysis would be of high relevance where rock/ gravel replacement of trenches is compared to designing for deep trenches in equilibrium condition.

8 FURTHER WORK

Line dynamics and its effect on trench geometry needs to be further assessed in a detailed design stage of floating offshore wind farm with a shared anchor configuration in very soft to soft clay.

The 3D effect of the inverse catenary for the situation of accidental damaged line should also be investigated further. The complex 3D shape of the chain cutting into virgin soil together with potential trench formation complicates the load situation. Potential reduction in global torsional load due to the inverse catenary may be further analysed.

One should be aware that the external fins may introduce a potential for channelling depending on the site-specific soil conditions and the in-place displacements. These effects should be studied further, as the design presented may not be a suitable solution for all projects. The detailed design of external fins furthermore needs to be conducted.

9 CONCLUSIONS

Scripting of FEA have made it possible to efficiently run a vast number of complex numerical simulation for an engineering setting to find optimal anchor geometry in terms of holding capacity. For a 3-lines suction anchor, when using optimum anchor placement of 0.7L, the reduction in holding capacity with trenches was found as about 16-23%, depending on failure mode. It was found that applying the padeye at 0.7L proved rational compared to an alternative with padeye at the top centre of the suction anchor in terms of structural steel.

Trenches must be assessed on a case-by-case basis depending on the soil conditions and mooring line configuration.

In the feasibility study, the line-failure was governing for the holding capacity of the suction anchors. External fins were included at the bottom of the anchor to enhance the torsional capacity for the line failure scenario. It is recommended to duly check the installation predictions when including such plates.

AUTHOR CONTRIBUTION STATEMENT

Erik Tørum: Formal Analysis, Methodology, Supervision, Writing- Original draft. **Aleksander Worren**.: Formal Analysis, Software, Conceptualization, Methodology, Writing – review & editing. **Robert Bendzovski**: Formal Analysis, Project administration, Supervision, Methodology, Writing – review & editing. **Valentine Declerck**: Supervision, Writing- Reviewing and Editing,

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