Design of a suction pile multi-line anchor system for floating offshore wind turbines

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday August 31 2021 at 02:00 PM.

Student number:	4207785	
Project duration:	November 9, 2020 – August 31, 2021	
Thesis committee:	Dr. O. J. Colomés Gené,	TU Delft, supervisor
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This thesis is confidential and cannot be made public until August 31, 2023.

TU Delft

Abstract

From the literature research it can be concluded that the suction pile anchor (SPA) is a suitable anchor for a multiline anchor system and that the most probable mooring configurations will be either the original single-line, the 3-line or the 6-line system. Furthermore it could be concluded that when using a catenary mooring solution for the 3-line system, that the anchor perceives a lower horizontal net force due to anchor lines coming from different directions and canceling parts of each other. This would, in theory, make the suction pile anchor for the 3-line multiline system smaller and also there would be 67% less anchors needed in a wind farm array. Furthermore the 6-line anchor does seem to have a bigger horizontal net force which requires the suction pile anchors to be bigger but 83% less anchors are needed in an array of wind turbines.

The looked at FOWT-system was the University of Maine VolturnUS-S reference floating offshore wind turbine semi-submersible, which supports the IEA-15-240-RWT turbine with a turbine rating of 15MW with all the main parameters being listed in Table 3.1. The SPAs that are designed in this thesis are the anchors in the middle of the array and the edge anchors will stil need to be looked at separately when a whole system is worked out. With the original mooring configuration being a catenary one a comparison has been made with a taut system and its implementation into a multiline anchor system has been researched. Lastly three different soil profiles have been chosen because of their appearance in deep sea waters: normally consolidated clay, slightly consolidated clay and loose sand.

In Chapter 4 Suction anchor concept design, the forces on the anchor are set up using the data set-up by NREL and the University of Maine [1] and the C. Fontana papers [13, 15]. In the NREL report a model is made using the OPENfast software: a multi-physics, multi-fidelty tool for simulating the coupled dynamic response of wind turbines. From this model the mooring line and anchor forces are predicted for the reference turbine. This way of setting up the anchor forces is an estimation because the 15MW wind turbine is not yet fully developed and is still being designed. By using the forces from this report and by using the factors set up by the C. Fontana papers we can define the 3-line and 6-line mean and maximum horizontal forces. A suction pile anchor has more bearing capacity when the mooring-anchor connection point is below the mudline. Because of this feature the mooring line attaches to the suction pile anchor at an angle and in this thesis a range of angles of approach are chosen to be investigated: 25 and 35 degrees for the chain and 45 degrees for the taut line. Furthermore, for the taut line another factor has to be introduced because from literature it can be said that the taut lines have a higher mean force and a higher max force compared to the same catenary system. Because of the angle there is a vertical force introduced to the anchor which need to be added together for each line. Because of this the total net force on the anchor is increased for the 3-line and 6-line anchors compared to the single-line anchor.

Now that the mean and maximum forces for each of the angles of approach are defined the calculations for the holding capacity/pull-out capacity can be set up by looking at the Ultimate Limit State (ULS) or maximum forces in the system. These calculations are taken from the DNV guidelines which are the industry standard. Here the vertical and horizontal capacities are calculated separately and the choice was made to set up a VHM-envelope by means of hand calculations to find the combined failure envelopes, instead of using finite element analysis software like PLAXIS. To set-up the first parameters estimation a embedment (h/D-ratio) starting value has to be chosen and from literature and in discussion with SPT offshore the starting values were set at 5 for the clay profile and 1.5 for the sand profile. Lastly before being able to solve these equations the weight of the suction pile anchor must be defined which was done as the mean vertical force applied to the anchors as such they will not be pulled out over time. In case of the 3-line anchor and especially the 6-line anchor, this is a considerable weight that will have to be compensated by adding extra ballast although the amount of ballast can only be calculated once the final parameters of the suction pile anchors are estimated. After making the first parameters estimation with the defined embedment ratio's the installation and removal calculations must be set up. Here the underpressures required to fully install the suction pile anchors are calculated. Furthermore, structural failure due to buckling is checked for and different soil failures are analysed. Lastly the removal pressure of each concept is checked which allows for complete removal of the suction anchor but is limited by the maximum pressure of the available deapsea pumps. By lowering the embedment ratios of the different concepts the pressures inside the anchors can be minimised and problems can be averted. Each time a lower embedment ratio is chosen the VHM-envelope is calculated again and new

parameters are set up. Lastly after all soil failures, structural failures and removal pressures are checked, the final parameters for each concept can be defined.
In the detailed design the full design of a in use suction pile anchor is shown and each part is defined. Furthermore, the one-line-broken criterium is discussed and it can be concluded that in case this happens the 6-line multiline system is very dangerous because a chain reaction can be started which can take out large parts of a wind farm array. Also a weight estimation of each suction pile anchor is made from which the extra needed ballast is calculated. Subsequently a cost estimation of each anchor concept, in the three different soil profiles and for each angle of approach, can be made by calculating the cost of each system from the structural weight, the ballast and the mooring line lengths. At a depth of 200m, at which this study is situated, the taut multiline system cannot be set-up but the single-line taut system can be compared to the catenary single line system. Lastly a parametric analysis is done where changes in different parameters are compared to each other.

List of Figures

List of Tables

1 Introduction

Floating offshore wind technology is a rapidly maturing sector and there will be a need of a reliable and efficient anchoring and mooring system connecting them to the seafloor. With floating wind turbines being installed in deeper waters than the bottom founded counterparts, ease of installation is very important and can save a lot of costs. Because of this the suction pile technology is a great starting point for a mooring system. Increasingly important environmental factors also play a large role in the development of the offshore sector. Especially ease of decommissioning, installation noise and destruction of the environment are important considerations to keep in mind when selecting offshore solutions. These are well represented in the suction pile anchoring solution, which will be compared to other anchors in the literature research.
Furthermore, a large portion of the total costs of a floating wind turbine are reserved for the substructure of the floating offshore wind turbine. This substructure has the objective to anchor and moor the system to the seafloor and reducing costs in that part of the floating wind turbine design would have a big impact on the total costs of the project or the Levelized Cost Of Energy (LCOE). The design philosophy of this thesis will be to design an efficient and cost effective mooring system. The solution studied is the multiline anchor configuration proposed by C. Fontana in her doctoral dissertations [14] and this solution would drastically decrease the amount of anchors needed in a windfarm array.

This thesis focuses on the technical feasibility of using suction pile anchors in different multiline systems and in different soil profiles for the chosen Floating Offshore Wind Turbine (FOWT). Subsequently, a study will be conducted on the size of these suction piles and also come with a design on how these suction pile anchors will look and what the critical points will be in the design. After this a small economic study is done on the costs of these different concepts for the chosen parameters and lastly a parametric study is performed.

SPT OFFSHORE

1.1. Background information

This thesis is conducted in cooperation with SPT Offshore who is a leading offshore contractor for suction pile foundations and anchors. SPT Offshore manages and undertakes Engineering, Procurement, Construction, Installation (EPCI) projects worldwide, from installing single suction anchors to mooring lines and self installing platforms. Experienced operational crew contracted by SPT Offshore have installed over 600 suction piles worldwide and have proven the technology of Self Installing Platforms (SIP), Self Installing Monopiles (SIM) and Suction Installed Wind Turbine (SIWT) on multiple occasions.
With the growing number of offshore floating wind farms, there is the need to develop this business for SPTs suction pile anchors (SPA). A better understanding of the merits of suction anchors for this application and the development of a dedicated design is of great importance for the further development. The difference between the anchors and the standard usage of a suction caisson is that the anchor experiences tension forces

instead of compression forces. A different set of challenges comes with this design difference.

1.2. Problem definition

With offshore wind sector expanding to deeper and deeper waters the industrial standard monopile or even jacket structure becomes obsolete. This is because the structures become so big that it economically unfeasible to keep using them. Because of this a floating solution is searched for. In the literature research the different available concepts are studied.
A large portion of the costs of a floating wind turbine system is in the mooring and anchoring design and installation. There are multiple viable options for anchoring the system to the seafloor, not only in anchors but also in mooring line options. Deciding on the best course of action is part of this thesis and an important factor when setting up a multiline system. Not every anchoring technique is viable for the multidirectional loading, which is an important factor in the multiline system.
For now the costs of building and maintaining a floating offshore wind turbine is still too high and looking for new technologies that might lower these costs will be crucial in the further development. The multiline system is still in its early stages but the research done by C. Fontana shows promising results [13, 15]. In this research the suction pile anchor is mentioned as a possibility for anchoring these multiline systems.
The idea of having Floating Offshore Wind Turbines (FOWT) has been around for some time and there are many projects currently being researched and tested. Many of these can be found in the literature research in the literature research and they are listed in Table A.2. These projects contain many different variations and this shows that the technology is still in early development with no optimal solution.

1.2.1. Research question

The main goal of this thesis is to research if a multiline anchoring system is technically feasible by looking at the forces introduced to the system and seeing if a suction pile anchor can be built that resists this forcing. If this is possible than it is prominent to know if the designed multiline anchoring system can be better than the single-line system that is the standard solution right now. From this the following research question can be formulated:

"Is it technically feasible and economically viable to use a multiline anchoring system to anchor a 15MW floating offshore wind turbine to the seafloor?"

1.2.2. Research objectives

The research question stated above is a large question that can be be answered by working out the following research objectives:
1) Make a literature study on existing multiline anchor concepts and analyse the different possibilities and chose multiple to be researched in this thesis.
2) Asses the Rules & Regulations / Codes applied in this field.
3) Analyse why the Suction Pile Anchor (SPA) would work for the multiline concept.
4) Chose wind turbine size and specifications.
5) Chose different soil profiles to be investigated.
6) Definition of the multiline loading on the anchors for both taut and catenary lines.
7) Estimate the different sized suction pile anchors by analyzing the pull-out capacity and the different soil- and structural failures that are of importance.
8) Set-up an economical picture with which the multiline systems can be compared to the single-line system.
9) Parametric analysis of the system to investigate how the multiline system can be improved.

After all the objectives are worked out the research question can be answered. Can a multiline anchoring system work for a floating offshore wind turbine? And is it economically viable?

2

Literature research

This chapter includes the most relevant conclusions and information of the complementary literature research. The complete literature research can be read in section A.1 where more information is added regarding all the topics and extra topics are discussed such as the multiline ring anchor or mooring connectors. In this chapter the different floater concepts for floating offshore wind turbines, the different mooring line configurations and the different anchor types will be discussed. Furthermore, the multiline anchor concept will be explained and why this is a good idea for an array of floating offshore wind turbines.

2.1. Floater concepts

In bottom founded offshore wind turbines the Wind Turbine Generator (WTG) is mounted on top of a substructure that is directly connected to the seafloor. For a floating offshore wind turbine at sea, the tower assembly is added on top of a floater. This floater is again connected to the seafloor by means of a mooring configuration. The floater and the mooring configuration together are supposed to hold the turbine into position, maintain deflections in an acceptable range for the electrical cables, counteract the turbine induced and hydrodynamic loads and transfer the loads from the structure to the dissipating medium [5]. The different floater concepts that will be discussed are listed below and shown in Figure 2.1.

1. Buoyancy stabilized - Semi-submersible platform

2. Ballast stabilized - Single Point Anchor Reservoir (SPAR) platform

3. Mooring stabilized - Tension Leg Platform (TLP)

In Table 2.1 the three discussed floater types are summarized. The numbers rank the different concepts from biggest (1) to smallest (3), complex construction (1) and least complex (3), lowest draft (1) and highest draft (3), easiest to install (1) most difficult to install (3) and finally their biggest positive and negative aspect.
The chosen floater type for this thesis project is the semi-submersible floater concept. This choice was made because the semi-submersible is the most accessible of the three concepts. It is easier to install than the other floater types because the WTG can be added on the floater in a port and than towed out to the desired location. Furthermore because of its size the forces on the system will most likely be the biggest and thus a conservative anchor system can be designed. The anchor forces for a SPAR will be less severe and the system will be able to adapt easily by scaling it down. When designing a TLP system only vertical forces will be applied which will apply more restrictions in the anchor choice and the system will have to be installed at sea which comes with considerable setbacks.

Figure 2.1: Most promising and available floating wind concepts. Courtesy: Floating Offshore Wind Farms [7]

Table 2.1: Summary of Semi-submersible, SPAR and TLP floater concepts

	Semi-submersible	**SPAR**	**TLP**
Floater Size	1	2	3
Construction Complexity	1	3	2
Lowest Draft	2	3	1
Ease of Installation	1	2	3
Biggest Positives	Low draft and easy installation	Ease of construction	Stiff system with good dynamic capabilities
Biggest Negative	Big size comes with higher costs and higher WWC forces	Depth restriction	Not stable without tendons

2.2. Mooring configuration

Mooring lines are one of the critical components in floating offshore wind turbines but also in other floating structures. If they break, collisions with other structures can cause damage not only for one structure but multiple. Because of this, many researchers study their static and dynamic behaviour. There are multiple ways of mooring a floating structure to the seafloor and the three most used are:

1. Catenary
2. Tension leg
3. Taut

A catenary mooring line is the earliest and most common mooring line that is used in the offshore industry. It has a very distinct shape of a free hanging line which can be seen in Figure 2.2. In this figure there are different conditions: A_1 with larger parts of the catenary line on the seafloor to A_4 with no part of the catenary line on the seafloor. The line lift off is due to the horizontal displacement of the floater or vessel and causes the line tension to increase and the angle relative to the horizontal to decrease. These two effects together cause a horizontal restoring force on the floater, that increases in a non-linear manner.

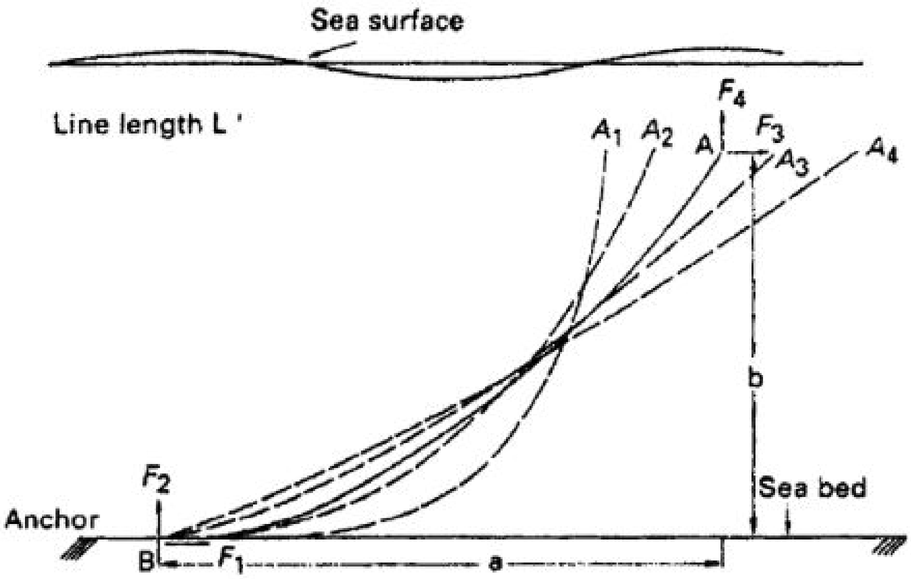


Figure 2.2: Shape of catenary mooring line at different positions. Courtesy: Handbook of Offshore Engineering [8]

Catenary mooring lines are mostly made of steel chains and/or wire and the restoring force is provided by the weight of the mooring line itself. This self weight causes a problem when used in deeper waters where the chain will succumb to its own weight. Large parts of the lower section of a mooring line are on the seafloor to provide additional strength in stormy conditions and to provide frictional resistance with the seafloor. Because the catenary mooring line lays on the seafloor, the anchors for these lines can be designed on purely horizontal force. When the connection point to the anchor is below the seafloor, some vertical forces can occur but this will be addressed in the detailed design [7, 8, 35, 37].

The tension leg is only used for the TLP floater concept and thus will not be further discussed. The taut

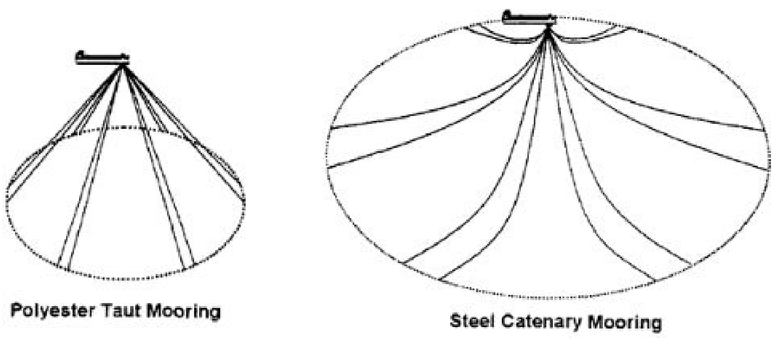


Figure 2.3: Taut system and Catenary system visualised. Courtesy: Handbook of Offshore Engineering [8]

configuration has a clear advantage for deep water applications because it uses less material than the catenary solution because the mooring line is more straight. In practice a lot of configurations that go to deeper waters have a combined system because taut lines get damaged easier than chains. At the top a collision with debris or a ship can snap the taut line and at the bottom the taut line can get damaged by sliding along the seafloor. An example of such a system is shown in Figure 2.4. Here you can see that the bottom part of the mooring line is a chain section which is connected to the suction pile anchor and to the middle part which is a taut fiber rope without a catenary shape and the bottom part is again a chain. The top part is again a chain with a chain that is connected to the floating structure. There are a lot of details in this figure that show the complexity of the mooring line. The chain is explained in subsection A.4.1 and the fiber rope is explained in subsection A.4.2. Lastly the connectors are explained in subsection A.4.3.

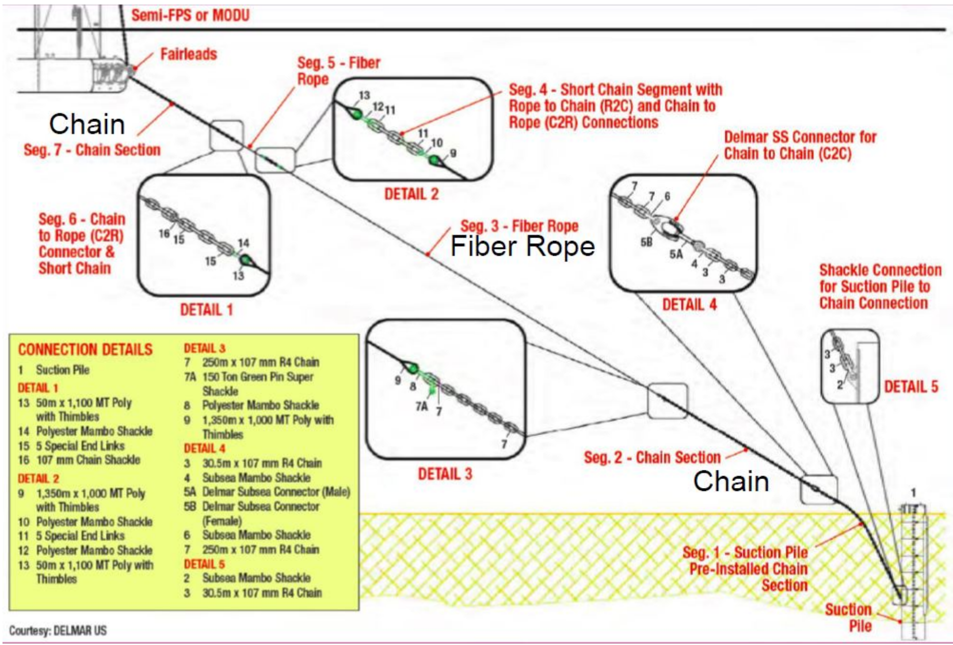


Figure 2.4: Example of a combined mooring system for a Semi-FPS or MODU. Courtesy: DELMAR US. Taken from "Floating Structures & Offshore Moorings Mooring Systems - Lecture 12 Mooring Systems" [33].

2.3. Anchor concepts

There are multiple different ways of anchoring a floating body to the seabed and in this chapter the different anchoring options are addressed and their advantages and disadvantages are discussed in their respective sections. In the figure below you can see the six different anchors commonly used in the offshore industry and which are addressed in this literature research. There is a difference made between horizontal and vertical forces the anchor can cope with. From mostly horizontal loading due to a catenary system to mostly vertical forces from a tension leg and finally a combination due to a taut system.

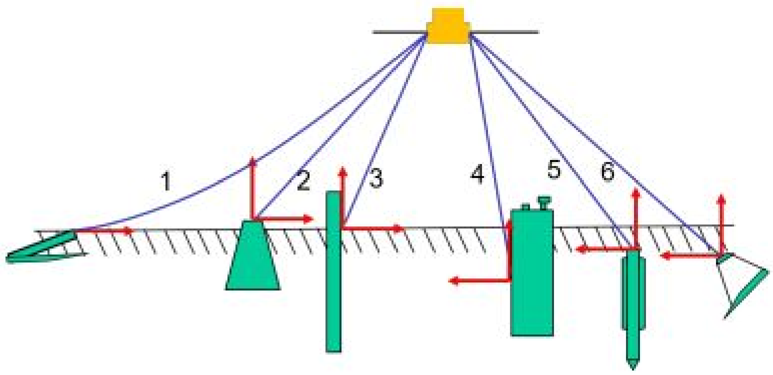


Figure 2.5: The discussed anchor types in this thesis. Courtesy: Doctoral theses Kun Xu [37]

- 1: Drag Embedment Anchor
- 2: Dead Weight Anchor
- 3: Pile Anchor
- 4: Suction Anchor
- 5: Gravity Installed Anchor/Torpedo Anchor
- 6: Vertical Load Anchor

The most used permanently moored anchors are the driven pile and suction pile anchors. These methods have been around for many years and have been researched extensively. High efficient drag embedment anchors (DEA) and vertical load anchors (VLA) are mostly used for non-permanent locations although their recent developments have made them strong contenders. When penetration is impossible the deadweight anchor is used. The gravity installed anchor (or torpedo anchor) is a relatively new anchor concept and on the rise. It has mostly been used in mobile offshore drilling units and permanent moorings but it needs site investigation, soil characterization, foundation analysis and foundation capacity assessment. Its ease of installation in deeper waters does give it a great advantage. Its biggest disadvantage is that the intellectual property and knowledge is with Petrobas.

Table 2.2: Summarizing the strengths and weaknesses of the different anchor types

	DEA	Deadweight	Pile Anchor	Suction Pile	Torpedo	VLA
Permanent mooring	no	yes	yes	yes	no	no
Decommissioning	yes	no	no	yes	yes	yes
Multidirection	no	yes	yes	yes	yes	no
Precise positioning	no	yes	yes	yes	yes	no
Deep water	yes	yes	no	yes	yes	yes
Efficiency	1	3	2	2	2	1

The six different anchor concepts that were discussed in this section are now summarized in Table 2.2. Every anchor can be specifically designed for a certain situation and thus some no's in the table can be changed into a yes in certain anchor designs. These changes do impact the overall design and might make the anchor design very expensive or defeat its purpose. The precise positioning that is not custom for DEA's and VLA's can be achieved when using a suction pile to install the anchors instead of dragging it along the seafloor until the desired depth is reached. This does come with extra costs because a suction pile will have to be brought along. Furthermore a drag embedment anchor is usually not used for permanent moorings but certain designs can be used as such and the same can be said for vertical load anchors. A deadweight anchor can also be decommissioned but because of its size and weight its very expensive and thus it is considered as not decommissionable. The summary table is made for the most general case of each anchor design.
Lastly the efficiency of the different anchor types is listed in three different categories. Here the drag embedment anchor and vertical load anchor are listed in category 1 meaning they are the most efficient weight to bearing capacity anchor. This is because they are more deeply embedded in the soil and thus get their bearing capacity from deeper soils that are stronger. The pile anchor, suction pile and torpedo anchor are in class 2 meaning because they get their bearing capacity mostly from the friction with the soil close to the mudline. Finally the deadweight anchor is in class 3 because it gets most of his capacity from his weight. Later on the efficiency increases a little but is still by far the worst weight to bearing capacity ratio.
The anchor that is used for a multiline anchor concept will experience multidirectional loading as will be explained in section A.6 and thus the chosen anchor concept has to be able to cope with this aspect. The anchor types that are in consideration when keeping in mind this specification are: pile anchor, suction pile, deadweight and torpedo anchor. The deadweight anchor is too inefficient and thus will not be chosen. Although it is proven that the pile anchor can be installed in deeper waters, it still comes with too many difficulties and thus the pile anchor will not be chosen. The torpedo anchor is patented by Petrobas and thus will not be used in this thesis. This leaves the suction pile anchor as the best candidate for the thesis on the design of multidirectional anchor system for floating offshore wind farms. This thesis is also conducted in cooperation with SPT Offshore which has considerable knowledge on suction piles.

2.4. Multiline anchor concept

Several floating offshore wind turbines with multiple mooring lines all connected to their own anchor currently exist and are being installed at sea. The amount of mooring lines and anchors differ from project to project ranging from three to six lines. When looking at an array of FOWT, which will be the next step in commercializing the FOWT-sector, a decision can be made to connect multiple lines from different FOWT to one anchor but keeping the amount of mooring lines the same. By doing this the amount of anchors and geotechnical site investigations needed for a floating offshore wind farm can be reduced significantly [13].

The geometric design of offshore wind farms is traditionally determined by economic considerations that a directly related to the power production of these FOWT. When multiple wind turbines are in a row the wake effects have to be considered and accounted for when positioning the wind turbines and should also be accounted for when choosing a multiline anchor lay-out. When the distances between turbines have to be increased because of these wake factors the mooring lines that are connected to the anchors also need to increase in length which carries considerable costs. These wake effects will be considered in the base of design and thus for now only the geometries of multiline anchor concepts will be considered and later scaled to the right distance.

The general practice is to use 3 mooring lines per FOWT but when using more mooring lines the reliability of the system increases also with respect to the broken line criterion. Using more lines could also make smaller anchor sizes possible. This will increase the costs because of the increase in the amount of mooring lines but the smaller anchor size will decrease the costs of the anchor.

There are multiple geometries that can be utilised such as the square or the hexagonal unit cells and the

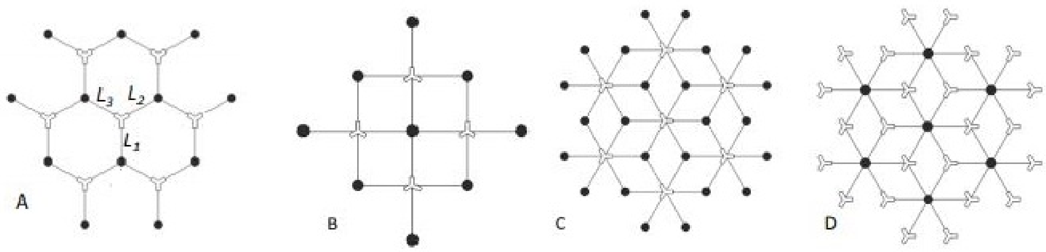


Figure 2.6: Different multiline concepts that are discussed. Courtesy: Casey Fontana [13]

amount of lines per anchor or per FOWT can differ. In a research done by Casey Fontana [13] a few options are given and the are shown in Figure 2.6. The first concept, A, having 3 mooring lines per FOWT and 3 mooring lines per anchor with a hexagonal shape. The second concept, B, using a squared approach with 4 mooring lines per FOWT and 4 mooring lines per anchor. The third concept, C, has 6 mooring lines per FOWT but only 3 mooring lines per anchor. Because of this the efficiency goes down compared to the first two concepts. The last concept has 3 mooring lines per FOWT but 6 mooring lines per anchor.

In another paper by Casey Fontana [15] a comparison is made in the amount of anchors used between three different cases. The three cases looked at are the cases that have 1, 3 or 6 mooring lines connected to each anchor. The reduction in amount of anchors is shown in a graph in Figure 2.7.

This approach to the mooring system, where one anchor shares mooring lines with multiple FOWT does

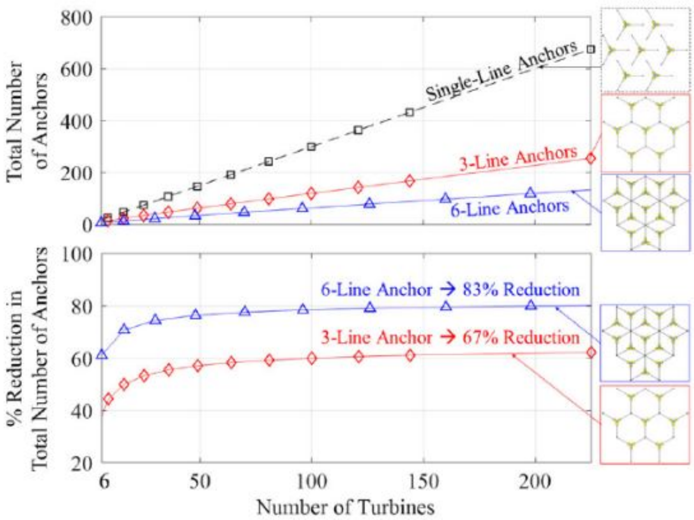


Figure 2.7: Total percentage of the reduction in the amount of anchors needed for a multiline system. Courtesy: Casey Fontana [15]

come with some setbacks. The loads acting on the anchor differ in magnitude and direction depending on where the waves and wind are coming from. When each anchor is only connected to one FOWT the force direction will have one direction in which the net force will work but now this net force vector will change direction. Not every anchor is equipped against these multi-directional loading conditions and thus this should be taken into account when working with a multiline anchor system [13, 15, 16].

2.5. Concluding remarks and discussion of the literature research

This thesis will conduct research on a suction pile multiline anchor system for a floating 15MW semi-submersible wind turbine. The first mooring configuration will be a catenary system. However, it will be compared to a taut system. The multiline system consisting of three mooring lines per anchor and three mooring lines per FOWT will be the most probable system, because it has advantages over a 1-line or a 6-line system. The most important advantage is that it has lower horizontal loads than both the 1-line and 6-line systems. Although, if the broken line criterion destabilizes the system too much, the 6-line system could be reconsidered as a possibility.

The DNV guidelines that will be used are listed in the table below. From these guidelines, multiple load cases are explained that have to be used to calculate the anchor forces. These load cases describe the wind-wave-current (WWC) distributions for different situations. Because this thesis will not be making a representative model of a floating offshore wind turbine to calculate the forces on the anchor, these will have to be taken from literature or calculated by means of scaling.

Table 2.3: DNV guidelines that are consulted and used for the calculations done in this thesis

Code	Title
DNVGL-ST-0119	Floating wind turbine structures
DNVGL-ST-0126	Support structures for wind turbines
DNVGL-ST-0437	Loads and site conditions for wind turbines
DNVGL-OS-E301	Position mooring
DNVGL-OS-E302	Offshore mooring chain
DNVGL-OS-E303	Offshore fibre ropes
DNVGL-OS-E304	Offshore mooring steel wire ropes
DNVGL-RP-0286	Coupled analysis of floating wind turbines
DNVGL-RP-E303	Geotechnical design and installation of suction anchors in clay
DNVGL-SE-0422	Certification of floating wind turbines

In the next stage of the thesis, the Base of Design (BoD), the setup for this thesis project will be further elaborated by setting up the exact to be looked at FOWT, the multiline anchor systems and the soil data. It is likely that more than one soil data set will be chosen, since this provides the opportunity to make a more general and robust design. The suction pile will be designed according to design standards supplied by the company SPT Offshore in compliance with the DNV guidelines.

3

Base Of Design

In this chapter the looked at FOWT-system is the University of Maine VolturnUS-S reference floating offshore wind turbine semi-submersible, which supports the IEA-15-240-RWT turbine with a turbine rating of 15MW with all the main parameters being listed in Table 3.1. The suction pile anchors that are designed in this thesis are the anchors in the middle of the array and the edge anchors will still need to be looked at separately when the whole system is worked out. With the original mooring configuration being a catenary one a comparison has been made with a taut system and its implementation into a multiline anchor system has been researched. Lastly three different soil profiles have been chosen because of their appearance in deep sea waters: normally consolidated clay, slightly consolidated clay and loose sand.

3.1. Floating Offshore Wind Turbine

The chosen floating offshore wind turbine is the University of Maine VolturnUS-S reference floating offshore wind turbine semi-submersible, which supports the IEA-15-240-RWT turbine with a turbine rating of 15MW. All data is taken from the Technical Report published by the University of Maine and the National Renewable Energy Laboratory (NREL) [1]. The reference turbine is depicted in Figure **??** and the relevant main parameters are given in Table 3.1. Because all the forces are setup with a catenary mooring system configured for a depth of 200m. Accordingly this depth is the depth examined in this thesis but in the parametric design subsection in Chapter 5 Detailed design, other water depths and their impact are analysed and discussed. With the fully catenary system being the system of choice for the NREL reference turbine this means that when setting up the multiline forces for a taut system requires some additional factors to be included.

Table 3.1: Relevant main parameters of the 15MW floating semi-submersible 15MW wind turbine. Courtesy: University of Maine [1]

Parameter	**Value**	**Units**
Turbine Rating	15	MW
Hub Height	150	m
Rotor Diameter	240	m
Rated wind-speed	10.59	m/s
Excursion (Length, Width, Height)	90.1, 102.1, 290	m
Water Depth	200	m
Mooring line length	850	m
Fairlead Depth	14	m
Anchor Radial Spacing	837.6	m
Fairlead Radial Spacing	58	m

Figure 3.1: A picture showing the university of Maine reference platform designed to support the IEA-15-240 RWT system definition. Courtesy: University of Maine [1]

3.2. Mooring line configuration

Three different mooring line configurations are considered in this research: single-line, 3-line and 6-line. The overall lay-out of the windfarm array will differ per configurations and they will be shown in each of their respective subsections. The default for the systems will be a 850m long R3 studless catenary chain which they are also using in the NREL document [1]. The diameter of these chains is 185mm which are the biggest catenary lines available at this time.

3.2.1. Single-line anchor system

This is the mooring configuration default: every anchor has one line leading towards it and every semi-submersible has three lines holding it in place. In Figure 3.2 this is shown with an anchor radial spacing taken from the NREL report: 837.60m [1]. This will also be the spacing used for this concept. What should be noted, is that the distance from fairlead to center line/rotation point of the floater is 58m thus the total horizontal distance from fairlead to anchor will be: 837.6m −58m = 779.6m.

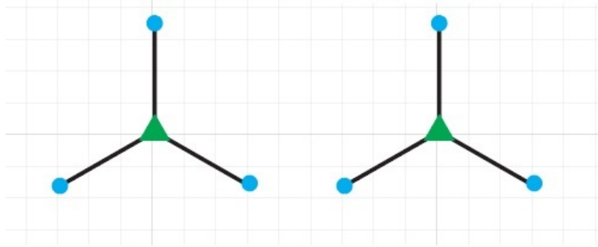


Figure 3.2: The single-line configuration with distances. Courtesy: UMaine and NREL [1]

3.2.2. 3-line anchor systems

There are two different configurations that can be set-up when using a 3-line anchor system. The first one, where the semi-submersible only has three mooring lines, and the second one, where the semi-submersible has six mooring lines. The second option would increase the amount of anchors and mooring lines but also add more redundancy to the system. Both configurations are shown below with the blue round dots being the anchors and the green triangles being the semi-submersibles.
The forcing for the second configuration will change compared to the first one as there will be more mooring lines connected to the semi-submersible and this means that the force distribution will change. To get accurate forces for this configuration a new OPENfast model can be created and the new values for a 6-line mooring system can then be set up.

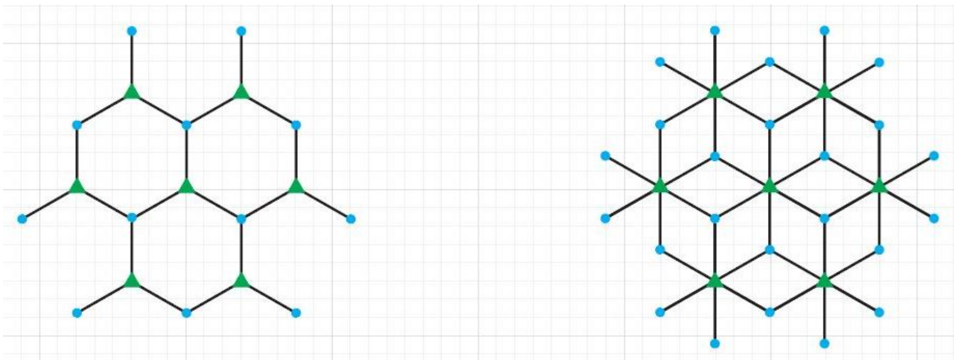


Figure 3.3: The two different 3-line configurations shown that can be set up shown in a grid

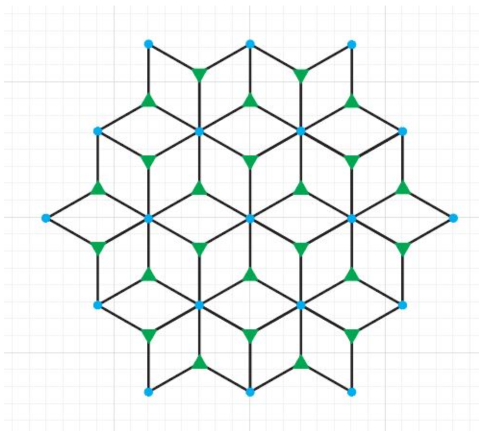


Figure 3.4: The 6-line anchor configuration shown in a grid

3.2.3. 6-line anchor systems

The 6-line anchor system that can be set up is shown in Figure 3.4. It is important to note that there will still be 3-lines attached to each semi-submersible but 6-lines to each anchor. When calculating the forces for this 6-line system, it would be very straightforward if this loading would be twice as big as the 3-line loading. This would mean that the forces for the situation with 1 upwind and 2 downwind lines would be the same as 2 upwind and 1 downwind line. As this is not the case the conclusion can be drawn that the forcing will be different. This is shown graphically in the figure below Figure 3.5.

The advantages of this system are that there is additional redundancy built into the system. When one line

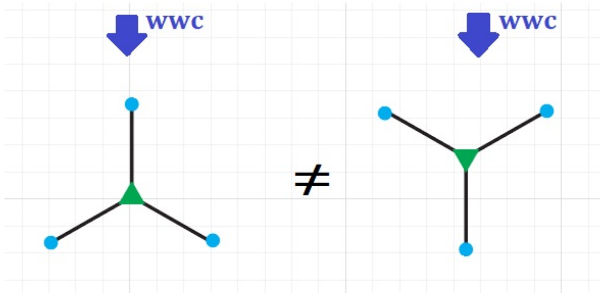


Figure 3.5: Two different situations for the semi-submersible anchor system

breaks the movement of the FOWT would be less than when only working with 3 lines. This is preferable because the direction of the force on the anchors would stay more in-plane with the padeye. The one-line-broken system is also looked at later in this thesis where it is further explained and elaborated.

3.2.4. Edge anchors

There are multiple cases at the edges of the array where there are anchors that have to be designed differently compared to the other 3-line or 6-line anchors that will be used in the center. In the center of the array, the anchors can all be designed on the same loading, however the anchors at the edges can be either single line anchors or 2-line anchors for the 3-line anchor concept. For the 6-line anchor concept there can be 2-line anchors or 3-line anchors. These edge anchors may have the same amount of lines connected to the anchor however, they are connected differently compared to the anchors at the center. The anchor concepts are shown in the figure below.

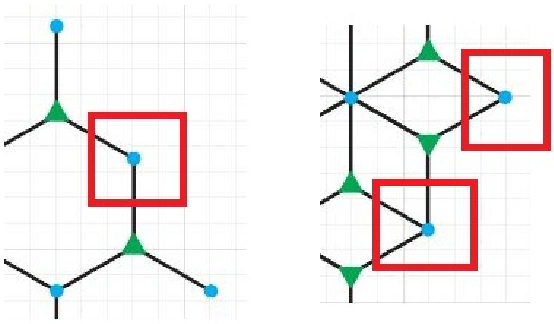


Figure 3.6: Different edge anchors in the different configurations placed in the grids shown in Figure 3.3 and Figure 3.4

3.2.5. Horizontal distances

When using a multiline anchor system, the horizontal distances from turbine to turbine are the same as they are in an array and they are dictated by the wake field a turbine creates. Different studies show different wake field interactions and losses depending on wind speed, on which turbine is looked at and multiple other things.

When working with Jensen's model a wake recovery of 90% requires a distance more than 15D which is a huge distance when the rotor diameter is 240m. This huge distance will not only make the electricity cables very long and expensive but when working with a multiline system, the mooring lines become very long as well. An optimisation study can be done between the wake losses and the increase in costs due to the longer cables but that is left out of this thesis and therefor a set inter turbine distance is chosen of eight times the diameter of the rotor ($8 * D = 8 * 240m = 1920m$). In Figure 3.7 the triangles for the different anchor line systems are shown with A, B, C and D being the floating wind turbines and E and F being the anchors. For the mooring line length a small correction still has to be made where fairlead radial distance still has to be subtracted from this horizontal distance and the catenary shape over the waterdepth has to be added for the chain. For the taut line length the depth and has to be added but the line can be seen as a straight line and the the fairlead spacing also has to be subtracted but this radial spacing is not in line with the mooring line thus the angle changes also.

$$L_{AF} = L_{BF} = \frac{1920/2}{\cos(30)} = 1108.5m$$

$$L_{CE} = L_{DE} = \frac{1920/2}{\cos(60)} = 1920m$$

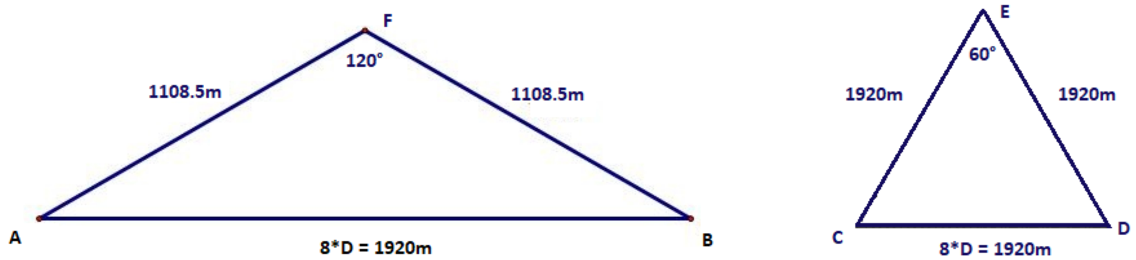


Figure 3.7: Horizontal distances between the centers of rotation of the semi-submersible wind turbines and the center of the suction pile anchor

3.2.6. Taut

When a taut system is used, the angle with the seabed is commonly 45°, which means that the horizontal distance over 200m depth is also 200m. If there is a straight line from the multiline anchor to the FOWT then the angle to the seabed would be $\arctan(\frac{200}{1108.5}) = 10.23°$ for the 3-line and $\arctan(\frac{200}{1920}) = 5.95°$ for the 6-line anchor. These angles are very shallow which would call for a very high pretension. In addition, the lines will be close to the water level for long periods of time, which can be very dangerous. The longer the lines stay close to the sea level, the more opportunity for collisions is created.

If a chain would be connected at the bottom to extend the line, then there would be a $1108.5 - 200 - 58 = 850.5m$ long chain extension for the 3-line anchor and a $1920 - 200 - \sin(60) \cdot 58 = 1669.8m$ long chain extension along the seafloor for the 6-line anchor. In these formulae $58m$ and $58 * sin(60) = 50.23m$ are subtracted because of the position of the fairlead padeye that has a radial spacing of 58m from the center of the semi-submersible floater. This extra chain on the seafloor could be used as reserve capacity for storms and the resistance of the chain along the seafloor could redistribute the higher forces due to the taut system. If the FOWT exploration for 15MW FOWT reaches deeper waters or smaller wind turbines with smaller interspace distances are used, purely taut solutions do become more attractive especially because the mooring lines do seem to have a lower footprint. As a result, the taut solution is examined and the situation is added to the overall equations although it might not be feasible solution when looking at the distances and angles that are present in the different systems.

3.3. Soil profile

The soil profiles that are chosen for the more generalized analysis are the soft clay and dense sand profiles. These were chosen together with experts from SPT Offshore as the soft clay layer is the most represented soil profile in the 200m water depth where the FOWT will be situated. The dense sand layer is chosen as a second profile because it will make a wider pile and a stiffer soil response compared to the soft clay layer. For both soil profiles the DNV guidelines ST-0119 has given tables with the expected values which are shown below. These will be used in the next chapter when the suction anchor sizing will be determined. The clay profiles will still be split up into two different cases: normally consolidated clay with a low undrained shear strength starting value (s_{u0}) and slightly consolidated clay with a higher starting value. A layered soil profile will be the next step in the research and it is considered in this research but not added in the calculations. Multiple soil failures exist that will only occur in layered soils and they must be accounted for before the multiline anchor concepts can be finalized.

Table 3.2: Geotechnical data taken from DNVGL-ST-0119 Floating wind turbine structures

Soil type	Undr. shear strength [kN/m^2]	Subm. unit weight [kN/m^3]	Poisson's ratio	Void ratio
Very soft	<12.5	4-7	0.45	1.0-3.0
Soft	12.5-25	5-8	0.45	0.8-2.5
Firm	25-50	6-11	0.45	0.5-2.0
Stiff	50-100	7-12	0.45	0.4-1.7
Very Stiff	100-200	10-13	0.45	0.3-0.9
Hard	>200	10-13	0.45	0.3-0.9

Table 3.3: Geotechnical parameters for sand taken from DNVGL-ST-0119 Floating wind turbine structure

Soil type	Friction angle	Subm. unit weight	Poisson's ratio	Void ratio
Loose	28-30	8.5-11.0	0.35	0.7-0.9
Medium	30-36	9.0-12.5	0.35	0.5-0.8
Dense	36-41	10.0-13.5	0.35	0.4-0.6

4

Suction anchor concept design

In this chapter the main parameters of the suction anchors for each concept will be calculated using the DNV guidelines and additional literature research. The three different mooring systems that will be evaluated are the 1-line, 3-line and 6-line concepts with each concept also being evaluated in a sand or clay profile. The forces on the anchor are set up using the data set-up by NREL and the University of Maine [1] and the C. Fontana papers [13, 15]. In the NREL report a model is made using the OPENfast software. From this model the mooring line and anchor forces are predicted for the reference turbine. By using the forces from this report and by using the factors set up by the C. Fontana papers we can define the 3-line and 6-line mean and maximum horizontal forces. A suction pile anchor has more bearing capacity when the mooring-anchor connection point is below the mudline. Because of this feature the mooring line attaches to the suction pile anchor at an angle with an inverse catenary shape. Because this inverse catenary shape depends on many different parameters, and because it is a time consuming and not relevant, this procedure it is left out of the scope of this thesis. Instead, a range of three different angles is set-up, resulting in 18 different concepts. Now calculations will be done to set-up the pull-out capacity of a suction anchor. From here the forces and the pull-out capacity can be solved with a VHM-failure envelope. To solve these equations an embedment ratio (h/D) must be chosen. This embedment ratio will change due to piping and ratholing for sand and due to plug-uplift and removal pressures in clay. When these failures are solved a final embedment ratio is defined and the final parameters for the different concepts are set up.

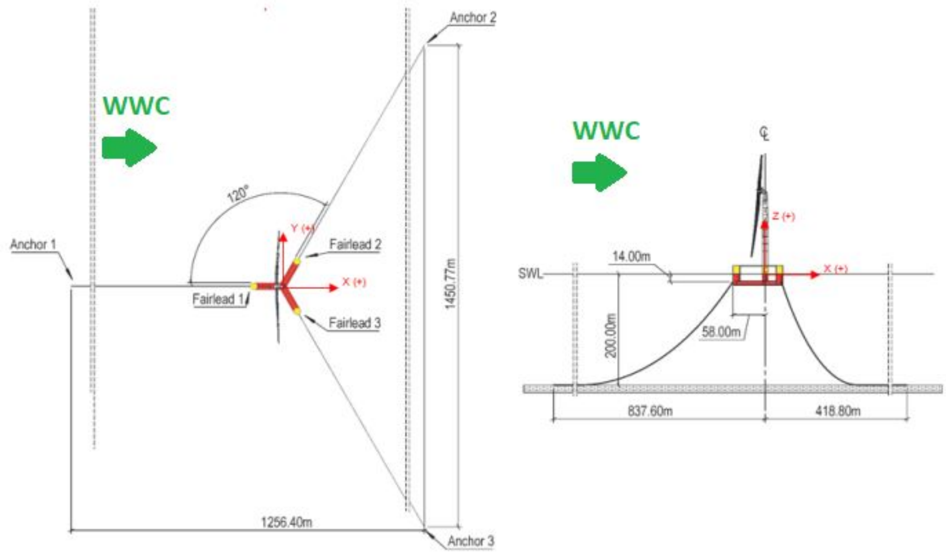


Figure 4.1: Configuration of the original single-line anchoring and mooring set up from the NREL and Umaine 15MW turbine. Courtesy NREL and Umaine [1]

4.1. Anchor forces

The anchor and mooring line forces are setup using a report from the University of Maine and the National Renewable Energy Laboratory (NREL) [1]. Here they used OpenFAST a multi-physics tool for simulating the coupled dynamic response of wind turbines. In their configuration they used three chains as mooring lines and calculated the forces in these mooring lines in six different governing load cases. In the report a graph was published with the different forces they calculated. As reading out graphs by eye is very inaccurate, a plot-digitizer was used where a graph is uploaded, a grid with assigned axis is created and finally points are set-up in the graph corresponding to the desired unknown coordinates. By reverse engineering the graph this way, a better estimate is given of the forces. This is done for Figure A.19 to get the maximum force magnitude values of the three different fairlead and anchor forces. The forces at the fairleads are important because they dictate the size of the anchor chains that are used. The anchor forces will be used to calculate the size of the suction pile anchors that are to be designed. In Table 4.1 the orientation of the anchor lines and their dimensions are shown. In the table below the forces for each load case are shown.

Table 4.1: Anchor forces generated by the plot-digitizer for the different DLCs

	Load cases	**Max[MN]**	**Mean[MN]**		**Load cases**	**Max [MN]**	**Mean [MN]**
Fairlead 1	DLC 1.1	4.74	3.29	**Anchor 1**	DLC 1.1	3.71	2.19
	DLC 1.3	4.82	3.25		DLC 1.3	3.73	2.16
	DLC 1.4	4.26	3.54		DLC 1.4	3.17	2.45
	DLC 1.6	5.69	3.09		DLC 1.6	4.38	2.00
	DLC 6.1	6.29	3.42		DLC 6.1	4.95	2.32
	DLC 6.3	4.72	3.04		DLC 6.3	3.42	1.96
Fairlead 2	DLC 1.1	2.56	2.19	**Anchor 2**	DLC 1.1	1.47	1.12
	DLC 1.3	2.58	2.21		DLC 1.3	1.51	1.13
	DLC 1.4	3.10	2.15		DLC 1.4	2.03	1.08
	DLC 1.6	3.08	2.25		DLC 1.6	1.68	1.19
	DLC 6.1	3.52	2.22		DLC 6.1	2.20	1.15
	DLC 6.3	3.19	2.24		DLC 6.3	2.12	1.18
Fairlead 3	DLC 1.1	2.50	2.15	**Anchor 3**	DLC 1.1	1.43	1.09
	DLC 1.3	2.56	2.15		DLC 1.3	1.51	1.09
	DLC 1.4	3.08	2.15		DLC 1.4	2.03	1.08
	DLC 1.6	2.92	2.21		DLC 1.6	1.64	1.14
	DLC 6.1	3.61	2.25		DLC 6.1	2.22	1.18
	DLC 6.3	3.15	2.30		DLC 6.3	1.97	1.23

4.2. Multiline anchor forces

In this section the multiline anchor forces for the chosen FOWT will be set-up. The force will be a multidirectional force that could be pointing in any direction as elaborated in the literature research. Because there are no simulations run using a multiline system on the 15MW FOWT, the forcing will have to be estimated by means of calculation. Simulations were run by C.Fontana [13, 15] on the National Renewable Energy Laboratory's (NREL) OC4-DeepCwind semi-submersible floating system 5-MW wind turbine and these will serve as a basis for this research.

When trying to use the vector summation to add the different forces together the problem arises that there is no certainty when, which anchor line, has maximum and minimum loading. Without running simulations on the 15MW wind turbine this can not be done. Because of the limited time available and the difficulty of running a OpenFAST simulation, the choice was made not to simulate but use the 5MW FOWT factors taken from literature [13]. Without running simulations to get actual force distribution in the different multiline anchor lines it is difficult to predict if this is correct but because the objective of this thesis is to make a comparison of the different sized anchors it is about getting the right order of magnitude. It is recommended that a follow up study is done to get the actual anchorline forces by using either OPENFAST or any other suitable aero- and hydrodynamic program.

Table 4.2: 5MW semi-submersible loading of the different WWC directions for the single-, 3-line and 6-line systems from the C. Fontana paper [13] [15]

DLC 1.6	0° WWC			30° WWC			60° WWC	
	Single-line	3-line	6-line	Single-line	3-line	6-line	Single-line	3-line
Maximum [kN]	2560	-16%	+20%	2250	-18%	+32%	1610	-16%
Mean [kN]	1238	-33%	+34%	1194	-29%	+40%	923	-17%

Table 4.2 is taken directly from the C. Fontana paper [13]. It shows shows the different factors that will be used to calculate the maximum and mean horizontal multidirectional force on the suction anchors. In the paper multiple load cases are simulated in OpenFAST: DLC 1.2, DLC 1.6 and a Survival Load Case (SLC). Because a Ultimate Limit State (ULS) will be conducted in this thesis the highest reasonable load case was used, DLC 1.6., with the SLC being an unreasonably high load case. In addition different angles from which the wind, wave & current can come from, are found in this research. What should be noted about Table 4.2, is that the 60° WWC case for the 6-line system is the same as the 0° 6-line system because the 6-line system has geometrical symmetry every 60°. Because of this and to avoid confusion it is not shown.

4.2.1. Maximum anchor force

It must be stressed that the loading for the 15MW wind turbine in DLC 1.6 is a lower than the DLC 6.1 case (Table 4.1) and thus the DLC 6.1 loading will be used to calculate the ultimate multiline loading. This is done because when comparing the entire table a trend can be seen that when the load cases get more severe, the difference becomes less between the multiline systems and the single line system. Thus using the DLC 6.1 loading with the DLC 1.6 coefficients can be seen as a conservative approach. Lastly, what can also be observed is that the maximum forces for the anchor lines will be highest for the 0°-case.
By now using Table 4.1 and taking the DLC 1.6 and DLC 6.1 maximum anchor forces of Anchor 1 and multiplying them with the percentages given in Table 4.2 the maximum forces can be setup. An example is given below and all values are given in Table 4.3.

$$F_{max,3-line,DLC1.6} = 4.38[MN] \cdot (1 - 0.16) = 3.68 MN$$
$$F_{max,6-line,DLC1.6} = 4.38[MN] \cdot (1 + 0.20) = 5.25 MN$$

Table 4.3: Maximum anchor forces for the researched 15MW floating offshore wind turbine

T_{max}	**1-line [MN]**	**3-line [MN]**	**6-line [MN]**
DLC 1.6	4.38	3.68	5.25
DLC 6.1	4.95	4.16	5.94

4.2.2. Mean anchor force

An estimate can also be given of the mean forces that will be used for the static analysis. The mean forces pulling on the suction pile should be equal tpo the weight of the suction pile itself. This was determined in consultation with SPT supervisors. If the structural weight is not enough than ballasting is a solution but this will be addressed in Chapter 5 Detailed Design. Because DLC 1.6 case is used to get the maximum forces, the DLC 1.6 and DLC 6.1 case will also be used for the mean forces ($T_m ean$).

Table 4.4: Mean anchor forces of the researched 15MW floating offshore wind turbine

T_{mean}	**1-line [MN]**	**3-line [MN]**	**6-line [MN]**
DLC 1.6	2.00	1.34	2.68
DLC 6.1	2.32	1.55	3.11

The maximum multiline loading will be used to make an Ultimate Limit State (ULS) analysis. In addition, it will be used to define the length and the diameter of the suction caisson anchor. By defining the magnitude of the maximum force for the different multiline anchor concepts, different sized suction caissons can be designed.

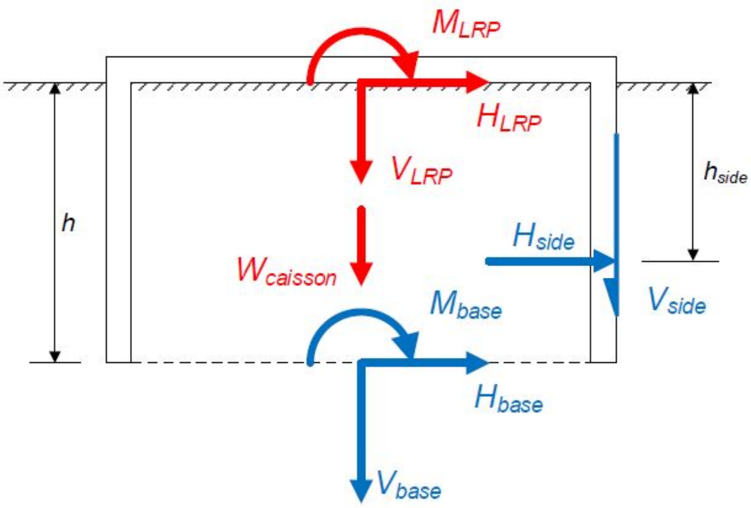


Figure 4.2: Free body diagram of a suction pile

4.3. Forces on a suction pile

A 2D free body diagram of a suction pile is shown in Figure 4.2 with in red the load reference point (LRP) and in blue the resulting forces applied to the soil. The LRP is shown at the top of the pile and is used to simplify the calculations. It is easier to work with a point that is the same in every calculation compared to the center of rotation that depends on the soil and the angle at which the anchor line connects to the suction pile.

When attaching the anchor line to a point below the mudline instead of at the top, the holding capacity of the suction pile is greatly increased [7]. When connecting the pile at the top, a large arm will be created towards the rotation point. For now, the centroid of resistance is estimated to be at: $h_{side} = \frac{2}{3}h$. In reality this point differs for clay and for sand layers and can be calculated exactly but for now this estimation is used in this thesis. When the connection point of the anchor line and the direction of the force are in line with the centroid of resistance then there will be no moment created by the anchor line but only a horizontal and vertical force that can be related directly to the reference point at the top of the pile as can be seen in Figure 4.3. From the free body diagram in Figure 4.2 the following equations can be set up by taking the vertical force equilibrium, horizontal force equilibrium and the moment equilibrium. It is important to be wary of the signs in these equations because there are different capacities for tensile and compression forces. These capacities are calculated in section 3.3 and the signs will be changed accordingly.

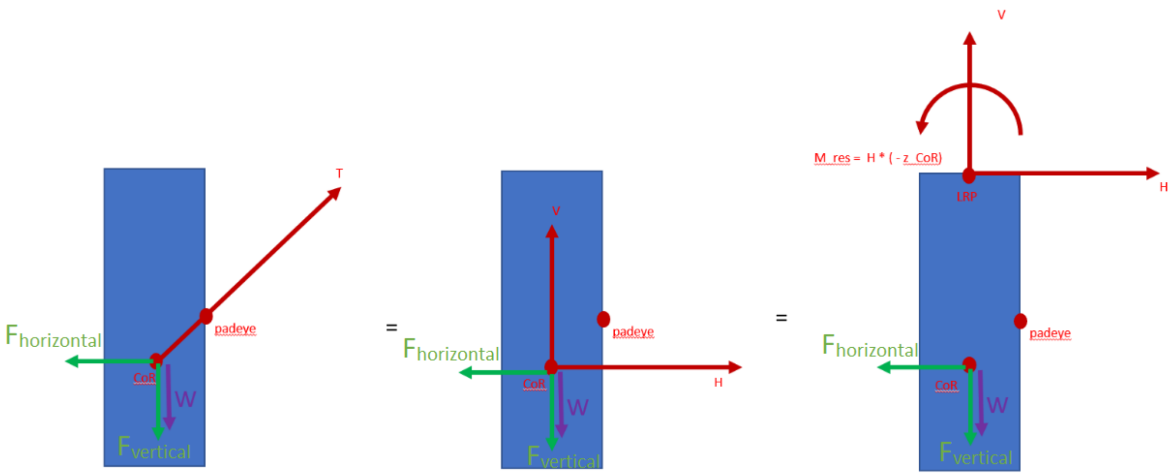


Figure 4.3: Explanation of the load reference point which eliminates the moment in the free body diagram (M_{LRP})

$$V_{LRP} + W_{caisson} = V_{base} + V_{side} \tag{4.1}$$

$$H_{LRP} = H_{base} + H_{side} \tag{4.2}$$

$$M_{LRP} = M_{base} - h_{side} \cdot H_{side} - h \cdot H_{base} \tag{4.3}$$

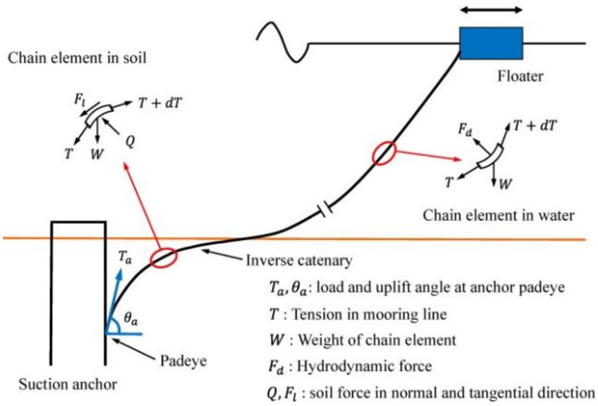


Figure 4.4: Inverse catenary shape due to the connection point beneath the mudline. Courtesy: [36]

4.3.1. Inverse catenary

When an anchor line is connected below the mudline, the shape the line assumes is an inverse catenary shape. Because of this the tension in the anchor line will change slightly due to the friction of the soil around the anchor line. This change is relatively small compared to the loading of the line thus it is assumed to be negligible. This means that the angled force at the padeye is the same magnitude as the horizontal force if connected at the top.

The calculation of the angle are left out of the scope of this thesis and is assumed to be between 25° and 35° for a catenary shape and 45° for a taut system. These values were chosen together in cooperation with SPT Offshore.

4.3.2. Taut conversion

It is important to note that the forces were set up using models where the chain was used to moor the system to the anchor and not a taut line. Based on literature, it can be said that the peak forces on a taut system will be higher and that should added adequately [3]. In Figure 4.5 there is a graph where a taut system for a tetraspar is compared to a catenary system at a depth of 180m. Based on the table it can be concluded that both the mean and the maximum forces for the taut system (Config 1) are higher than the forces experienced by the catenary system. In addition what is also noticed is that the deviation of forces is lower in a taut system than in a catenary system.

To account for this change in mean and maximum force from catenary to taut mooring configuration a factor is set-up using data statistics where both the taut and the catenary mean and max forces are known. From this a factor could be set-up for the 200m depth that was defined earlier. As research implies that the catenary system is a lot more susceptible to depth changes than a taut system, this depth should be kept close to this value [26]. This susceptibility to depth changes is because of the weight of the chain which impacts the line tension. This claim is also substantiated in the data taken from D. Qiao (2012) [31] which is shown in Table 4.5. This data is set up using a semi-submersible floating structure with 12 different mooring lines but the most loaded mooring line is used to compare the taut and catenary forces. From the table can be concluded that the factors between the mean and max for taut divided by catenary forces, decrease the deeper you go. This implies that the catenary forces increase faster than the taut lines. The factor used to multiply the force with is 1.47 for the mean force and 1.35 for the maximum force.

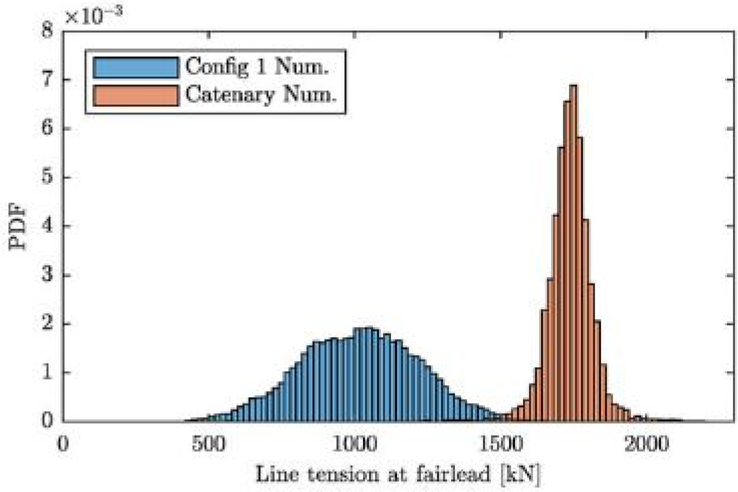


Figure 4.5: Taut vs catenary line tension at fairlead for a 10MW Tetraspar wind turbine at a depth of 180m and a 50-year survival wave condition [3]

Table 4.5: Setting up the catenary to taut factor using literature research [31]

Depth [m]	500	1000	1500
Catenary			
Mean [kN]	2323	3815	4690
Max [kN]	2877	5251	5645
Taut			
Mean [kN]	3409	5126	5691
Max [kN]	3881	6278	7677
Taut/catenary factor			
Mean [-]	1.47	1.34	1.21
Max [-]	1.35	1.20	1.36

4.3.3. Final forces on the suction pile anchor

The angles mentioned earlier are based of the experience from SPT Offshore supervisors and can be used to calculate the horizontal and vertical contribution of the angled force. The maximum forces calculated earlier are now used to give the horizontal and vertical distribution of forces. These are used for the Ultimate Limit State (ULS) calculations that dictate the main parameters of the suction pile.

$$F_H = cos(\theta_a) * T_a \tag{4.4}$$

$$F_V = sin(\theta_A) * T_a * n_{lines} \tag{4.5}$$

Also taken into account is the fact that there are three or six anchor lines that connect to one multiline anchor which add up in vertical direction. Because of this the number of lines (n_{lines}) is added in the equation to get the total vertical force on one anchor.

The final vertical, horizontal and total forces on the suction anchors are shown in Table 4.6. What can be noted is that the total forces on the suction pile anchor are higher in the 3-line case although the horizontal net forces on the anchor were smaller. This is due to the anchor-mooring line connection point being under the mudline.

Table 4.6: Force mean and maximum values for each of the concepts with different angled inverse catenary lines

	1-line	**3-line**	**6-line**		**1-line**	**3-line**	**6-line**
Force maximum values	4.95	4.16	5.94	**Force mean values [MN]**	2.32	1.55	3.11
25 deg							
$F_{H,max}$ [MN]	4.49	3.77	5.38	$F_{H,mean}$ [MN]	2.10	1.41	2.82
$F_{V,max}$ [MN]	2.09	5.27	15.06	$F_{V,mean}$ [MN]	0.98	1.97	7.88
$F_{total,max}$ [MN]	4.95	6.48	15.99	$F_{total,mean}$ [MN]	2.32	2.42	8.37
35 deg							
$F_{H,max}$ [MN]	4.05	3.41	4.86	$F_{H,mean}$ [MN]	1.90	1.27	2.55
$F_{V,max}$ [MN]	2.84	7.15	20.44	$F_{V,mean}$ [MN]	1.33	2.67	10.70
$F_{total,max}$ [MN]	4.95	7.92	21.01	$F_{total,mean}$ [MN]	2.32	2.96	11.00
45 deg							
$F_{H,max}$ [MN]	4.72	3.97	5.66	$F_{H,mean}$ [MN]	2.41	1.61	3.23
$F_{V,max}$ [MN]	4.72	11.90	33.99	$F_{V,mean}$ [MN]	2.41	4.84	19.35
$F_{total,max}$ [MN]	5.88	12.54	34.46	$F_{total,mean}$ [MN]	3.40	5.10	19.62

4.4. Capacity of the suction anchors

In this section the uplift capacity of the suction anchors will be described and calculated. In this analysis linear elastic soil stiffness is used. It should be noted that non-linear stiffness, hardening and cyclic stiffness degradation are not taken into account in these calculations. A complementary geotechnical thesis should be conducted to evaluate these additions to the model and their impact on the overall design. In the following formulas the geotechnical parameters are taken from the DNV-guidelines-ST0119 Floating wind turbine structures and used in the formulas. They are shown in section 3.3. Normally for either drained or undrained cases it is recommended that dedicated testing is undertaken to determine these parameters for each suction pile location. By doing so an optimised suction pile design can be guaranteed with the accurate soil failure description.

Because the diameter and the height of the suction pile are yet to be determined, arbitrary values are used to set up the equations. After setting up the equations and the failure envelopes, a non-linear excel solver is used to solve for the height and diameter of the suction pile. The weight of the suction piles is already defined as the mean vertical forces in Table 4.6. After the height and diameter are calculated installation calculations are done to get the installation pressures and from that the plate thickness of the shell can be calculated. With those thicknesses the true weight of the suction piles can be estimated and additionally required ballast can be defined in Chapter 5 Detailed Design.

4.4.1. Effective foundation Area

If the padeye is not connected in line with the center of rotation and the applied force, a moment is created together with an already existing horizontal and vertical force. When this eccentric load is applied on the circular foundation, only part of the solid beaneath the foundation will carry the load. This area is called the effective area and is shown in Figure B.1 in Appendix B. The formulas used to calculate the effective area are taken from DNVGL-RP-C212 Offshore Soil Mechanics and Geotechnical data and are stated in Appendix B.

Due to the location of the padeye anchor connection point no moment is created. Thuus the effective area is the area under the suction pile: $A_{eff} = A_{total}$. If the location of the padeye is revisited, then the effective area equations will have to be used in Appendix B.

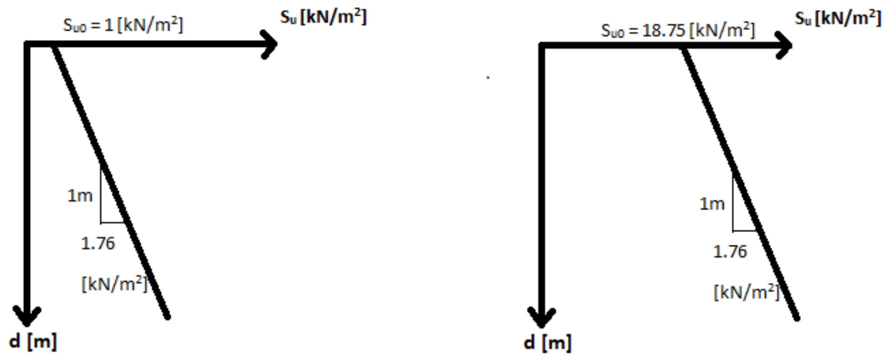


Figure 4.6: Shear strength profile of the two clay profiles: 1) normally consolidated clay 2) slightly overconsolidated clay

4.4.2. Clay layer

For the clay layer the undrained and drained clay equations will both be used. For the chain configuration the larger loads will only be applied over a short period of time with a lower constant force pulling on the anchor. Because the clay is not permeable enough to let the water escape in the time it takes for the load to be applied, undrained loading can be used for the chain system. When assuming a taut solution a larger constant force will be pulling on the suction pile because of the large pretension in the line as explained in **??**. This higher force will drain the clay layer even though the permeability is not high and thus also the drained equations will have to be evaluated.
As explained in section 3.3 there are two different clay soil profiles that will be investigated: normally consolidated clay and overconsolidated clay. In Figure 4.6 the undrained shear strength profile over the depth is shown for both clay profiles.

Undrained soil resistance

In the free body diagram in Figure 4.4 there are terms to be defined that describe the frictional resistance of the soil. The vertical compression resistance (V_{side}) and horizontal resistance (H_{side}) for undrained clay can be calculated using the following formulas taken from the DNV guidelines:

$$H_{side} = Dh\left(\frac{\gamma' h}{2} + 2s_{u1}\right) \tag{4.6}$$

$$V_{side} = \pi D h \alpha s_{u1} \tag{4.7}$$

With:

α = adhesion factor = 0.65
s_{u0} = undrained shear strength at the mudlayer Figure 4.6)
s_{u1} = undrained shear strength average over suction pile depth = $s_{u0} + \frac{\rho h}{2}$
γ' = submerged unit weight = $6.5 kN/m^3$ (Table 3.2)

In these formulas the standard geotechnical data is defined by the DNV guidelines as a range. These data are shown in Table 3.2, when a range is given the average is chosen. The adhesion factor is defined as 0.65, which is also taken from the DNV guidelines and in consultation with SPT supervisors. It should be noted that the adhesion factor is lower during installation as the soil is disturbed and needs time to settle again. When the soil is disturbed, the adhesion factor is defined by the sensitivity, which is further explained in the installation calculations. The undrained shear strength of clay (s_u) is defined as a linear profile with a slope dependent on the submerged weight of the soil as described in DNVGL-RP-C212. The clay layer becomes stronger as the suction anchor reaches deeper. Accordingly, a slender suction anchor is more efficient in a clay layer.
The horizontal capacity of the suction pile at the base of the suction pile is calculated by assuming that the suction anchor, which encases the soil, forms a plug and slides along the soil. The capacity can be calculated using the area of the suction anchor times the undrained shear strength of clay at that depth of the base $s_{u2} = s_{u0} + \rho h$.

$$H_{base} = \frac{\pi D^2}{4} s_{u2} \tag{4.8}$$

$$V_{base} = A_{eff} \cdot \left(F \cdot \left(5.14 \cdot s_{u0} + \frac{k \cdot b_{eff}}{4} \right) \cdot (1 + s_{ca} + d_{ca} - i_{ca}) + p'_0 \right) \tag{4.9}$$

With:

F = correction factor for smooth footings from Figure 4.7
k = rate of increase with depth of undrained shear strength
s_{ca} = shape factor taken from Figure 4.8
d_{ca} = depth factor
i_{ca} = load inclination factor Equation 4.10
p'_0 = overburden pressure = $\gamma' \cdot h = \gamma_{subm} \cdot h$

$$i_{ca} = 0.5 - 0.5\sqrt{1 - \frac{H_{base}}{A_{eff} \cdot s_{u0}}} \tag{4.10}$$

In the equation for the shape factor (s_{ca}), the shape factor for circular foundations (s_{cv}) is defined in Figure 4.8. This graph is set-up using the data from Table 5-1 from DNVGL-C212.

$$s_{ca} = s_{cv} \cdot (1 - 2i_{ca}) \cdot \frac{b_{eff}}{l_{eff}} \tag{4.11}$$

$$d_{ca} = 0.3 \frac{s_{u1}}{s_{u2,DNV}} \cdot \arctan\left(\frac{D}{b_{eff}}\right) \tag{4.12}$$

$$s_{u2,DNV} = \frac{F \cdot \left(5.14 \cdot s_{u0} + \frac{k \cdot b_{eff}}{4}\right)}{5.14} \tag{4.13}$$

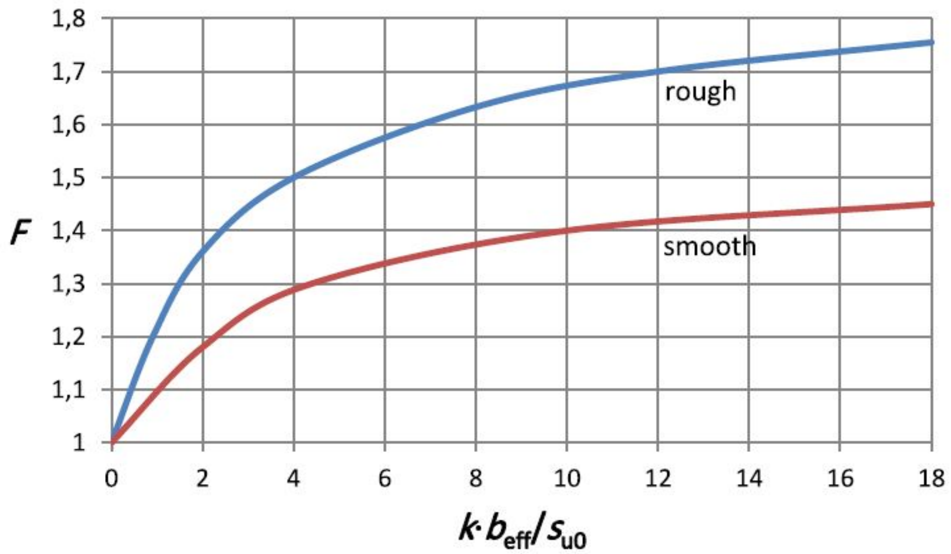


Figure 4.7: Correction factor for rough and smooth footing taken from DNVGL-RP-C212

Drained soil resistance

When working with a taut mooring configuration, a high pretension will be on the lines connected to the anchor. This force will be constant and will cause the clay to drain. When the clay is drained, the forces on the tips of the pile will be negligible compared to the frictional forces on the side of the suction pile ($V_{base} = H_{base} = 0$). In other words: the plug on the inside will not resist together with the suction pile concluding in twice the cohesive resistance on the side of the suction pile. Once on the outside of the pile and the second on the inside of the pile:

$$V_{total,drained} = 2 \cdot V_{side} = 2 \cdot \pi D H \alpha s_{u1} \tag{4.14}$$

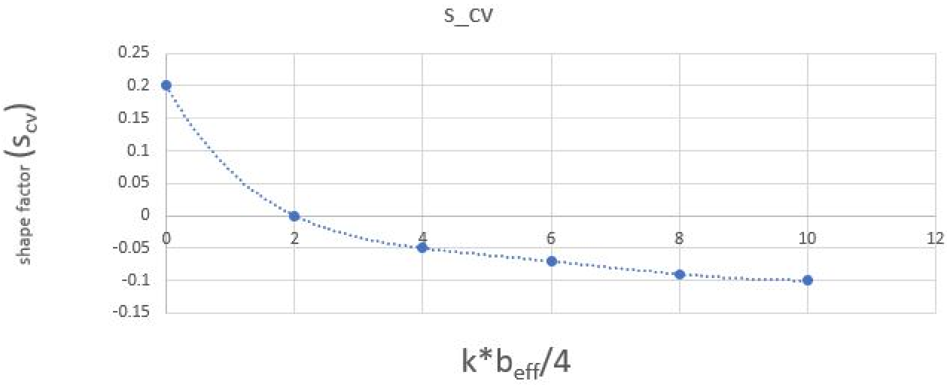


Figure 4.8: Shape factor for circular foundations (s_{cv}) taken from DNVGL-RP-C212

Because the horizontal resistance at the base of the suction pile is assumed to be negligible, only the horizontal resistance at the side of the suction pile has to be calculated. This is done with the same formula as the horizontal resistance of the undrained clay.

$$H_{total,drained} = H_{side} \tag{4.15}$$

Reverse end bearing capacity

The formulas used up to now can be used to calculate the compression forces a suction pile can resist. However, the suction anchor is loaded in tension. The soil failure that will transpire is a reverse end bearing failure and to calculate this a reverse end bearing, a capacity factor is implemented to find the tensile maximum vertical resistance. This factor is an engineering value and chosen to be 80% compared to the compression maximum vertical resistance ($C_{tensile}$ = 0.8) [28]. More difficult and time consuming ways of describing the reverse end bearing maximum force are possible but evaluated to be undue for the scope of this thesis. In the equations below it is shown how this engineering value is added to the equations.

$$V_{max,clay} = V_{LRP,tension} = (V_{base} + V_{side}) \cdot C_{tensile} + W_{caisson} \tag{4.16}$$

$$H_{max,clay} = H_{LRP} \tag{4.17}$$

4.4.3. Sand layer

For the sand layer the drained analysis is used instead of undrained analysis as on one hand sand drains a lot quicker than clay, but on the other hand there are only partially correct and quite complicated models. Furthermore, undrained sand has a higher resistance than drained sand and thus this using the drained model is a conservative approach and is thus preferred. What is described in the vertical load capacity in compression is the friction resistance on the outside and the inside of the suction caisson and can be estimated as:

$$V_{side} = 2 * \pi D h \frac{\gamma' h}{2} K_0 \tan(\delta) \tag{4.18}$$

With:

φ = friction angle = 30 deg
δ = external steel - soil friction angle = $\varphi - 5deg$ = 25 deg
γ' = submerged weight‘= 9.75 kN/m^2 (Table 3.3)
K_0 = lateral earth pressure at rest = $1 - \sin(\varphi)$ = 0.5

What can be noted is that this formula is twice the frictional resistance of the soil, once on the outside of the wall and once on the inside of the wall which is the same as the drained analysis for clay. The horizontal and vertical stress relation, also called the lateral earth pressure at rest (K_0) is defined by Jaky's formula (1944). The external steel - soil friction angle (δ) is defined in consultation with a geotechnical advisor from SPT Offshore. The horizontal capacity on the side of the suction pile in sand can be estimated as:

$$H_{side} = \frac{\gamma' h^2 D}{2} \cdot (K_p - K_a) \tag{4.19}$$

Both the horizontal and vertical load application point may be estimated at $h_{side} = \frac{2h}{3}$. The active and passive earth pressure coefficients, K_p and K_a, are defined as:

$$K_p = \frac{1}{K_a} = \frac{1+\sin(\varphi)}{1-\sin(\varphi)} \tag{4.20}$$

The vertical soil resistance in tension at the base of the suction pile in sand is really small and thus assumed to be zero ($V_{base} = 0$). The horizontal resistance at the base of the suction pile is defined as part of the vertical resistance: $H_{base} = V_{base} \cdot \tan(\varphi)$. Because the vertical tip resistance is zero the same can be said for the horizontal tip resistance. Furthermore, there will always be a gap between the plug and the topplate of the suction pile due to erosion and plug settlement [25]. This means that there is no contribution in bearing capacity of the suction pile. Now the the maximum horizontal- (H_{LRP}) and vertical resistance (V_{LRP}) for the sand layer can be evaluated:

$$H_{max,sand} = H_{LRP} = H_{side} \tag{4.21}$$

$$V_{max,sand} = V_{LRP} = V_{side} \tag{4.22}$$

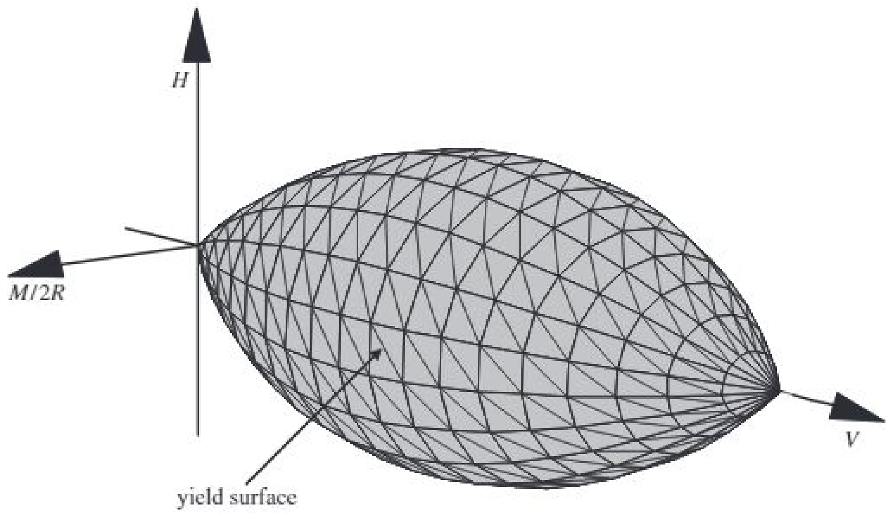


Figure 4.9: Conceptual 3D depiction of a VHM-envelope/yield of a flat footing on sand. Courtesy: Byrne (2004) [6]

4.4.4. Combined vertical and horizontal loading

The most advanced models for analysing combined loading in suction anchors take into account strength anisotropy, loading rate effects, cyclic degradation effects, tilt, misorientation and coupling between vertical and horizontal resistance components. Furthermore, you can also add 3D effects, set-up effects at the interface between the wall and the clay layers and also vertical cracks that can appear on the active side of the soil. Most of these are not in the scope of this thesis but these are factors that can be used in more advanced models. The other factors should adequately be corrected with a safety factor that is taken from the DNV-guidelines and is defined in Table 4.7.

What will be evaluated are the couple effects between moment, vertical and horizontal translation modes: VHM failure envelopes. Conceptual VHM envelopes for shallow skirted foundations under drained and undrained loading are shown in Figure 4.10 and a 3D image is shown in Figure 4.9. There is extensive literature behind these methods, which involve both drained and undrained loading, surface foundations and embedded foundations and different soil profiles. In this literature computational data together with experimental data will be used to define the failure envelopes.

The VH-envelope is defined as critical and thus will be evaluated. This envelope is critical because the moment in the suction pile will be minimised and thus close to zero. If this changes the MH-envelope should be set-up as well and a 3D VHM-envelope should be set-up and analysed.

The formulas used to describe the VH-envelope of soft clay are taken from Kay & Palix (2010, 2011, 2015) [22]

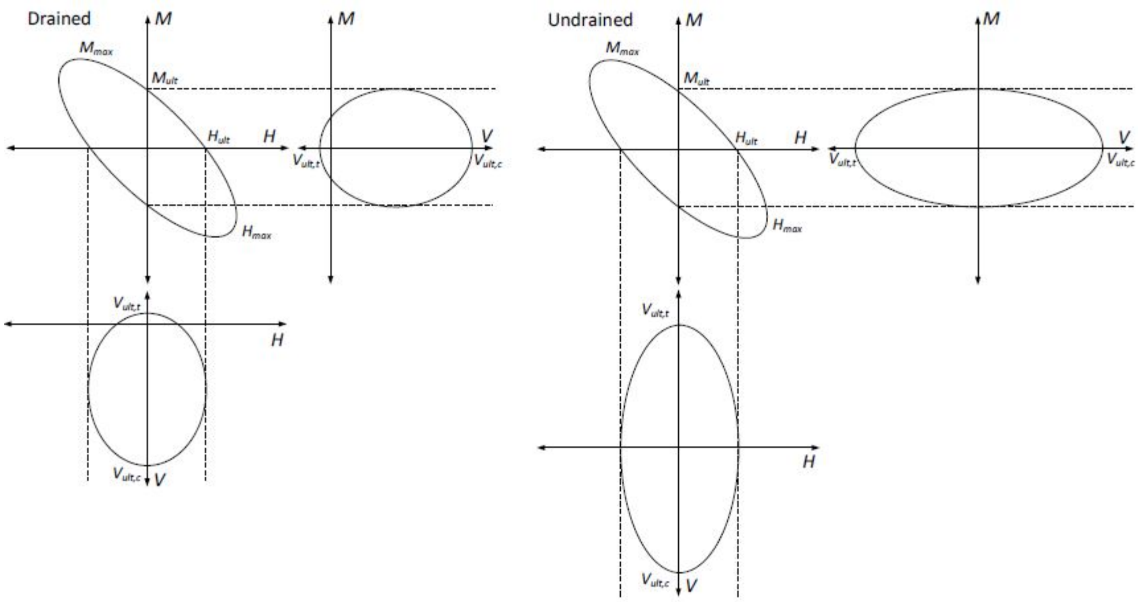


Figure 4.10: VHM failure envelopes for conceptual shallow skirted foundations under drained and undrained loading

[23] [30] and the VH-envelopes for sand are taken from the paper by Laszlo Arany & S. Bhattacharya (2018) [2]. This formula describes an elliptic surface and can be used for both the sand and the clay layers although the reduction factors (a_{VH} & b_{VH}) will differ for both situations. which is further explained in the next section.

$$\left(\left|\frac{H_{max,V}}{H_{max}}\right|\right)^{a_{VH}} + \left(\left|\frac{V}{V_{max}}\right|\right)^{b_{VH}} = 1 \tag{4.23}$$

VH-envelope for clay

In the papers mentioned before the failure envelopes are worked out by means of ±5500 quasi 3D finite element HARMONY runs for the clay data. The reduction factors, a_{VH} & b_{VH}, are smooth functions reliant on the h/D-ratio and the analytical vertical eccentricity of the undrained shear strength of the clay over the height of the suction pile ($e_{z,su}/h$). This vertical eccentricity is shown in Figure 4.11 for two different situations, constant and normally consolidated clay. Because the soil profile chosen for this thesis has both a constant shear strength at the seafloor and a linear increasing strength the lower you go, a combination of these different reduction factors and ellipses has to be sought for. For both the normally consolidated case and the constant case two different reduction factors will be defined. Both will then be combined by means of linear interpolation between the values and this new reduction factor will be used to set-up the final ellipse. For both cases the different reduction factors are defined as:

for $e_{z,su}/h = 1/2$:

$$a_{VH,C} = -\frac{9}{8} + \frac{5h}{D} \qquad b_{HV,C} = 53/8 - \frac{11h}{4D} : h/D < 1.25$$

$$a_{VH,C} = 4.5 + \frac{h}{2D} \qquad b_{HV,C} = 3.5 - \frac{h}{4D} : h/D \geq 1.25$$

for $e_{z,su}/h = 2/3$:

$$a_{VH,NC} = \frac{7}{8} + \frac{3h}{4D} \qquad b_{HV,NC} = 5.5 - \frac{h}{D} : h/D < 1.5$$

$$a_{VH,NC} = 0.5 + \frac{h}{D} \qquad b_{HV,NC} = 4.5 - \frac{h}{3D} : h/D \geq 1.5$$

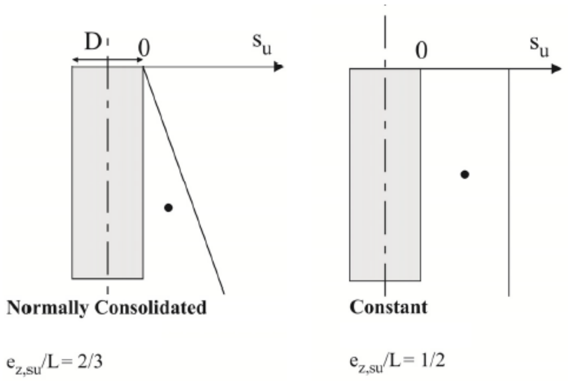


Figure 4.11: Normally consolidated and constant clay layer depiction of the undrained shear strength over the depth. Courtesy: Kay & Palix (2010, 2011, 2015) [22] [23] [30]

To define a combined VH-envelope the following factors are defined to interpolate between the two different values of a_{VH} and b_{VH}. These new values will then be used to set-up the VH-ellipse that defines the failure plain with no external moment applied $M_{LRP} = 0$.

$$C_C = \frac{A_{constant}}{A_{total}} = \frac{s_{u0}}{s_{u0} + (s_{u2} - s_{u0}) * 0.5} \tag{4.24}$$

$$C_{NC} = \frac{A_{consolidated}}{A_{total}} = \frac{(s_{u2} - s_{u0}) * 0.5}{s_{u0} + (s_{u2} - s_{u0}) * 0.5} \tag{4.25}$$

$$a_{VH,final} = a_{VH,C} * C_C + a_{VH,NC} * C_{NC} \tag{4.26}$$

$$b_{VH,final} = b_{VH,C} * C_C + b_{VH,NC} * C_{NC} \tag{4.27}$$

By now using Equation 4.23 and the new defined a_{VH} and b_{VH} the ellipse can be set-up for both the normally consolidated case and the constant case together:

$$\left(\left|\frac{H_{max,V}}{H_{max}}\right|\right)^{a_{VH,final}} + \left(\left|\frac{V}{V_{max}}\right|\right)^{b_{VH,final}} = 1 \tag{4.28}$$

With:

$H_{max,V} = F_{H,max} * \gamma_f$ from Table 4.6
$V = F_{V,max} * \gamma_f$ from Table 4.6
γ_f = load factor provided by DNVGL-ST-0119 Floating wind turbine structure Table 4.7 = 1.35
$H_{max} = H_{max,clay}$ Dependent on the height (h) and the diameter (D) of the suction pile
$V_{max} = V_{max,clay}$ Dependent on the height (h) and the diameter (D) of the suction pile

Table 4.7: Partial safety factor for floating offshore wind turbines taken from DNVGL-ST-0119 Floating offshore wind turbine structure Table 4-2

Functional and environmental loads					**Permanent loads**		
ULS		**FLS**	**ALS**	**SLS**	**ULS**		**FLS, ALS, SLS**
Normal	Abnormal				Favourable	Unfavourable	
N 1.35	A 1.1	F 1.0	F 1.0	F 1.0	0.9	1.1	1.0

VH-envelope for sand

For the sand layer the same formula is used as the one for clay in Equation 4.23 and the following correction factors are taken from a paper by Laszlo Arany & S. Bhattacharya (2018) [2]:

$$a_{VH} = \frac{h}{D} + 0.5$$

$$b_{VH} = \frac{h}{3D} + 4.5$$

4.5. First parameter estimation

Before being able to solve these ellipse equations the height over diameter ratio, also the embedment ratio = h/D needs to be determined. Otherwise there will be a linear solution to the problem and thus there will not be one optimal solution. Another way of solving the problem would be defining the lowest costs of the suction pile or solving for the lowest amount of steel used.

The embedment ratio for clay is chosen in discussion with the geotechnical expert from SPT Offshore and the first estimate of the embedment ratio is 5. From experience these embedment ratios will yield appropriately slender suction piles that are more efficient than wider piles. This is because the strength of the clay layer increases linearly with depth. A problem that arises with slender suction piles is that with higher embedment ratios the installation pressure might surpass critical values. These critical values will be calculated in the installation- and removal-phase calculations in the next sections. If problems are pinpointed in these calculations other embedment ratios may be chosen. In the paper by Houlsby en Byrne (2005a) the ratio of 5 is also chosen as the highest embedment ratio[18]. What can be noted is that the piles in the normally consolidated clay (NC) are bigger than the slightly overconsolidated (OC) case. This was expected because the strength of the slightly OC profile has a stronger strength profile from the moment the suction anchor is lowered into the seabed.

For the sand profile an embedment ratio of 1.5 is chosen which is wider than in the clay layer. This is because the resistance of the suction pile in a sand layer is purely defined by the frictional resistance of the suction pile which does not increase the deeper you go. therefor it is more efficient to increase the frictional resistance by increasing the diameter rather than the height of the suction pile.

Table 4.8: First estimation of the height and diameter of each suction pile anchor needed for each of the concepts with different angled inverse catenary lines

		Clay OC			**Clay NC**			**Sand**		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	h [m]	15.88	16.56	22.90	18.25	20.69	27.73	9.28	12.23	16.36
	D [m]	3.18	3.31	4.58	3.65	4.14	5.55	6.19	8.15	10.90
35°	h [m]	15.44	18.21	25.79	17.97	22.87	29.08	9.89	13.49	18.08
	D [m]	3.09	3.64	5.16	3.59	4.57	6.46	6.59	8.99	12.05
45°	h [m]	16.93	21.96	30.71	18.73	26.79	35.38	11.37	15.78	21.01
	D [m]	3.39	4.39	6.14	3.75	5.36	7.08	7.58	10.52	14.00

4.6. Installation calculations

The design of the in-service performance is not the only criteria the suction pile will have to be designed for, the installation phase is equally as important. Some aspects will be designed using the DNV guidelines and others will be taken from the API documentation. The entire installation process should be treated as a managed process in which expected performance is predicted. During the suction pile installation there are 6 different stages that can be distinguished:

1. Initial crane lift and overboarding
2. Lowering through splash zone
3. Lowering through the water column
4. Touch-down
5. Self-Weight Penetration (SWP)
6. Suction penetration to target depth

The first four stages do not dictate the suction pile parameters but they will have to be managed carefully as to not damage the suction pile in any way. In this thesis the penetration resistance and from that the self-weight penetration, required underpressure for suction penetration and the problems that arise from suction penetration will be looked at. These problems include critical underpressure, cavitation, buckling and different soil failures.

4.6.1. Penetration resistance

First the penetration resistance over the height of the suction pile will be evaluated for both the clay and the sand profiles. For the clay profile the guidelines provided by DNV in the document: "DNV-RP-E303 Geotechnical design and installation of suction anchors in clay", and Houlsby and Byrne, (2005a) will be used. For the sand profile a simplified model by Houlsby and Byrne (2005b) [19] will be used. The basic equation that will be used in both the sand and clay profiles is as following:

$$V + s \cdot A_{caisson} = R_{inside} + R_{outside} + R_{tip} \tag{4.29}$$

With:
V = effective vertical load (accounting for buoyancy
s = suction applied during installation/underpressure
R = resistance
A = area

Clay layer
The equation from Equation 4.29 will be updated for the clay layer:

$$V + s\left(\frac{\pi D_o^2}{4}\right) = \alpha_o \pi D_o d s_{u1} + \alpha_i \pi D_i d s_{u1} + \left(\gamma_s d + N_c s_{u2}\right)(\pi D t) \tag{4.30}$$

Filling in all the different parameters and making it a function of the depth of the suction pile "d" the equation becomes:

$$V + s\left(\frac{\pi D_0^2}{4}\right) = \frac{\rho h^2}{2}\left(\alpha_o \pi D_o + \alpha_i \pi D_i\right) + h\left(s_{u0} \cdot (\alpha_o \pi D_o + \alpha_i \pi D_i)\gamma_s \pi D t + \pi \rho D t N_c\right) + \pi D t N_c s_{u0} \tag{4.31}$$

In this formula, the amount of suction is already included with the term "s". During the self-weight penetration phase this term will be equal to zero. The subscript "o" is for the outer area of the suction pile and the subscript "i" is for the inner surface area and the thickness that will be used is defined in discussion with SPT Offshore at an estimate value of: $t = D/250$. Additionally when installing a suction pile in clay the adhesion factor will change from the first defined 0.65 to another value that is defined by the clay sensitivity ($\alpha = \frac{1}{S_f}$). Here the sensitivity is chosen at 2. This is because the clay is disturbed whilst installing the suction pile and after some settling time the adhesion factor will again increase to 0.65.

Sand layer
The equation from Equation 4.29 will be updated for the sand layer:

$$V + s\left(\frac{\pi D_0^2}{4}\right) = \frac{\gamma_s h^2}{2}(K_0 \tan(\delta))_o(\pi D_o) + \frac{\gamma_s h^2}{2}(K_0 \tan(\delta))_i(\pi D_i) + \left(\gamma_s h N_q + \gamma_s \frac{t}{2} N_{\gamma_s}\right)(\pi D t) \tag{4.32}$$

With:
h = height of the suction pile
N_q = bearing capacity factor (overburden) = $\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \cdot e^{\pi \tan(\phi)} = 18.4$
N_γ = bearing capacity factor (self-weight) = $1.5 \cdot \left(N_q - 1\right)\tan(\phi) = 15.1$

This equation underestimates the force and suction required for full penetration but will be used for this thesis as a indication. No account is taken of the enhancement of vertical stress close to the pile due to the frictional forces further up the caisson. In the paper by Houlsby & Byrne (2005b) [19] these are added by 1) assuming that the vertical effective stress is constant across each section of the suction pile (inside and outside) 2) that by creating suction, flow occurs from outside the suction pile, into the suction pile. This flow affects the penetration resistance and is added in the equation below.

$$V + s \cdot \left(\frac{\pi D_i^2}{4}\right) = \left(\gamma_s + \frac{as}{h}\right) \cdot Z_o^2 \left(\exp(h/Z_o) - 1 - h/Z_o\right) \cdot K\tan(\delta)_o \pi D_o$$
$$+ \left(\gamma_s - \frac{(1-a)s}{h}\right) \cdot Z_i^2 \left(\exp(h/Z_i) - 1 - h/Z_i\right) \cdot K\tan(\delta)_i \pi D_i$$
$$+ \left[\left(\gamma_s - \frac{(1-a)s}{h}\right) Z_i \left(\exp(h/Z_i) - 1\right) N_q + \gamma_s t N_\gamma\right] \pi D t \quad (4.33)$$

With:

a = ratio of excess pore pressure at tip of caisson skirt to beneath caisson top plate
Z = parameter controlling stress enhancement for installation in sand

The factor "a" determines the fraction of the suction transmitted to the caisson tip and is itself a function of the caisson penetration and of assumptions made about the soil permeability. For very shallow caisson penetrations in soil of uniform permeability this factor would be 0.5 and reducing to 0.15 for h/D = 1. The factor can be modified to account for increased permeability within the caisson due to soil loosening as the installation process proceeds and suction is applied, loosening the soil. In the paper Houlsby and Byrne (2005b) [19], a graph describing "a", can be found where different approximate fits are set-up by means of experimentation.
The variable "Z" with underscore "i" and "o", for inner and outer, accounts for the stress enhancement. It depends on the area of soil over which the friction forces are distributed. In the formulas below where this variable "Z" is described the assumption is made that the internal friction is carried uniformly across the soil plug and the factor "m" is described as 1.5. Furthermore, if internal stiffeners or external pieces are fitted on the suction piles, they will have to be added into these variables.

$$Z_i = \frac{D_i}{4(K\tan(\delta))_i} \quad (4.34)$$

$$Z_o = \frac{D_o(m^2-1)}{4(K\tan(\delta))_o} \quad (4.35)$$

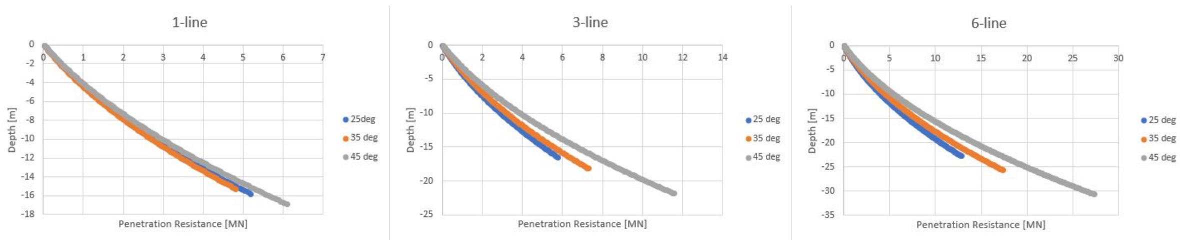


Figure 4.12: Penetration resistance of the OC clay profile over the depth for different multiline systems

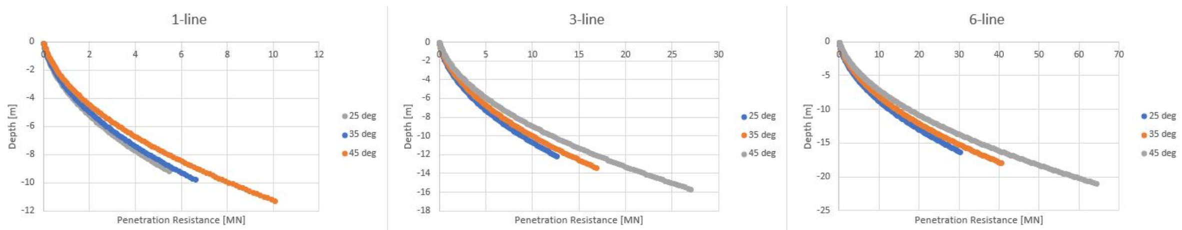


Figure 4.13: Penetration resistance of the sand profile over the depth for different multiline systems

What can be noted from these graphs is that with the increase in inverse catenary angle, bigger suction piles with more penetration resistance need to be used to compensate for the additional vertical pull-out force generated by the increase of the inverse catenary angle. Furthermore what can be seen is that the 45 degrees taut solution will have a substantial bigger anchor with more penetration resistance.

4.6.2. Self-weight penetration

During the self-weight penetration phase it is essential that the crane is lowered to the seafloor slowly and in a controlled manner. This is done to allow for a slow penetration into the seabed and a certain degree of control is assured in case of any sudden reduction in resistance or tilt development. Furthermore, the suction caisson should be well vented during the self-weight penetration phase to allow for a minimum build up of over-pressure, securing optimal self-weight penetration with minimum risk of piping or ratholing which are further explained in a later section. By monitoring all the parameters that are of influence in this procedure, an intact and working seal between caisson and ground can be created for the next suction-assisted phase. The following should be monitored:

1. Crane load (vertical load on caisson)
2. Vertical penetration
3. Tilt
4. Overpressure within the caisson (internal pressure minus external pressure)

The self-weight penetration phase is an essential step in the installation process and due to it a closed seal will form at the bottom of the suction pile. This seal allows for the possibility of a pressure difference along the top plate. This pressure difference is applied by pumping out the water from the suction caisson and thus installing the suction pile to the final depth. This required underpressure will be calculated in the next subsection.
During the self-weight penetration phase the installation force equals the submerged weight of the suction pile. Furthermore, the suction applied is zero in Equation 4.30 ($s = 0$). The penetration will continue until the installation force and the soil resistance have reached an equilibrium:

$$W_{submerged} = R_{inside} + R_{outside} + R_{tip} \tag{4.36}$$

By now using Equation 4.31 and Equation 4.32 and substituting the height of the suction pile "h", with the selfweight penetration depth "d_{pen}" the equation can be solved for this. The equation must be equal to the weight of the suction pile and this will give the penetration depth.

4.6.3. Suction-assisted penetration

Using Equation 4.31 for the clay profile and Equation 4.32 for the sand profile and subtracting the submerged weight of the suction pile it can be solved for the suction (s). This will be the required underpressure that will have to be created to fully install the suction pile to the required depth and this suction is shown in Table 4.9. Other critical components in the suction assisted penetration are:

1. Pump capacity/required underpressure
2. Cavitation
3. Structural failure due to buckling
4. Soil failure

The amount of water that will have to be displaced from inside the suction pile to the outside to create a pressure difference will be the water inside the cylinder. Because clay is not very permeable the volume of the water on the inside of the cylinder will be all. However, sand is permeable and a flow from outside, through the plug is created. This is described by the the seepage low rate (q) with its equation in Equation 4.37 where uniform excess pore pressure across the base of the suction pile is assumed. The equation can be modified to account for increased permeability within the caisson due to soil plug loosening. By knowing the amount of water that has to be displaced, the size of the pumps and the pipework can be estimated.

$$q = \frac{kDs}{\gamma_w} \frac{(1-a)\pi}{\frac{4h}{D}} \tag{4.37}$$

When the absolute pressure of the water anywhere in the caisson is equal to the vapour pressure of water (<2kPa), then the water will cavitate. Cavitation is a problem in shallower waters where there is no large water column adding to the absolute pressure and thus it will not be a problem in the formulated boundaries. A safety margin of 0.8 is used in Equation 4.38.

$$p_{abs,min} = p_a * 0.8 + \gamma_w * h_w - s < 2kPa \tag{4.38}$$

Table 4.9: Penetration resistance, penetration depth and required underpressure of the first parameters estimation

		Clay OC			Clay NC			Sand		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	R_{pen} [MN]	5.22	5.78	12.91	3.60	5.22	12.39	5.56	12.71	30.39
	d_{pen} [m]	4.27	7.39	16.34	9.18	12.43	21.92	3.42	4.16	7.60
	s [bar]	5.37	4.44	3.07	2.52	2.42	1.88	1.53	2.07	2.42
35°	R_{pen} [MN]	4.87	7.29	17.43	3.44	7.00	15.83	6.72	17.06	41.06
	d_{pen} [m]	5.68	8.72	18.58	10.89	13.83	23.68	3.91	4.62	8.43
	s [bar]	4.75	4.45	3.23	2.09	2.64	1.57	1.59	2.27	2.67
45°	R_{pen} [MN]	6.10	11.61	27.30	3.88	11.18	25.48	10.20	27.30	64.38
	d_{pen} [m]	8.51	11.85	24.56	14.56	17.33	30.64	44.99	5.83	10.65
	s [bar]	4.15	4.49	2.69	1.35	2.82	1.56	1.74	2.59	2.94

4.6.4. Structural failure

The structural integrity of both the top plate and the shell should be verified for the design underpressure of the system. A shell structure like the suction pile is susceptible to buckling. The critical underpressure is dependent upon the skirt strength, thickness and curvature and the effective buckling length of the cylinder. The formulas are taken from guidance documents such as Buckling Strength of Shells DNV-RP-C202:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{L}\right)^2 \tag{4.39}$$

With:

- f_e = distributed force on the suction pile = suction = s
- E = Young's modulus = 210 GPa
- ν = Poisson's ratio = 0.3
- t = thickness of the suction pile
- L = unembedded length
- C = reduced buckling coefficient

The reduced buckling coefficient "C" may be calculated as:

$$C = \Psi\sqrt{1+\left(\frac{\rho\varepsilon}{\Psi}\right)^2} \tag{4.40}$$

In this equation the ρ, Ψ and ε, are defined for different loadcases and during the installation calculations these loadcases will be due to hydrostatic pressure, or underpressure. For this particular load case the following coefficients can be defined taken from the Buckling Strength of Shells DNV-RP-C202:

$$\Psi = 2$$

$$\rho = 0.6$$

$$\varepsilon = 1.04\sqrt{\frac{L^2}{rt}\sqrt{1-\nu^2}} \tag{4.41}$$

In Figure 4.14 an arbitrary situation is shown of the suction pile at some point during the installation process. The underpressure and unembedded length of the suction pile will change during the installation process: at the start there will be a large unembedded length and a small underpressure but at the end a large underpressure and smaller unembedded length. It is important that the calculations are done for all the different

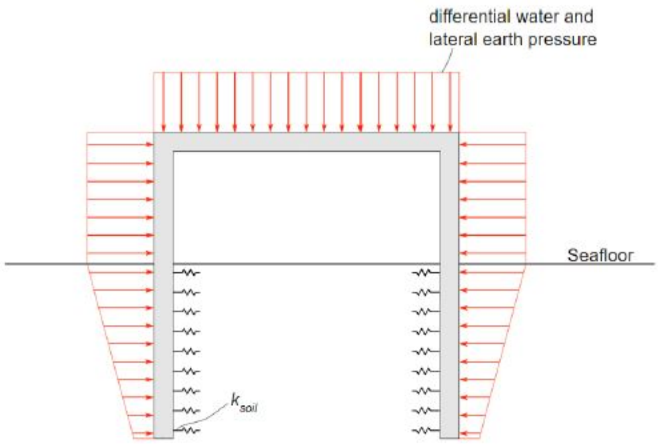


Figure 4.14: Structural integrity assessment of the suction pile anchor installation at an arbitrary situation

combinations of unembedded length ("L") and underpressure ("$s = f_E$"). The chosen thickness $t = D/250$ can be used in the formulas and if buckling occurs the thickness will be increased. A lower optimal value is not sought for because sufficient thickness will be needed for the topplate and decoupling both thicknesses from each would add to much unwanted complexity to this research.

4.6.5. Soil failure

Apart from structural failure also different soil failure mechanisms will be checked. Between clay and sand there will be different mechanisms that are important to examine:

1. Piping & Ratholing (sand)
2. Plug uplift (clay and layered soils)
3. Punch-through or squeezing (layered soil)
4. Gapping (clay)

Piping & Ratholing

When the upward hydraulic gradient in the soil becomes sufficient to reduce the effective stresses of the soil near to zero, is when erosion will happen. If this is the case or piping will start to occur. This critical upward hydraulic gradient will be achieved at a critical piping pressure at which internal erosion begins and regresses until a pipe-shaped discharge tunnel is formed between the hydraulic boundaries. When it is a full sized tunnel it is called a rathole. A rathole can also be a pre-existing hole or tunnel between the skirt tip and the soil due to limited initial penetration and incomplete skirt-soil contact. Piping or ratholing is especially prevalent in sands or coarser materials that are freely draining and will define the critical underpressure in the sand profile.
If piping occurs various adverse effects are felt such as the inability to apply further suction because the soil will just give way. Excessive loosing of the soil within the caisson will also increase the flow, and thus also the chance of ratholing, and decrease the stability of the suction pile. The critical underpressure at which piping will occur in sand layers can be calculated by the formula taken from Senders (2009) [29]:

$$s_{crit} = 1.32\gamma' D \left(\frac{h}{D}\right)^{0.75} \tag{4.42}$$

Using this formula we can set-up graphs for the twelve different concepts in which the maximum applied suction minus the critical underpressure at which piping occurs are shown. This difference should have a negative outcome so that the maximum applied pressure is below the critical underpressure. From here the critical embedment ratios for the suction piles installed in the sand, can be defined. The graphs are shown in Figure 4.15 and the final embedment ratios are shown in Table 4.11.

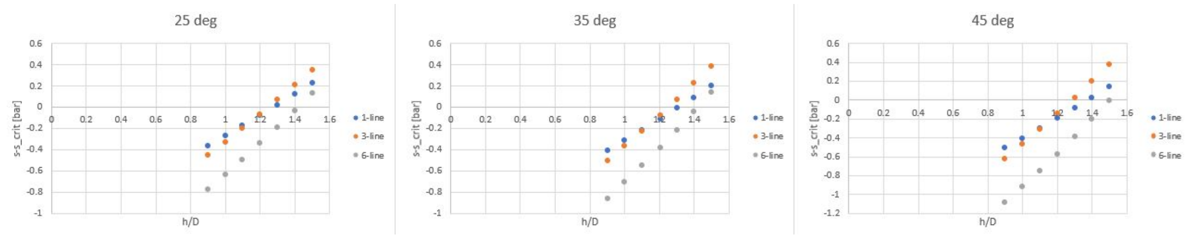


Figure 4.15: Maximum suction minus the critical piping suction for different embedment ratios

Plug uplift

In layered soils with a layer of relatively impermeable material such as clay, over a freely draining material such as sand, the suction applied to install the pile might lift the clay layer which functions as a plug. This uplift will create a void beneath the plug which is clearly undesirable and needs to be addressed by appropriately. The formula used is taken from the thesis by Cotter (2009) [10] and is formed by re-arranging the general formula given in Equation 4.30:

$$p_{plug} = \frac{4}{D_i^2}\left(s_{u1} D_i \left(h(\alpha - 1) + z_{clay}\right) + \gamma'_z z_{clay} \frac{D_i^2}{4}\right) \tag{4.43}$$

In this formula the thickness of the clay layer (z_{clay}) is defined as the pile embedded length at each iteration step. Because the clay layer is disturbed the adhesion factor will again be taken as: $\alpha = \frac{1}{S_f}$ with sensitivity (S_f) defined as two. In each iteration step the plug uplift pressure must be lower than the applied suction for that depth. If this is observed, the embedment ratio must be lowered which results in lower installation pressures. The embedment ratio reductions are shown in Table 4.10.

Table 4.10: New embedment ratios due to plug-uplift behaviour and piping or ratholing

		Clay OC			Clay NC			Sand		
		1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
25°	h/D	1.8	4.9	5.0	5.0	5.0	5.0	1.2	1.2	1.4
35°	h/D	2.8	5.0	5.0	5.0	5.0	5.0	1.2	1.3	1.4
45°	h/D	5.0	5.0	5.0	5.0	5.0	5.0	1.3	1.2	1.4

Because higher mean vertical tensions are experienced in the 3-line and 6-line setups, higher ballast are added. Accordingly, there is a higher selfpenetration of the suction piles. Because of this there is also a lower underpressure needed to fully install the suction anchors which in turn means the 3- and 6-line anchors are less susceptible to plug uplift occurring. Because of this reason the 1-line anchor for the 25° OC has the lowest embedment ratio due to plug-uplift.
The reason there will not be any plug uplift failures in the normally consolidated clay is because the suction anchor sinks in further than in the NC clay case. This ensures a thicker clay plug before suction is applied and this plug is more difficult to destabilize. In addition, the piles sink in further there is less suction needed to fully install them.

Punchthrough or squeezing

Punch through or squeezing is an issue that arises in layered soils when a strong overlying and a weaker lower layer results in reduction in penetration resistance at the interface between the layers. The results is a potential uncontrolled penetration which is classified as a punch-through. Squeezing or lateral soil displacement is a problem that occurs when a soft layer is pressed against a significantly stronger underlying layer and results in soil being pushed to the side. When this happens the suction pile itself can tilt which is clearly undesirable.

Gapping

When evaluating the holding capacity of a suction anchor, a system without a gap is used in this thesis, but it is a topic of debate whether this should be added into the design process of a suction anchor. When an anchor is used with one anchor line a gap can be formed at the "rear-side" of the suction pile [17]. Randolph et al.(1998) [32] has reported centrifuge model tests of suction anchors in normally consolidated clays that show a gap is formed only at larger displacements of 36% of the anchor diameter and Cluckey et al. (2003) [9] showed no gapping even at large displacements in NC clays. If the clay is lightly OC, than a gap is quickly formed and this shows with a considerable drop in holding capacity [32]. However, what should be noted is that these studies were performed for suction anchors that had one force direction and not a multidirectional force.

It can be concluded that for the NC clay profile the holding capacity most likely will not be reduced, however it should be checked regularly because the big decrease in holding capacity can not be underestimated and could lead to failure of the suction anchor. On the other hand, for the OC clay profile there most likely will be some gapping induced reduction to the holding capacity which should be checked in a complementary geotechnical thesis together with multidirectional loading the suction pile will be subjected to.

4.7. Removal analysis

One of the big advantages of using a suction pile anchor is the ability to be able to decommission the anchor. The offshore regulations in the European Union require that decommissioning should be considered during the design process and that the seabed should be returned to its original state after decommissioning.

The suction pile anchor is extracted by reversing the installation procedure specified earlier. First water is pumped into the caisson to create pressures inside the caisson that push it out of the seabed. This is done with the assistance of a crane which also lifts the suction pile through the water column on board of the ship. The needed pressure to decommission the suction pile anchors is calculated using the following formula taken from API RP2SK E3.2.2:

$$p_d = \frac{R_{tot} + W_{total}}{A_{in}} \tag{4.44}$$

With:

R_{tot} = total soil resistance at time of retrieval
W_{total} = structural weight + ballast
A_{in} = area of the inside of the suction pile

The limiting factor in this procedure is the maximum differential pressure pump capacity. Right now the deep water pump provided by SPT Offshore, the Specifications Suction Pump Spread SAPS-008, has a maximum differential pressure of 5bar and can go to a depth of 3000m. There is also the Suction Pump Spread SAPS-007S, which is not a deepwater pump but has the capacity of 7bar. Because this is a project designed for the future in consultation with SPT Offshore the decision was made to combine both pumps to get a deepwater pump with a maximum capacity of 7bar.

Furthermore, it is important that structural monitoring and changes to the structure response during the operational lifetime of the structure are well documented because a damaged suction pile may break in the process of removal. It is also important to take note of the aging, thixotropy and consolidation of the soil which could significantly improve the soils strength. This is especially prevalent in clay soil profiles because the adhesion increases over time. Because of this the pressures for the decommissioning are higher than the installation pressures. Because of this the topplate will have to be designed with stiffeners that protect the topplate from buckling out when the pile is being extracted. In consultation with SPT Offshore specialists the stiffeners needed will be stiffeners with 800mm high web and 20mm thickness and a top flange 500mm wide and 30mm thickness. These stiffeners have a weight of $250 kg/m$ which will be needed in the calculations for the weight of the suction pile and the ballast needed.

What can be noted is that the NC clay concepts do not have any plug-uplift issues and that especially in the 1-line case do not have any removal analysis issues. For the 3-line and 6-line systems there is a lot of extra additional weight because the mean vertical forces are so high and because of this the removal pressure become very high and thus the embedment ratio must be lowered. If the ballast could be designed to disconnect from the suction embedded anchor than the embedment ratios do not have to be decreased at all apart from the 6-line, 45deg, taut case ($h/D = 4.5$). This would result in more "efficient" suction anchors.

Table 4.11: New embedment ratios due to plug-uplift behaviour and piping & ratholing

		Clay OC			Clay NC			Sand		
		1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
25°	h/D	1.8	3.3	2.5	5.0	5.0	3.8	1.2	1.2	1.4
35°	h/D	2.8	3.2	2.4	5.0	4.9	3.5	1.2	1.3	1.4
45°	h/D	3.2	3	2.3	5.0	4.2	2.9	1.3	1.2	1.4

The piles installed in sand do not have any removal problems because they have a bigger area which leads to lower pressures needed and the removal pressures. The problem that does arise in sand piles is the piping and ratholing soil failure. These need to be checked for carefully because even though the calculations do not seem to show any problems, constant erosion of the inside of the pile does destabilizes the entire anchor.

4.8. Final parameters

With all the different failure mechanisms it is important to check them again each iteration. The embedment ratios for clay started at 5 and with each failure mechanism that ratio had to go down in steps of 0.1 until there was no plug uplift and such that extraction of the suction pile was possible. For the sand profile the embedment ratios started at 1.5 and also went down in steps of 0.1 until the piping and ratholing was kept below a certain threshold. With the final embedment ratios in Table 4.11 the main parameters are setup in Table 4.12. The diameter and height and thickness of the suction pile will be rounded up to industry standard measurements when the suction pile anchors will be built. This is because the machines don't have an infinite amount of accuracy.

Table 4.12: Final main parameters for the three different soil profiles, the three different concepts and the 3 different angles

		Clay OC			Clay NC			Sand		
		1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
25°	h/D [m]	1.8	3.3	2.5	5	5	3.8	1.2	1.2	1.4
	h [m]	10.23	13.58	15.71	18.25	20.69	24.16	8.69	11.39	15.99
	D [m]	5.68	4.11	6.28	3.65	4.14	6.36	7.24	9.50	11.42
	t [mm]	23	16	25	15	17	25	29	38	46
	R_{pen} [MN]	5.16	5.44	10.24	3.60	5.22	10.88	5.94	13.41	30.83
	d_{pen} [m]	2.48	6.17	12.98	9.18	12.43	20.39	2.98	3.63	7.33
	s [bar]	1.65	2.62	0.76	2.52	2.42	0.95	1.21	1.62	2.25
	p_d [bar]	3.02	6.79	6.83	5.42	6.51	6.94	1.68	2.17	3.78
35°	h/D [m]	2.8	3.2	2.4	5	4.9	3.5	1.2	1.3	1.4
	h [m]	12.05	14.34	17.09	17.97	22.66	25.30	9.25	12.88	17.68
	D [m]	4.30	4.48	7.12	3.59	4.62	7.23	7.71	9.91	12.63
	t [mm]	17	18	28	14	18	29	31	40	51
	R_{pen} [MN]	4.83	6.39	13.09	3.44	6.95	13.52	7.18	17.59	41.61
	d_{pen} [m]	4.25	7.38	14.77	10.89	13.75	22.33	3.42	4.25	8.12
	s [bar]	2.41	2.37	0.60	2.09	2.56	0.69	1.26	1.94	2.48
	p_d [bar]	5.23	6.97	6.96	5.73	6.99	6.90	1.82	2.63	4.18
45°	h/D [m]	3.2	3	2.3	5	4.2	2.9	1.3	1.2	1.4
	h [m]	14.30	17.45	22.12	18.73	24.61	24.85	10.88	14.67	20.53
	D [m]	4.47	5.82	9.62	3.75	5.86	8.57	8.37	12.23	14.67
	t [mm]	18	23	38	15	23	34	33	49	59
	R_{pen} [MN]	6.35	10.99	25.89	3.88	10.36	15.50	10.60	28.62	65.23
	d_{pen} [m]	6.79	9.54	18.07	14.56	16.52	27.72	4.61	5.11	10.28
	s [bar]	2.58	2.42	1.18	1.35	2.06	-0.67	1.50	2.03	2.73
	p_d [bar]	6.61	6.92	6.84	6.78	6.80	6.87	2.36	2.85	5.01

Firstly what can be concluded is that all the different concepts, catenary and taut and for each of the soil profiles, are able to be made, even when the vertical forces become higher. What appears is that the 45 degrees taut solution for the normally consolidated clay profile, the mean vertical force is so high due to the six different lines adding up, that the extra ballast pushing on the pile has more force than is needed for the full penetration of the pile. Due to this in the calculations there is a negative suction and a penetration depth that is larger than the height of the suction pile. This huge extra weight is a recurring theme that causes large extra penetration depths in the 6-line cases. This problem only arises when using a suction pile as an anchor because there is a constant force pulling on the suction pile anchor (SPA) which demands for this extra ballast to be added to make sure the pile or anchor is not slowly being pulled out. The static behaviour is dependent on the weight and the dynamic forces are handled by the frictional forces. Consequently, it can be concluded that having a more shallow inverse catenary shape is better for the overall design of a multiline suction pile anchor because less ballast is needed.

This is supported by the fact that the lower horizontal force the 3-line anchor perceives does not show in a smaller pile but in a pile which is larger. This is again due to vertical peak forces that are summed up for multiline systems and even though there is extra weight added to the pile, the overall suction pile still needs to be bigger because there is also more friction needed to compensate the dynamic force. Because of these two problems combined the 6-line multiline anchors are substantially bigger than the single line anchors and have more ballast.

When piles also become increasingly bigger in clay layers, at some point the embedment ratios are forced to become bigger, because decommissioning/removing the piles just becomes too difficult with pressures skyrocketing because of the increased soil strength when going deeper. If in the future the pumps are further developed this problem will be less likely to hold back the design/development of the suction anchors. These bigger removal pressures do come with the setback that the stiffeners in the topplate will have to be increased to accommodate for this extra pressure.

The extra forces due to the taut mooring system and the increased angle of approach to the suction pile anchor make for a substantially bigger pile than the catenary concepts. It is however possible to design and install suction pile anchors for all three chosen soil profiles.

An idea that could result in a more efficient single line system for the overconsolidated clay profile would be to add more ballast to the suction pile anchor or to press on the suction pile. This would increase the penetration depth before suction has to be applied to fully install the anchor. This would result in a bigger plug which would reduce the impact of the plug uplift soil failure and than the embedment ratio can be higher making for a more efficient suction pile anchor.

5

Detailed design

In this chapter the full design of an in use suction pile anchor is shown and each part is defined. Furthermore, the one-line-broken criterium is discussed from which can be concluded that in case this happens the 6-line multiline system is very dangerous because a chain reaction can be started which can take out large parts of a wind farm array. The 3-line system does not have this problem but the padeye will be loaded out-of-plane which can lead to padeye failure. Also a weight estimation of each suction pile anchor is made from which the extra needed ballast is calculated. Subsequently a cost estimation of each anchor concept, in the three different soil profiles and for each angle of approach, can be made by calculating the cost of each system from the structural weight, the ballast and the mooring line lengths. At a depth of 200m, at which this study is situated, the taut multiline system cannot be set-up but the single-line taut system can be compared to the catenary single line system. Lastly a parametric analysis is done where changes in friction angle, adhesion factor, wake distance and water depth are compared and discussed.

5.1. Suction Pile

The clay and sand piles will look quite alike only because of the different embedment ratios (h/D). The suction piles in the soft clay soil profile will be more slender and higher and the suction piles for the dense sand will be wider and shallower. A suction pile anchor that was installed by SPT Offshore for an FPSO (Floating Production, Storage & Offloading) unit in deepwater clay is shown in Figure 5.1. In this example there are two skidlanes including the 45degrees lanes on top, that are meant for running over the stern roller of an anchor handling vessel and they are optional. The trunnions on the side are meant for the handling of the suction pile on the yard. What can also be seen are the padeye, the anchor chain and the chain connector cradle. With the chain being pre-connected to the SP, so that after installation the connection between the top of this ‘bottom chain’ and the mooring leg bottom chain is established with a special connector and the help of an ROV (Remotely Operated Vehicle). These additional protruding masses on the outside of the suction pile add towards the penetration resistance which should be included. This will increase installation suction underpressure and the removal pressure. The holes at the bottom of the suction pile are meant to avoid "floating" of the suction pile over the seabed in case of rapid landing.

5.2. One-Line-Broken

The padeye is well suited for pulling in-plane but not capable of taking loads from another direction. When an array of wind turbines is connected via a multiline system and one of the lines breaks then the location of the wind turbine changes inside the predetermined grid. This situation is often designed for the in the Oil & Gas sector and mentioned in the DNVGL-ST-0119 Floating wind turbine structure section 4.6.3 Design load cases. There are two separate design load cases, 2.7 and 7.4, where the stationary situation after the loss of one mooring line or tendon is addressed. In Figure 5.2 the new location of the FOWT in an wind farm array can be seen. For the 3-line multiline system there does not seem to be a problem but for the 6-line multiline system there is the danger of collision between two turbines. Furthermore, usually the padeye would have an in-plane force, however now it will experience an out-off-plane force for which it is poorly equipped.

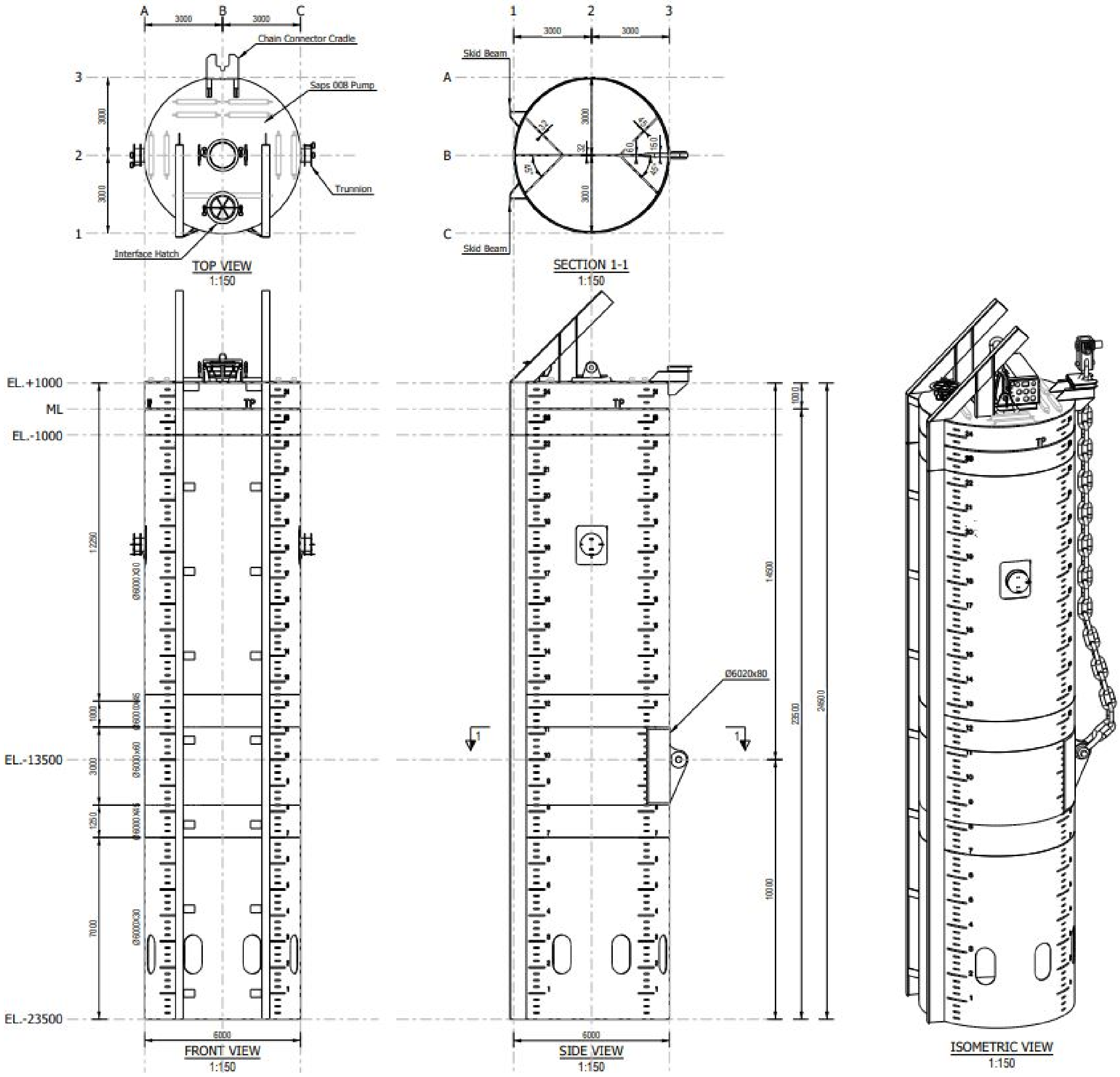
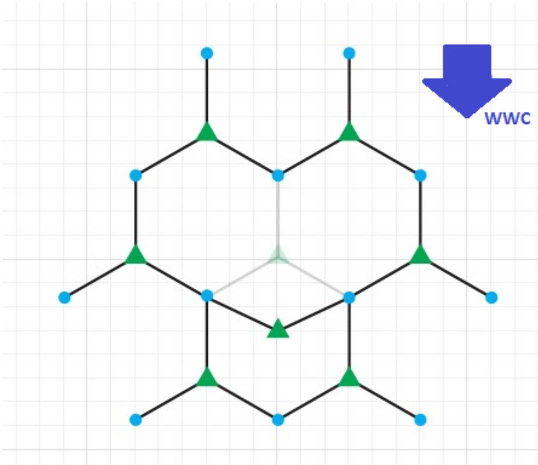


Figure 5.1: Deep water clay suction pile anchor designed for a Floating Production, Storage and Offloading unit

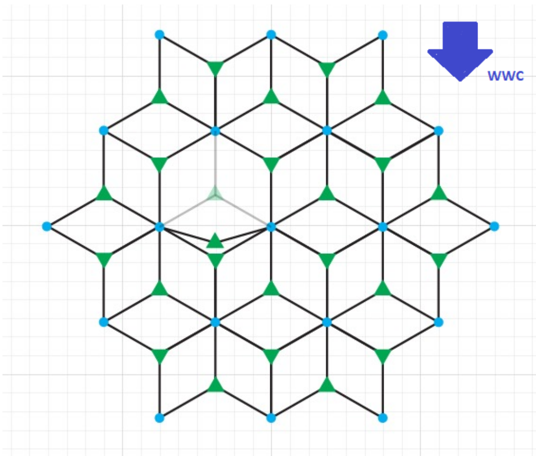
As can be seen in the figure there is a big difference in the angle of approach from the the original situation, especially for the 3-line concept compared to the 6-line anchor concept. On one hand this will introduce a torsional force on the suction anchor and this is dangerous for the integrity of the suction anchor. It can be compared to opening a wine bottle with a cork, when you twist the cork it will come out easier because when only pulling on the cork there will be a static friction coefficient and when pulling and twisting the cork will start moving and there will be a dynamic friction coefficient which is lower. The same can be said for a suction pile in clay: by applying torsion, the suction anchor might rotate, which will remold the soil and decrease the adhesion from 0.65 to 0.5 which in turn will lower the pull-out capacity of the suction anchor. If the suction anchor has enough torsional resistance for it not to rotate then the padeye will still be subjected to an out-of-plane force and will have to be designed accordingly.

A way of solving this can be done by strengthening the padeye so that it will be able to take the load. This does make this part bulkier leading to a higher penetration and removal resistances. Every protruding piece on the outside of the suction pile anchor adds to this including trunnions and the optional skidlanes and the mooring chain.

Figure 5.2: Stationary situation in case of broken line for:



(a) the 3-line multiline anchor



(b) the 6-line multiline anchor

5.3. Weight estimation

The weight estimation for the different suction piles is done by calculating the weight of the used steel. The ISO density of steel is used: 7850 [kg/m^3], and it is assumed that the thickness of the suction pile anchor (SPA) is the same everywhere. Only at the top plate there are three extra girders that span the entire diameter of the topplate with a weight of [250kg/m] as explained in section 4.7. By working this out the dry structural weight ($W_{d,SPA}$ [t])of each suction anchor can be estimated but the submerged weight of each suction anchor must be equal or more than the vertical mean forces subjected to the anchors. To get the submerged weight of the structural steel it is multiplied by a factor depending on the density of the seawater and the density of steel: $\frac{7850-1028}{7850} = 0.83$. From here the submerged ballast can be calculated by subtracting the structural submerged weight from the minimum required weight and finally dividing by the submerged weight multiplier 0.83 to get the ballast dry weight that has to be added. This ballast has to be added separately to the system and a system has to be designed that attaches the ballast to the SPA. This is a rough estimation of the weight of the suction anchor and there are multiple extra additions for instance: welds, trunnions, skidlanes, padeye and chain connector cradle. These will be added by adding 5% to the weight. The results are shown in Table 5.1.

$$V_{steel} = \pi D t h + \left(\frac{\pi}{4}(D+t)^2\right) \cdot t \tag{5.1}$$

$$W_{girders} = 3D \cdot 250[kg/m] \tag{5.2}$$

$$W_{d,SPA} = V_{steel} \cdot \rho_{steel} + W_{girders} \tag{5.3}$$

$$W_{subm,SPA} = W_{d,SPA} \cdot \frac{\rho_{steel} - \rho_{water}}{\rho_{steel}} \tag{5.4}$$

$$W_{ballast} = \left(\frac{F_{V,mean}}{g = 9.81[m/s^2]} - W_{subm,SPA}\right) \cdot \frac{\rho_{steel}}{\rho_{steel} - \rho_{water}} \tag{5.5}$$

What can be noted is that there is a large amount of ballast needed to make the 6-line case work sufficiently. On the other hand the 3-line cases need a more moderate amount of ballast. This ballast needs to be added to the suction pile system as a whole and thus a space has to be reserved for this. This amount of ballast will require new buckling calculations which could lead to thicker shells which in turn leads to more weight added to the suction pile and a small correction for the extra ballast.

Table 5.1: Structural weight of the suction pile anchor and the ballast weight needed to counteract the mean vertical force

		Clay OC			Clay NC			Sand		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	$W_{d,SPA}$ [t]	44	29	76	29	42	113	63	136	264
	$W_{ballast}$ [t]	74	204	852	87	191	817	55	101	673
35°	$W_{d,SPA}$ [t]	29	36	105	28	56	152	75	164	354
	$W_{ballast}$ [t]	129	280	1155	85	129	260	1110	157	917
45°	$W_{d,SPA}$ [t]	35	71	243	32	97	212	101	284	551
	$W_{ballast}$ [t]	249	500	2039	252	475	2068	186	297	1745

5.4. Cost estimation suction anchor systems

Now that the weights of the system are calculated the costs of the different concepts can be estimated. From a quote from SPT Offshore for a suction pile anchor (SPA) it can be concluded that structural steel costs including labour, assembly, welding, non-destructive testing and corrosion protection is: 3492€ per ton steel. The ballast weight, consisting of scrap metal, costs will be 475€ per ton. Using the values from Table 5.1 we can calculate the costs per Suction Pile Anchor (SPA) for each of the 18 concepts which are shown in Table 5.2. The 1-line system needs 3 anchors per FOWT thus the anchor system costs ($System$) will be costs per SPA times three. For the 3-line system each anchor will only need 1 anchor because each anchor is shared thus for the anchor system it is multiplied by 1 and for the 6-line system only half an anchor is needed per FOWT. The mooring line costs still have to be added to the "$System$"-costs.

Table 5.2: Costs of the structure and ballast per suction pile anchor and as a system for each profile and each multiline concept in 10^3€

		Clay OC			Clay NC			Sand		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	$Structural$ [€]	152	101	264	219	97	139	375	476	922
	$Ballast$ [€]	35	97	405	41	91	388	26	48	320
	SPA [€]	187	198	669	139	230	764	245	524	1242
	$System$ [€]	561	198	335	416	230	382	736	524	621
	Cost comparison	100%	35%	60%	100%	55%	92%	100%	71%	84%
35°	$Structural$ [€]	100	125	366	93	188	507	262	573	1237
	$Ballast$ [€]	61	133	549	61	123	527	40	75	436
	SPA [€]	161	258	915	155	311	1034	302	648	1673
	$System$ [€]	483	258	457	465	311	517	906	648	837
	Cost comparison	100%	53%	95%	100%	67%	111%	100%	72%	92%
45°	$Structural$ [€]	124	248	848	105	324	705	352	994	1925
	$Ballast$ [€]	118	237	968	120	225	982	88	141	829
	SPA [€]	242	485	1816	225	549	1687	441	1134	2754
	$System$ [€]	725	485	908	674	549	844	1322	1134	1377
	Cost comparison	100%	67%	125%	100%	81%	125%	100%	86%	104%

The cost comparison for the 3- and 6-line systems will be made with the original 1-line system. By doing so, the cost savings in each part of the mooring system can be compared. What can be noted is that both multi-line systems are more expensive when looking at the costs for a single suction pile anchor but because fewer anchors are needed per FOWT it will be cheaper to use the multiline systems. The 3-line system does look cheaper than the 6-line system and when the inverse catenary angle becomes higher the 6-line eventually becomes more expensive than the 1-line system but the 3-line system does seem to stay below the single line original system.

Cost estimation mooring lines

Based on various quotes for mooring line components, gathered from the SPT Offshore database, the following costs could be estimated for the mooring lines:

Chain costs = $0.3742 \cdot 10^4$ [€/m/N]
Taut costs = $0.2243 \cdot 10^4$ [€/m/N]

For the taut system costs the top part and bottom part will consist of chain section as can be seen in Figure 2.4. With the DLC 6.1 design load being 4.95 MN and a permanent mooring system with consequence class 1 from DNV-GL-OS-E301 Position mooring a safety factor of 1.35 is applied. This results in: $4.95[MN] * 1.35 = 6.68[MN]$ design load.

Chain costs = 0.00003742 [€/m/N] * $6.68 \cdot 10^6$ [N] = 250 €/m
Taut costs = 0.0000148275 [€/m/N] * $6.68 \cdot 10^6$ [N] = 150 €/m

Now the mooring line lengths have to be calculated for the different systems and then the costs of the different mooring systems can be estimated. In the NREL report about the 15MW reference turbine [1] a mooring system setup is already designed for which the turbine is moored safely with the correct limitations on the movement of the total system. In Table 3.1 the length of the original line can be seen: 850m traversing 837.6m horizontally. As explained in subsection 3.2.5, the horizontal distance the mooring line has to traverse is 1108.5m for the 3-line and 1920m for the 6-line system. Thus the extra added length of the chain for the 3-line system is $1108.5 - 837.6 = 270.9m$ and for the 6-line system $1920 - 837.6 = 1082.4m$. Because there are three lines per FOWT the costs of 1 of the mooring lines is multiplied by three.
For the taut-system a 45° angle is used to set-up the forces and that will also be the angle of the taut lines. This would mean that the anchor will be placed very close to the FOWT at a horizontal distance of only 200m. The taut mooring line would then have a straight line length of $\sqrt{200^2 + 200^2} = 273.12m$ and each FOWT would still have 3 taut lines. Because of this close distance there is no possibility for a multiline system and thus only the 1-line cases will be compared to the single line catenary system. A semi-taut system could be considered to gain extra horizontal length but more research needs to be done on this before it can be applied. Also the force set-up will have to be done again with which all the suction pile calculations from Chapter 4 Suction anchor concept design.

Table 5.3: Costs for catenary mooring lines, taut mooring lines and mooring line system costs in 10^3 €

Catenary	**1-line**	**3-line**	**6-line**	**Taut**	**1-line**
Costs mooring pattern [€]	638	841	1456	Costs mooring pattern [€]	123

Total costs mooring system

Now that both the costs for the mooring lines and the costs for each SPA are estimated a total picture can be made. In this picture the 3-line and 6-line multiline taut systems are not evaluated because they could not be set-up with size of the turbines and the big wake depended interspace distances that result from this. The single-line taut system is compared with the single-line catenary system.

What can be concluded from the economic picture shown in Table 5.4 is that the extra length of the mooring lines is more expensive than the costs saved by using fewer suction anchors for the 6-line situation. Because only in the 25 degrees catenary situation the multiline 3-line system total costs per mooring system, are substantially less than the original situation with 3 anchors per FOWT. Because this thesis does not examine the design of the mooring lines closely, these numbers could still be optimized and this could lead to another conclusion for the multiline anchor system design. Nonetheless it can be said that the extra length of the mooring lines which is depended on the FOWT inter spacing and depth of the ocean, does have a big impact on the overall costs and thus on the efficiency of the multiline system. Consequently it is recommended that a research is done on the design of the mooring lines and its essential in the continuation of the multiline design.
Lastly the Table 5.4 the 45 degrees single-line taut systems are still compared to the single line catenary systems and what can be seen is a lower overall costs in both clay layers but more costs for the sand layer. Even

Table 5.4: Total costs per multiline concept, for each profile and angle of approach in 10^3 €

		Clay OC			Clay NC			Sand		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	SPA [€]	561	198	335	416	230	382	736	524	621
	$Mooring$ [€]	638	841	1456	638	841	1456	638	841	1456
	$Total$ [€]	1199	1038	1790	1054	1071	1837	1374	1365	2077
	Cost comparison	100%	87%	149%	100%	102%	174%	100%	99%	151%
35°	SPA [€]	483	258	457	465	311	517	906	648	837
	$Mooring$ [€]	638	841	1456	638	841	1456	638	841	1456
	$Total$ [€]	1121	1099	1913	1102	1152	1973	1544	1489	2292
	Cost comparison	100%	98%	171%	100%	105%	179%	100%	96%	148%
45°	SPA [€]	725	485	908	674	549	844	1322	1134	1377
	$Mooring$ [€]	123			123			123		
	$Total$ [€]	848			797			1445		
	Cost comparison	76%			76%			105%		

though the anchors have to be bigger because of the increased vertical pull-out force, the decrease in mooring line costs makes the total system cheaper. Thus when deeper waters are considered so the taut lines can be used for a multiline system or if smaller FOWT are considered than this multiline system might work. If 8D is still used as the distance between the turbines than a depth of about 1100m should be considered. The loading on the anchor and the lines will change so a new suction anchor design can be made with the calculations shown in Chapter 4 Suction anchor concept design.

5.5. Parametric analysis

There are many different parameters that were defined whilst calculating the uplift capacity, most of them being site dependent. If, for instance, the friction angle of the sand would go up then the piles would become smaller due to the increased friction with the pile. These geotechnical parameters are very site specific and could already change when looking from anchor to anchor inside a wind farm array. Because of this, it is important to check what would happen if these parameters change. Because there are so many parameters a selection was made:

1. Friction angle (φ)
2. Adhesion factor (α)
3. Interturbine distance
4. Water depth

During this parametric analysis these parameters will change but the embedment ratios will be kept the same, such that a comparison can be made with the final design of the suction piles. A change to the embedment ratio will be discussed each time because it is one of the most important parameters. By looking at the structural- and soil failures that are explained in Chapter 4 Suction anchor concept design we can see if the embedment ratios should be increased or lowered. An increase in embedment ratio can be seen as an improvement and a decrease as a worsened situation that leads to higher costs.
Only the parameters that can be changed and seem critical to the design have been chosen. The first two parameters are soil dependent changes and the latter two are stand alone parameters that are purely dependent on the wind farm array design and they are choices made by the author of this thesis in discussion with SPT supervisors. As the geotechnical parameters, that were chosen in the first place, were used because they represent the most probable soil profiles that are at these depths, these changes will not be further calculated. However, the wake distances and the turbine size will be looked at in more detail and the costs picture will be updated and compared.

Friction angle

The friction angle (φ) and the external steel - soil friction angle (δ) are linked thus when the friction angle is increased to 40° then the external steel - soil friction angle increases to 35°. As stated earlier this increase in friction angle results in smaller suction piles but at the same time the underpressure, or suction required, would be higher. Subsequently this will lead to more ratholing and piping, which is not desired. To solve this smaller embedment ratios have to be chosen. This higher embedment ratio leads to a bigger diameter which increases the used structural steel and thus makes the piles more expensive and less efficient.

Adhesion factor

The static adhesion factor of clay (α) is an important parameter that is defined as 0.65 and when disturbed as: $\frac{1}{S_f} = 0.5$. First we will look at the change of the static adhesion factor and keep the sensitivity the same and afterwards the opposite will be discussed.
The adhesion factor and the friction angle perform similar because when decreasing the adhesion factor, bigger SPAs will be needed for the same forces because the soil produces less friction with the SPAs shell and subsequently bigger piles for more area is needed to hold the pile. It does make the removal of the piles easier, thus the embedment ratios of the piles can be increased making them more efficient. If the disturbed adhesion factor is changed, the plug uplift will be less likely to occur because the pile sinks in further. This will lead to a bigger plug which is less likely to be loosened due to the underpressure. This is especially nice for the piles that have less ballast added to them because of which their selfweight penetration is lower.

Inter turbine distance
If the inter turbine distances are changed the efficiency of the FOWT will decrease but the multiline anchor concept will become better because the distances between the turbines decreases. Subsequently this means that the mooring line lengths decrease. As a result of this the efficiencies of the multiline systems improves because the costs per anchor remain the same and the mooring line costs decrease for the 3-line and 6-line system. In Table 5.5 the new cost comparisons are shown for different wake distances ranging from 5D to 10D.

Table 5.5: Total costs per concept for each profile and inverse catenary angle but for 5D wake distance

		Clay OC			**Clay NC**			**Sand**		
		1-line	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**	**1-line**	**3-line**	**6-line**
25°	10D	100%	104%	179%	100%	121%	208%	100%	114%	177%
	9D	100%	95%	164%	100%	111%	191%	100%	107%	164%
	8D	100%	87%	149%	100%	102%	174%	100%	99%	151%
	7D	100%	78%	134%	100%	92%	157%	100%	92%	138%
	6D	100%	69%	119%	100%	82%	140%	100%	84%	125%
	5D	100%	61%	104%	100%	72%	123%	100%	77%	112%
35°	10D	100%	117%	203%	100%	123%	212%	100%	110%	172%
	9D	100%	107%	187%	100%	114%	195%	100%	103%	160%
	8D	100%	98%	171%	100%	105%	179%	100%	96%	148%
	7D	100%	89%	155%	100%	95%	163%	100%	90%	137%
	6D	100%	79%	139%	100%	86%	146%	100%	83%	125%
	5D	100%	70%	122%	100%	76%	130%	100%	76%	113%

When we reach an interspace distance of 10D we can see that none of the multiline systems are better than the single line systems. Also we can see that in the OC clay the 3-line system stays the cheapest the longest compared to the NC clay and sand. The 6-line system is never more cost efficient than the single line system even if we go down to 5D.
Thus what can be concluded that the efficiency of both multiline systems greatly increases when the turbines are closer together. This is a direct result of the geometry of the multiline system and there are multiple ways of achieving this increase in efficiency. The first one was already done by decreasing the wake induced interspace distance and the second way of achieving this would be to investigate the multiline anchor system for the 10MW or even 12MW FOWT. Because their rotor diameters are smaller, this results in smaller inter

turbine distances. This would mean that the forces on the anchors would change thus the relation of costs for each SPA would also change and a whole new study can be setup for this.

Water depth

When the water depth increases the forces on in the mooring lines also increase because the weight of the longer lines increases the tension in the lines. Because these forces increase the sizes of the anchors increase and additionally the embedment ratios change. This is because the removal pressure increases with bigger piles but the capacity of the pumps is still 7 bar. Furthermore, the plug uplift has to be respected in clay profile and the ratholing and piping has to stay below a thresh hold (s_{crit}) for the sand layer. Due to the water depth increasing the original mooring line configuration for the catenary situation does not apply anymore and a new location at which the anchor is positioned has to be calculated and a new length of the catenary line is to be estimated. Lastly also the costs estimation for the mooring lines in section 5.4 will change because the Design Load will change.

Subsequently it was decided that by changing the water depth so many parameters will change that the analysis of the resulting system will be uncertain and far removed from this study that it is not further worked out. Comparing the multiline anchor systems in different water depths would however be very interesting but can't be done in this thesis.

6
Conclusions and recommendations

In this chapter the conclusions made and the recommendations to improve the research on multiline anchor systems for FOWT are stated and summarized. The main goal of this thesis is to research if the multiline anchoring system is technically feasible and if it is better than using a single-line system. This is done by comparing the sizes and amount of anchors needed but also by comparing the distances that need to be spanned between the anchors and the floating offshore wind turbines.

6.1. Discussion

In this discussion all the drawn sub-conclusions are summarized and a small discussion on why this conclusion can be made is given. All here mentioned conclusions are made on the literature research and on calculations set up with the DNV guidelines that are mentioned in Table 2.3. Sometimes other research was included that was advised by SPT Offshore supervisors who have considerable knowledge in the design and installation of suction piles. The results are all summarized and explained in the respective chapters, sections and subsections in this report. Extra data is added in the Appendices in which the calculations can be followed for one profile. All conclusions that can be drawn from this thesis research are summarized in bullet points as to keep an organized overview of the results.

1) In the literature research different anchor concepts are compared for the multiline anchor system. With the torpedo anchor being patented by Petrobas and also having limited vertical pull-out capabilities and normal piling being impractical deeper waters, it can be concluded that the suction pile anchor is best suited for the multidirectional loading in a multiline system.

2) Also concluded in the literature research was the fact that the horizontal forces on the anchor are lower for a 3-line multiline system and that this would maybe result in smaller suction pile anchor compared to the single line anchor. This however is not the case because the vertical forces of each mooring line are added up instead of partly canceling each other. The vertical forces are introduced to the system because the connection point between the mooring line and the suction anchor is below the mudline. The resulting multidirectional net force on the SPA is higher for the 3-line multiline system than the force experienced by the single line system resulting in a bigger SPA in the 3-line multiline system.

3) When a suction pile anchor is subjected to vertical forces it is important that the mean vertical forces are lower than the weight of the suction pile anchor. If this is not the case the suction pile anchor can slowly be pulled out of the soil which lowers the pull-out capacity. Because the vertical mean forces are high, ballasts have to be added to the anchors as the structural weight of the anchors is not enough to counteract this force.

4) Having a lower angled inverse catenary shape is better for the overall design of a multiline suction pile anchor because the anchor is subjected to less vertical forces. This translates to a smaller anchor but also the anchor needs less ballast. Subsequently the overall costs between the different concepts are better for the 3-line and 6-line concepts when the angle is lower for all three soil profiles.

5) It is technically feasible to install suction pile anchors in each of the chosen soil profiles for the forces calculated in subsection 4.3.3. This can be concluded from the fact that the sizing of the anchors can be determined for each force.

6) The looked at system with 200m water depth and an interspace distance of eight times the diameter, does not support multiline taut systems. If the depth increases then a multiline taut system can be setup and it seems very promising when comparing the single-line catenary cost estimations with the taut cost estimation. If a minimum interspace distance of 5D is applied to the wind farm array, the depth for a 3-line multiline taut system must be around 1200m. Suction pile anchors have no depth limitation and have been installed in depths up to 2500m [34]. With the taut system being more optimal than the catenary system in deeper waters the conclusion can be made that the multiline taut system looks very promising in clay profiles in deeper waters.

7) The 6-line multiline system has a problem in case there is a broken-line because a collision with another FOWT can occur. This is very dangerous and can cause a chain reaction taking out multiple FOWT. This is unwanted and one of the reasons why the 6-line system is inferior to the 3-line system.

8) Furthermore the extra mooring line costs due to the high distances from the geometry of the system do make the 6-line multiline system less attractive and more expensive than both the 3-line system and single line system.

9) Additionally the huge amount of ballast hampers the commercially attractiveness and workability of the anchor. The bigger size of the anchor is only a fraction of the extra ballast needed due to the enhanced mean vertical pull-out force of all six lines adding up.

10) When looking at Table 5.2 it can be concluded that the 3-line anchor looks very promising in each soil profile. The costs per suction pile anchor are slightly higher than that of a 1-line system and the amount of anchors needed are 67% less compared to a single-line system. However, if the angle of approach of the mooring line becomes higher the vertical forces induced due to the 3-lines adding up, do make the anchor a less efficient.

11) For an interspacing of 8D it can be concluded that the 3-line system is a little more cost efficient than the single-line system in overconsolidated clay and the sand profile but not more cost efficient in the normally consolidated clay. This difference between Table 5.4 and Table 5.2 can be contributed to the mooring lines adding a lot of costs to the overall system. Henceforth it can be concluded that, the added length of the mooring line adds more costs than saved by having less anchors. If the mooring line system is optimized the 3-line system can work very well. This can either be done by increasing the water depth or decreasing the wake spacing as shown in section 5.5.

12) In section 5.5 the results of decreasing the space between the FOWT is shown up to five times the diameter. It can be concluded that it is more efficient for the catenary multiline mooring to be closer together.

6.2. Recommendations

In this thesis the feasibility of the multiline system together with the suction pile anchor is researched by also comparing the cost efficiency between the single line concept and the multiline concepts. There are multiple ways this research could still be improved and these recommendations are given in bullet points in this section.

1) The forces are setup using factors instead of making dynamic models in which the dynamic behaviour of the mooring lines can be simulated. In the literature this is done for a 5MW FOWT and thus this could be done for the 15MW FOWT. For the NREL turbine there is a model available online which could be used in OPENfast to simulate the multiline system. In addition OPENfast or Orcaflex or any other suitable program could also be used to get the taut mooring line forces instead of using literature. Because this was not the essence of this thesis this was not implemented.

2) In this research two homogeneous clay profiles and a homogeneous sand profile are analyzed although in reality this most likely will not be the case. A layered soil profile consisting of both clay and sand will be more likely. Depending on these conditions slightly different suction piles anchors will have to be designed compared to the anchors in this thesis.

3) Instead of setting up a VH-envelope a finite element analysis could be carried out to get a more accurate pull-out capacity of the suction pile anchor and to verify the VH-envelope. An example software that could be used is PLAXIS. Using these software would include theory such as: non linear cohesion and non-linear stiffness. Likewise macro-element modelling or force-resultant modelling can be used to make a more integrated structural and foundation design.

4) No fatigue analysis or cyclic degradation is added to the calculations in this thesis but these do have an impact on permanent mooring systems. Adding these will very much add to completing the research into multiline anchor system. In addition this is required in the DNV guidelines in the Fatigue Limit State (FLS) but also in the Servicable Limit State (SLS) where the accumulated deformation of the foundation during the design life of the turbine is verified.

5) As already touched upon in section 5.2 when a mooring line breaks, torsion is added to the system which can impact the pull-out capacity of the suction pile anchor. This should be included in a follow up research.

6) In addition, the Accidental Limit State (ALS) should also be added to the overall design. An example of such an event is a boat impact but because it was not of major concern this was not added into this thesis.

7) A concern that was touched upon in this thesis was the issue of the padeye being loaded out-of-plane. Padeyes are not designed for this and this can be a real concern because if these snap off the FOWT can traverse into other wind turbines creating a chain reaction.

7) The edge anchors were not fully worked out in this thesis but these anchors may end up being bigger than the multiline and single-line anchors designed in this thesis. This is because the two anchorlines connected will be pulling into the same direction adding up and pulling on the anchor with twice the force. Because of this these anchors should also be designed and added into the system overall costs to get a more accurate picture of the total costs of the system.

8) Gapping was briefly touched upon in subsection 4.6.5 where it was concluded that this most likely will not be a problem but it might have an impact in slightly OC clay profiles. Because the anchors are also multi-directionally loaded this should be considered in the research.

9) Tilt is an important parameter when installing a suction pile anchor which should be monitored closely. This is especially prevalent when installing suction anchors on a sloped bottom. This was not investigated in this thesis but could play an important role when installing suction pile anchors in the deepsea environment.

10) The length of the mooring line is directly related to the interspace distance between the wind turbines, which is related to the rotor diameter and the wake distance chosen. Because of this it is recommended that

the multiline system is worked out for the 10MW FOWT and/or the 12MW wind turbine as the multiline system is more cost effective for smaller distances and thus might be even better for these smaller turbines. This is the case for both the 3-line and the 6-line multiline options.

6.3. Conclusion

From the discussion and from the limitations and recommendations given in the previous sections a conclusion can be made on the research question stated in subsection 1.2.1:

"Is it technically feasible and economically viable to use a multiline anchoring system to anchor a 15MW floating offshore wind turbine to the seafloor?"

To answer the research question the question is split into three parts:

1. Single-line system
2. 3-line system
3. 6-line system

6.3.1. Single-line

The single-line system is the industry standard right now with 3 anchors per floating offshore wind turbine (FOWT). To compare the multiline systems with this this value a anchor is set up that follows the same calculations done in this thesis. This is done for both the catenary mooring line and for the taut mooring line at 200m water depth in normally consolidated clay, overconsolidated clay and in loose sand. After analysing the structural integrity and the soil failures that arise when installing a suction pile anchor in these soils, it can be concluded that it is technically feasible to moor the FOWT to the seafloor using both a catenary system or a taut system. The final dimensions of the single-line anchors are shown in Table 4.12 together with all the relevant information. This is the standard solution right now thus this is the benchmark the other two are compared with.

6.3.2. 3-line system

When setting up a 3-line system in 200m depth with a 15MW semi-submersible FOWT it is not possible to use a taut mooring system because the distances are too big. Because of this only the catenary solution is concluded here. It is technically feasible to install a 3-line multiline anchoring system in all three different soil profiles. Here also the structural integrity and all the soil failures that arise are taken into account.
The 3-line multiline system is also economically viable to be installed instead of a single-line anchor for a 15MW FOWT, up to a spacing of 8D for the OC clay, up to 7D for the NC clay and up to 8D for sand. The closer the turbines are together the more economically viable the multiline system becomes.

6.3.3. 6-line system

Using a 6-line system was at first thought to be safer with more redundancy but after analyzing the one-line-broken criterium it was concluded that this is not the case because multiple collisions can occur as can be seen in Figure 5.2. Together with the fact that the high mean vertical forces induced on the anchor by all 6-lines coming together and pulling up, it is decided that this multiline system is technically feasible but not advised. Needing so much extra ballast weight that the suction pile can be installed without suction is a disappointment and not viable.
Furthermore this 6-line multiline anchor is at 200m water depth, and for the 15MW semi-submersible FOWT, not economically viable although 87% less anchors are needed in a system. This is due to the huge distances the mooring lines have to span to connect the system together.

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A
Appendix

A.1. Literature research

This chapter of the report covers the literature research of the Master Thesis Project about the design of a suction pile multi-line anchor system for floating offshore wind farms. It starts with an explanation on what the different configurations of a floating offshore wind turbine (FOWT) could look like with respect to: the floater system, the mooring lines and the available anchors. After that, the multiline anchor concept will be looked at as well as why this is a viable option when looking at a larger array of FOWT's. Finally, the magnitude of the forces that are exerted on the anchor(s) are discussed and how and by what means they are calculated.

A.2. Wind Floaters

In bottom founded offshore wind turbines the wind turbine generator (WTG) is mounted on top of a substructure that is directly connected to the seafloor. For a floating offshore wind turbine at sea, the tower assembly is added on top of a floater. This floater is again connected to the seafloor by means of a mooring configuration. The floater and the mooring configuration together are supposed to hold the turbine into position, maintain deflections in an acceptable range for the electrical cables, counteract the turbine induced and hydrodynamic loads and transfer the loads from the structure to the dissipating medium [5]. The different floater concepts that will be discussed are listed below and shown in Figure A.1.

1. Buoyancy stabilized - Semi-submersible platform
2. Ballast stabilized - Single Point Anchor Reservoir (SPAR) platform
3. Mooring stabilized - Tension Leg Platform (TLP)

A.2.1. Semi-submersible

A semi-submersible platform is a buoyancy stabilized platform that achieves stability by using distributed buoyancy. The semi-submersible platform has been used by the oil & gas sector since the 1960s and it has shown to have excellent pitch and heave motion stability in waves. It usually consists of large columns that provide the main volume under water and it has braces that connect these larger volumes. Together they form a heavy and large structure that uses its size to maintain stability. The number of columns between different concepts can differ and the choice for the right amount have to be made according to the design conditions. Many add-on tools exist that can be designed to further improve the static and dynamic behaviour of the semi-submersible platform. The restoring forces of the semi-submersible structure are in roll, pitch and heave meaning that the mooring lines will have to deal with the surge, sway and yaw motions [7]. Another attribute of the semi-submersible structure is its low draft which allows the concept to be installed in all water depths. The lower draft is also important when assembling the FOWT because this means that the semi-submersible structure can be towed in and out of ports or harbours. Because of the relatively complex shape a semi-submersible is more difficult for serial production which makes it more expensive [7][35].

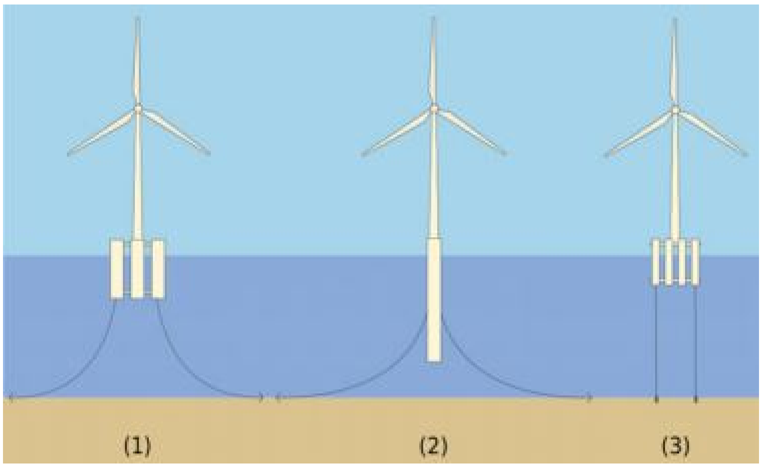

Figure A.1: Floating wind concepts. Courtesy: Floating Offshore Wind Farms [7]

A.2.2. SPAR

A Single Point Anchor Reservoir (SPAR) is a large vertical cylindrical structure which supports a WTG. A SPAR will be ballasted at the bottom of the cylindrical structure so the centre of gravity will be lower than the centre of buoyancy. This will ensure the stability of the structure because it creates a righting moment and a high inertial resistance to pitch and roll. The lower the ballast is positioned the higher the righting moment. This balance between weight and positioning creates a high draft. Together with the relatively big waterplane area of the large cylinder the SPAR concept can offset some of the heave motion but it will still require the mooring lines to contribute their part. The higher draft does also complicate logistical matters such as: transportation, installation and assembly. The SPAR can not be towed in or out of most ports when assembled with a WTG which means that it needs to be installed on location or some other suitable place. In Norway this problem is solved by having a safe deep watered area where this can be done, the fjords. But in for example Japan there are no safe areas and thus it becomes a bigger challenge. The big advantage of the SPAR is that the simple nature of the structure allows for easy fabrication and even serial production. This makes it very attractive when designing a wind farm with 100+ FOWT [7] [35].
Because of the symmetrical nature of a SPAR the yaw rotations are negligible however they are again introduced due to the aerodynamic properties of the WTG on top. Because of this the mooring lines will have to restrain the yaw movements. In addition the mooring lines will also have to constrain the movements in surge and in heave to some extend [7].

A.2.3. Tension Leg Platform

A Tension Leg Platform (TLP) is a mooring stabilized floating platform that consists of a semi-submerged buoyant structure that is anchored to the seabed using vertical mooring lines under tension. When using a TLP the buoyancy force is larger than the gravity force of the structure which leads to a net upward force and this will be balanced with the tensile force of the mooring lines [37]. This tension in the mooring lines creates the righting stability of the system and because of that a smaller and lighter structure can be used which also means that this system could be used in shallower waters. A negative effect of using this system is that it is not stable without the mooring lines and for transport the floater needs to be ballasted to become stable [7].
The stiff system, because of the tensioned mooring lines, allows for a good performance when looking at the dynamic capabilities of the structure as a whole [35]. There are some challenges in the installation process and not all available anchors are suited for a large vertical force. The anchors that are available are soil dependent, have an earthquake sensitive construction and are relatively expensive [35]. In addition there is a increased operational risk in case of a tendon fails the whole system could become unstable and topple over [7].
Because of the high tension in the mooring lines the structure behaves like a bottom founded/fixed structure would and the motions that are restricted are: roll, pitch and heave . This rigid body tendency is reflected in the natural frequencies of the modes and should be taken into account when designing a TLP. It should also be noted that when using this design there is some compliance in surge, sway and yaw [7].

Table A.1: Summary of three discussed floater concepts

	Semi-submersible	SPAR	TLP
Floater Size	1	2	3
Construction Complexity	1	3	2
Lowest Draft	2	3	1
Ease of Installation	1	2	3
Biggest Positives	Low draft and easy installation	Ease of construction	Stiff system with good dynamic capabilities
Biggest Negative	Big size comes with higher costs and higher WWC forces	Depth restriction	Not stable without tendons

A.2.4. Conclusion Floater Concepts

In Table A.1 the three discussed floater types are summarized. The numbers rank the different concepts from biggest (1) to smallest (3), complex construction (1) and least complex (3), lowest draft (1) and highest draft (3), easiest to install (1) most difficult to install (3) and finally their biggest positive and negative aspect.
The chosen floater type for this thesis project is the semi-submersible floater concept. This choice was made because the semi-submersible is the most accessible of the three concepts. It is easier to install than the other floater types because the WTG can be added on the floater in a port and than towed out to the desired location. Furthermore because of its size the forces on the system will most likely be the biggest and thus a conservative anchor system can be designed. The anchor forces for a SPAR will be less severe and the system will be able to adapt easily by scaling it down. When designing a TLP system only vertical forces will be applied which will apply more restrictions in the anchor choice and the system will have to be installed at sea which comes with considerable setbacks.

Table A.2: Floating Offshore Wind Projects

Type	Name	Developer	Size (MW)
Semi-submersible	Windfloat	Principle Power	5-10
	Vertiwind	Technip	2
	SeaReed	DCNS	5
	Tri-Floater	GustoMSC	5
	Spinfloat	EOLFI/GustoMSC	6
	Nautilus Semi-Sub	Nautilus Floating Solutions	5-10
	Nezzy SCD	Aerodyn Engineering	8
	TetraFloat	Tetrafloat Ltd.	-
	VolturnUS	DeepCwind Consortium	6-12
	Groix and Belle-Île	Naval Energies/EOLFI	9.5
SPAR	Hywind	Equinor/Statoil	2.3-8
	Sway	Sway A/S	2.5-10
	WindCrete	U.P. Catalunya	2-10
	Hybrid SPAR Concrete-Steel	Toda Construction	2
	Seatwirl	Seatwirl Engineering	1
	TetraSpar	Stiesdal Offshore Technologies A/S	2-10
	DeepWind Spar	DeepWind Consortium	-
TLP	PelaStar	Glosten/PelaStar LLC	6
	Blue H TLP	Blue H Group	5-7
	GICON-SOF	GICON	6-10
	Eco TLP	DBD Systems	6-7
	Advanced Floating Turbine (AFT)	Nautica	-

A.2.5. FOWT Projects

There already are multiple projects realized and there will probably be no single best design. The different designs have different site conditions and are influenced by local infrastructure and supply chain capabilities [7]. Some of the projects are only in pilot stage or even design stage, others are already in their pre-commercial array stage and could be economically viable in the near future. The table with the different projects is shown in Table A.2 and the sizes that are being researched or developed are also in the table. It can be expected that every project or design will be scaled up in the future to suit the bigger floating offshore turbines that are being developed.

A.3. Mooring configuration

Mooring lines are one of the critical components in floating offshore wind turbines but also in other floating structures. If they break, collisions with other structures can cause damage not only for one structure but multiple. Because of this, many researchers study their static and dynamic behaviour. There are multiple ways of mooring a floating structure to the seafloor and the three most used are:

1. Catenary
2. Taut
3. Tension leg

A.3.1. Catenary

A catenary mooring line is the earliest and most common mooring line that is used in the offshore industry. It has a very distinct shape of a free hanging line which can be seen in Figure A.2. In this figure there are different conditions: A_1 with larger parts of the catenary line on the seafloor to A_4 with no part of the catenary line on the seafloor. The line lift off is due to the horizontal displacement of the floater or vessel and causes the line tension to increase and the angle relative to the horizontal to decrease. These two effects together cause a horizontal restoring force on the floater, that increases in a non-linear manner.

Catenary mooring lines are mostly made of steel chains and/or wire and the restoring force is provided by

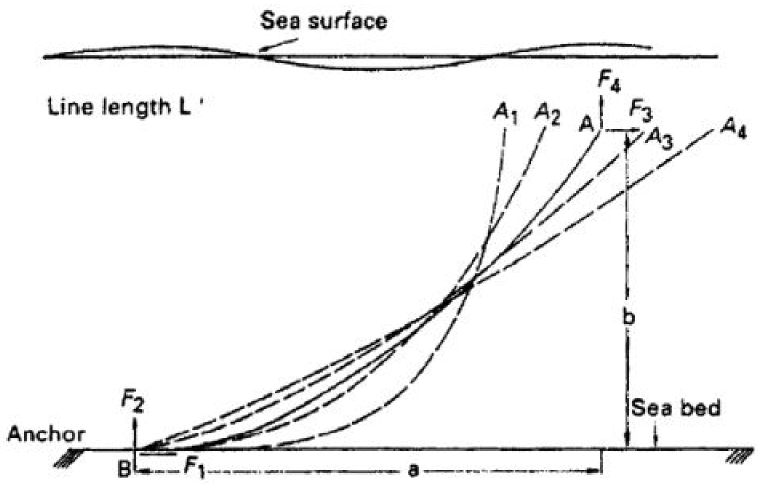

Figure A.2: Shape of catenary mooring line at different positions. Courtesy: Handbook of Offshore Engineering [8]

the weight of the mooring line itself. This self weight causes a problem when used in deeper waters where the chain will succumb to its own weight. Large parts of the lower section of a mooring line are on the seafloor to provide additional strength in stormy conditions and to provide frictional resistance with the seafloor. Because the catenary mooring line lays on the seafloor, the anchors for these lines can be designed on purely horizontal force. When the connection point to the anchor is below the seafloor, some vertical forces can occur but this will be addressed in the detailed design [7][8][35][37].

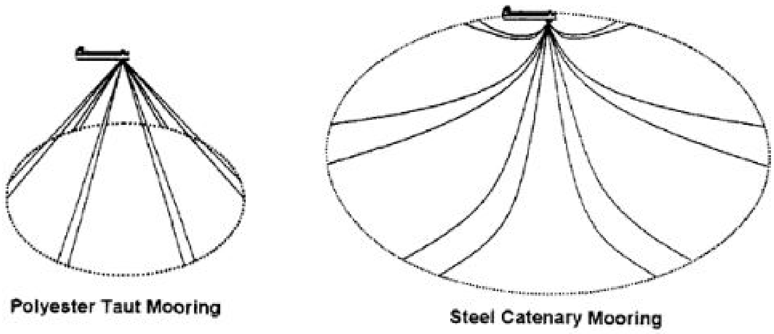

Figure A.3: Taut vs Catenary system. Courtesy: Handbook of Offshore Engineering [8]

A.3.2. Taut

A taut system consists of a group of stretched mooring lines of which the total submerged weight is so small that it can be ignored [37]. The restoring force of a taut system is defined by the elastic stretch of the used wire and tension in the wire is kept by making use of the buoyancy of the floater. This elasticity is very complex and is not constant but varies with: the load range, mean load and age of the line [8]. Other important factors that should be taken into consideration when working with taut lines are hysteresis, heat build up, fatigue and creep. Compared to a catenary system, a taut system is described as a straight line that is connected to the seafloor at an angle. This means that both horizontal and vertical forces are applied on the anchor which has to be taken into account when choosing an anchor [7] [37].
Taut lines are often made of synthetic materials that are a lot less expensive and have a smaller footprint than the material catenary mooring lines are made of. The fabrication of these synthetic lines are often also a lot less complex and their fatigue properties can be a lot better than that of a steel catenary system. Furthermore the absence of a curve decreases the length of the line. This last factor makes a taut system a very attractive option for deepsea applications where the catenary mooring lines tend to get too long [7] [35] [37].

A.3.3. Tension Leg

The tension leg mooring system is specially used for tension leg platforms. The buoyancy of the floater is larger than its weight which leads to an upwards net force without a mooring system. The tension leg mooring system connected to the platform is under tension which equals the upwards net force. The horizontal motions of the system are limited because of the tethers, but small vertical motions can occur in extreme conditions. These small vertical motions can lead to snapping loads on the system which have to be dealt with carefully. When one of the tethers snaps or breaks, the whole system becomes unstable which is catastrophic for the FOWT as a whole [37].

A.3.4. Concluding Remarks Mooring Configuration

When comparing the three discussed mooring configurations the tension leg configuration can be compared to a taut system because the lines are in a straight line and under tension. These two configurations have the clear advantage that they are better for deep water applications because they use less material than the catenary solution. In practice a lot of configurations that go to deeper waters have a combined system. An example of such a system is shown in Figure A.4. Here you can see that the bottom part of the mooring line is a chain section that can be described as a inverse catenary shape. This part is connected to a suction pile anchor and to the middle part which is a taut fiber rope without a catenary shape. The top part is again a chain with a catenary shape that is connected to the floating structure. There are a lot of details in this figure that show the complexity of the mooring line. The chain is explained in subsection A.4.1 and the fiber rope is explained in subsection A.4.2. Lastly the connectors are explained in subsection A.4.3.

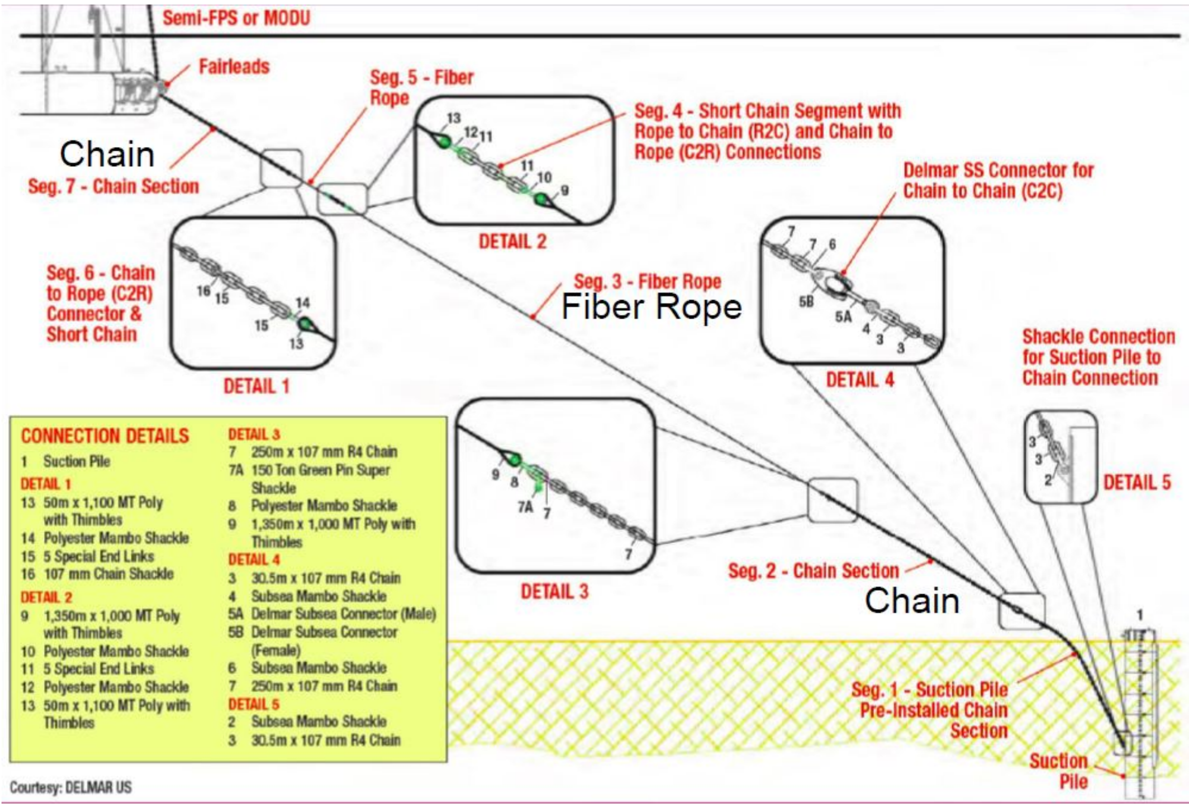

Figure A.4: Example of a combined mooring system for a Semi-FPS or MODU. Courtesy: DELMAR US. Taken from "Floating Structures & Offshore Moorings Mooring Systems - Lecture 12 Mooring Systems" [33].

A.4. The Mooring Line

The mooring lines can be made of either a chain or a rope and different materials can be used depending on the requirements. There is the chain, used for the catenary mooring lines and there is the wire or rope which is used for the catenary, taut and tension leg solution. A lot of times the chain and wire can also be combined and use each others strengths to make a complete system.

A.4.1. Chain

The chain is either a stud-link chain or a studless chain and both are shown in Figure A.5. The stud-link option is commonly used for FPSOs that are only designed to stay at one location for a certain duration. It is proven to be strong, reliable and relatively easy to handle compared to the studless chain. The studless chain is used for permanent mooring solutions because of its better fatigue life. The absence of the stud results in a decrease in weight per unit of strength [7] [8].

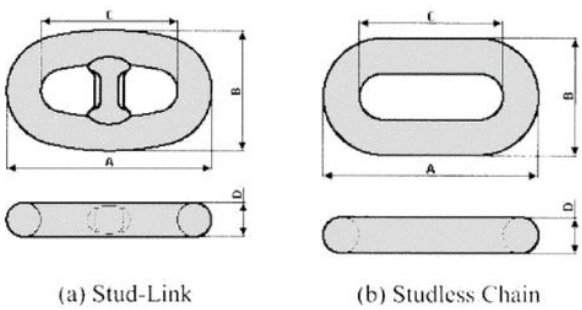

Figure A.5: Stud-link chain vs Studless chain. Courtesy: Handbook of Offshore Engineering [8]

A.4.2. Rope

The rope consists of individual wires that are wound in a helical pattern to form a "strand". There are three commonly used cables: the six strand cable, the spiral strand cable and the multi-strand cable. These are shown in Figure A.6. The six strand cable is the most used type in offshore applications because of its lateral flexibility and great longitudinal stiffness. It typically consists of 12, 24 or 37 wires per strand, depending on strength requirements [7][8][37].

The core of the cable is important for support of the outer wires and in some cases, when required, it can ab-

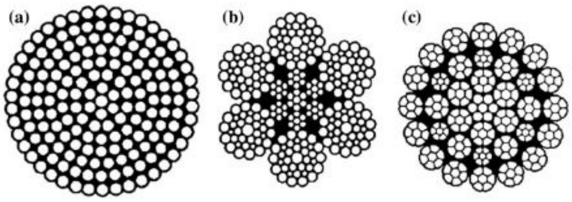

Figure A.6: Spiral strand, six strand and multi-strand cable. Courtesy: Floating Offshore Wind Farms [7]

sorb shock loading. There are different materials that can be used depending on the required capabilities. An example is a fibre core but it is not commonly used in the offshore industry. For steel wires, API "Specification on mooring chain 2F" specifies a certain oversize to take into account the corrosion. In case this becomes too expensive, plastic or zinc can be used to create a casing [8].
There are also non-metallic lines, ropes or cables that can be used as a mooring line in the offshore industry. Examples of such a material would be synthetic materials like: Polyester, Aramid and HMPE ropes [11]. These ropes do not corrode or deteriorate and can be a lot lighter, cheaper, have a lower footprint and can have better fatigue properties than the steel wires. An disadvantage is that they can be cut relatively easy compared to steel wires or chains [7]. Because of this, the top part of the mooring system, could be made of a steel wire or chain and thus eliminate this problem. This does require mooring connectors between the different sections which are explained in subsection A.4.3. The material properties of synthetic wires can be quite complex and when utilizing these materials extensive research is required. When the wire is put under tension and thus loses its catenary shape, it is called a taut system as explained in subsection A.3.2.

A.4.3. Mooring connector

When connecting a mooring line to the anchor or to the floater there are different connection methods to be evaluated. These connectors can also be used in mooring configurations where taut and catenary systems are combined. All of the discussed connector are shown in Figure A.7
The most used is the Shackle or D type connector which consists of a body with two holes through which a bolt is inserted. It can be used for both temporary or permanent mooring lines. Another widely used connector is the kenter which is used to connect two chain links o the same size. A kenter is not used in permanent moorings because its fatigue life is less than the chains fatigue life.

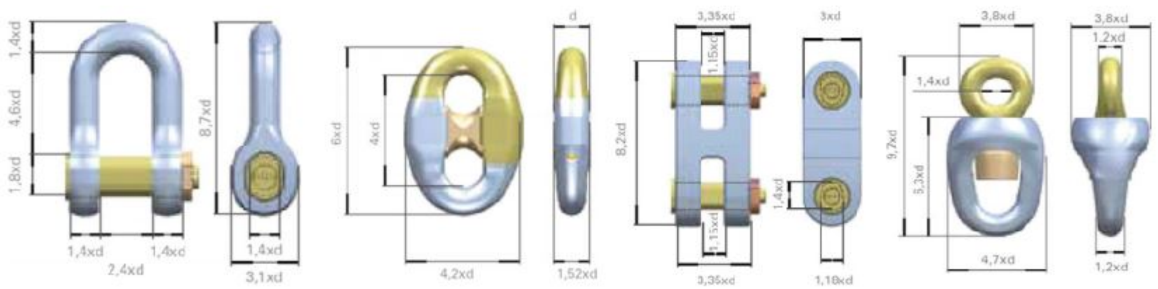

Figure A.7: Shackle (D-type), Kenter, H-type and Swivel connectors. Courtesy: Floating Offshore Wind Farms [7]

The H-type connector is valued in the offshore industry because of its robustness and flexibility. It can almost be used as a universal connector since it can connect almost anything. It can be used to adjust lengths dur-

ing installation, or a subsea connector and it can be designed as a strong lifting point for installation and/or recovery[7].
The swivel is a type of connector that prevents twisting and bending of lines by enabling degrees of freedom. It is commonly used near the anchoring system. It is important to note that in the internal mechanism large amounts of friction occur due to the high loads. This can be prevented by using certain special surfaces as bearings [7].

A.5. Anchor concepts

There are multiple different ways of anchoring a floating body to the seabed and in this chapter the different anchoring options are addressed and their advantages and disadvantages are discussed in their respective sections. In the figure below you can see the six different anchors commonly used in the offshore industry and that are addressed in this literature research. There is a difference made between horizontal and vertical forces the anchor can cope with. From mostly horizontal loading due to a catenary system too mostly vertical forces from a tension leg and finally a combination due to a taut system.

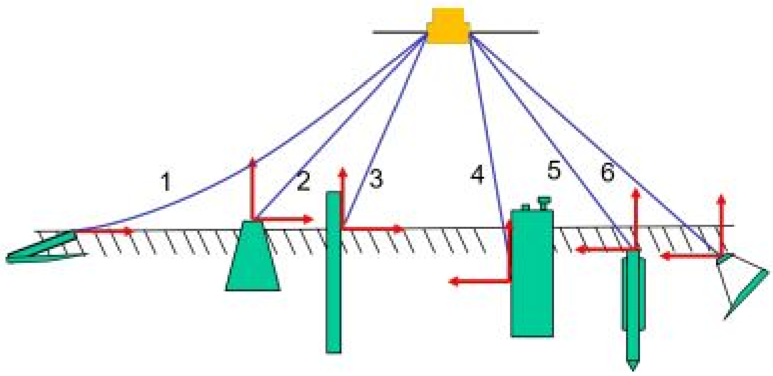

Figure A.8: Different Anchor designs. Courtesy: Doctoral theses Kun Xu [37]

1. Drag Embedment Anchor
2. Dead Weight Anchor
3. Pile Anchor
4. Suction Anchor
5. Gravity Installed Anchor (or Torpedo Anchor)
6. Vertical Load Anchor

The most used permanently moored anchors are the driven pile and suction pile anchors. These methods have been around for many years and have been researched extensively. High efficient drag embedment anchors (DEA) and vertical load anchors (VLA) are mostly used for non-permanent locations although their recent developments have made them strong contenders. When penetration is impossible the deadweight anchor is used. The gravity installed anchor (or torpedo anchor) is a relatively new anchor concept and on the rise. It has mostly been used in mobile offshore drilling units and permanent moorings but it needs site investigation, soil characterization, foundation analysis and foundation capacity assessment. Its ease of installation in deeper waters does give it a great advantage. Its biggest disadvantage is that the intellectual property and knowledge is with Petrobas.

A.5.1. Drag Embedment Anchor

Drag embedment anchors (DEA) or fluke anchors are installed by dragging the anchors along the seafloor with an anchor handling vessel and the anchor sinking in due to the drag. They can be designed to fully penetrate into the seabed but some are also designed to only partly sink in. This installation process is relatively low costs compared to methods used by other anchors. Another advantage of a DEA is that it is recoverable during decommissioning. In their early implementation they were not used as permanent moorings but through considerable progress in the technology they are now used as such [7][27].
Drag anchors can be described with triangular geometry or similar, known as the fluke, which generates the holding capacity in horizontal direction. The fluke is attached to the anchor line by a "shank" that consists of 1 or more plates and has the sole task of connecting the 2 components. The angle between the fluke and the shank should be set at such an angle that soil failure occurs roughly parallel to the fluke. This angle is typically set around 30 degrees for most soils but for soft clays it is set at 50 degrees [27]. In Figure A.9 a DEA example is shown.
The holding capacity is determined by the resistance of the soil in front or above the anchor. Because the

Figure A.9: Typical Drag Embedment Anchor. Courtesy: Vryhof Anchor

anchors mostly do not penetrate very far the vertical resistance is mostly negligible compared to the horizontal holding capacity. There are charts that provide an estimate of holding capacity, drag resistance, and penetration depth as a function of anchor weight or range of soil types. These charts are anchor specific and not used as design standards but more as a rough guidance in estimating the anchor size. A DEA is quite an attractive option for mooring solutions because it has a high efficiency (weight compared to holding capacity). The efficiency can be between 20-90 times its own weight depending on soil conditions [37] [27]. A DEA does however have the disadvantage that the installation method of dragging the anchor does not achieve precise positioning compared to other anchors. The load capacity of the anchor of the anchor depends on the depth of the anchors penetration but this cannot be predicted with a high degree of certainty. Because of this uncertainty in DEA load capacity the anchor has to be checked with a proof load test after installation. This does require a certain bollard pull capacity and special equipment on the anchor handling vessel [27].
In sands and stiff clays the DEA will experience shallow penetrations and because of this there will be minimal vertical pull-out resistance. But when a DEA is installed in a soft clay the penetration can be significant and because soft clays exhibit increasing strength with depth, a DEA can provide substantial vertical resistance. In this case a DEA can also be used for a taut mooring system [27].

A.5.2. Dead Weight Anchor

The gravity anchor or deadweight anchor has been commonly used for centuries. As implied in the introduction of this section the deadweight anchor is mostly used when there is no penetration possible. This will typically occur in a rock seabed but does not mean this is the only implication of the deadweight anchor. It can also be used in softer soils, where the anchor might sink in and create additional loading capacity. Over time the anchor can sink in further and further which means the force it can handle will progressively increase [7].
The vertical loading capacity is equal to its submerged weight which is relatively small compared to other anchoring types (order of tonnes). The horizontal load capacity can be determined by the submerged weight and an appropriate friction coefficient reliant on the soil conditions. Because only the submerged weight

counts for the horizontal and vertical load capacity the efficiency is very low compared to the other anchoring options [27].
Due to its large size and weight the anchor is commonly seen as difficult and costly to install and remove. The low costs for the fabrication, due to its usage of scrap metal, does balance the balance the costs. Another advantage of a deadweight anchor is that it retains its usage even after a storm moves it from its original position when the holding capacity is exceeded [7].

A.5.3. Pile Anchor

The pile anchor is a open-ended pipe that can have a large diameter and are relatively simple to fabricate. They are able to resist horizontal and vertical loading which makes them good for a wide variety of applications: taut, catenary and TLP systems. A pile anchor can also be installed in almost any soil condition which makes them the most widely applicable anchoring system. The installation process is done through hammering the piles into the soil or by using vibrations to let them sink into the soil. With longer piles, greater depths can be achieved which means that they can make use of the high soil strengths at those depths [7][27]. The holding capacity is determined by the friction between the surface of the pile and the surrounding soil. With different soil layers different friction coefficients are needed to determine the holding capacity. With these py-curves can be constructed in which the applied force is put against the displacement of the pile. Another advantage is the accuracy of the positioning of the anchor. This is particularly important when multiple anchors for one construction are installed [7].
A disadvantage of pile driven anchors is that it becomes difficult to install them in deeper waters. When working under water it is difficult to create enough force to hammer them into the soil. Nevertheless, this method has been used up to water depths of 2400m due to the means of hydraulic underwater hammers [27]. The noise impact and vibrations from the hammering of the piles causes grievous harm for the marine life. Because of this there are multiple ways of cancelling this noise and other ways of installing these piles are being researched. Another disadvantage of driven piles is its impossibility to remove them after installation. This is a limiting factor for its application in some countries [7].

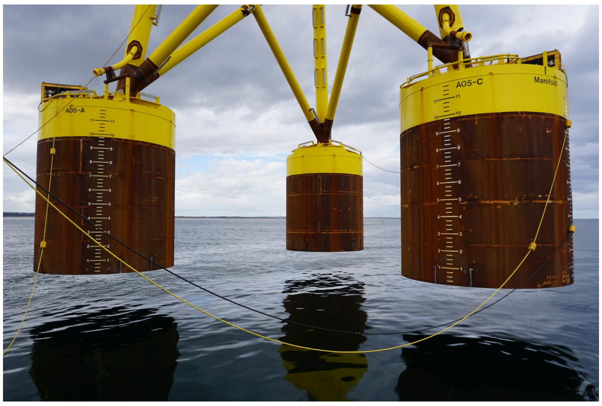

Figure A.10: Suction Pile by SPT Offshore

A.5.4. Suction Anchor

A suction anchor or suction pile consists of a large diameter cylinder with a pump to suck out the water and an example can be seen in Figure A.10. Because of its ability to cope with vertical and horizontal loading the suction piles have been used for TLP's in the past but they are mostly used for catenary and taut mooring systems. A suction anchor is partially installed by self-weight and for full installation the pump is used to create a "suction effect" by pumping out the water from the cylinder. This induces a differential pressure that pushes the cylinder deeper into the soil. This installation method has clear advantages compared to pile anchors because it does not require heavy underwater hammers and is a lot less invasive when looking at the noise and pollution of the surrounding area. Furthermore the removal of of suction piles is very easy because the installation process only needs to be reversed and than the relatively light constructions can be lifted of the seafloor. Its accuracy of placement is a very important advantage just as the driven piles [7] [27].

Suction piles are typically designed with relatively thin walls which increases the risk for buckling. As means of countering this plate stiffeners and ring stiffeners may be installed on the inside of the cylinders. If the cylinder does not sink in far enough, the "plug", which needs to be formed to seal of the cylinder at the bottom, will rise or will let in too much water. When this happens the cylinder will not sink in further and thus will not work. This plug thickness needs to be considered carefully. When installing suction piles a sufficiently high water column is needed to create a pressure difference and to avoid cavitation in the pumps used to pump out the water [7].
Suction piles are limited by their installation process and matters become more complicated when loose sandy soils, stiff clay soils or rocky sediments are encountered. These limit the penetration by self weight or do not create the "suction effect". It is not unfeasible but other tools need to be added to fully install the suction pile. You could for example push the suction pile through the layer of soil that complicates the installation [7][27].

A.5.5. Gravity Installed Anchor

The gravity installed anchor, also called the torpedo anchor, penetrates the seabed due to the kinetic energy obtained from free falling through the water column. This installation method saves a lot of time compared to other methods and it does not require a installation vessel with significant bollard power. It does require a certain depth for the anchor to have enough time to reach the desired velocity it needs to penetrate the seafloor to the required depth. That's why these types of anchors are typically used in ultra deep waters and are widely used in Brazil where, by estimation, 2000 torpedo piles were installed by Petrobas [12]. Here they are used for Floating Production Storage and Offloading (FPSO) facilities.
The gravity installed anchors have both out of plane lateral and vertical loads it can handle depending on the used design. Their loading capacity comes from the friction of the sediment and lateral sediment resistance. These anchors usually consist of a cylindrical structure with a nose cone and stabilizing fins. An example can be seen in Figure A.11. It is important to note that having good assertive soil data is a must when trying to install these torpedo anchors. Otherwise their behaviour and holding capacity is unpredictable. Another gravity installed anchor is the OMNI-Max anchor designed by Delmar Systems. It also uses torpedo like structure but is additionally rotated into the seafloor creating more loading capacity [7][27].

Figure A.11: Torpedo Anchor a gravity installed anchor. Courtesy: InterMoor

A.5.6. Vertical Load Anchor

For vertical load anchors or plate anchors it is common to have 2 modes in which they operate: the first being the installation mode and the second being the normal loading mode. Depending on design a shear pin or a difference between installation line and loading/operating line is made to switch between the two modes. Depending on this design the anchor can or cannot be removed. A vertical load anchor has a lot of similarities to the drag embedment anchor: it has a fluke and a shank. The fluke to generate load capacity and the shank connecting the fluke to the anchoring/loading line. When the loading mode is engaged the operating line will be perpendicular to the fluke and generate as much vertical pull-out resistance as possible.
A vertical load anchor can also be installed with combined load capacity meaning that both vertical and horizontal forces can be resisted. Its shape is usually triangular or rectangular but there are many specific designs

for different soils and/or different conditions. There are two ways of installing these anchors: either by dragging them or using suction piles to push them [7].

A.5.7. Conclusion Anchor Concepts

The six different anchor concepts that were discussed in this section are now summarized in Table A.3. Every anchor can be specifically designed for a certain situation and thus some no's in the table can be changed into a yes in certain anchor designs. These changes do impact the overall design and might make the anchor design very expensive or defeat its purpose. The precise positioning that is not custom for DEA's and VLA's can be achieved when using a suction pile to install the anchors instead of dragging it along the seafloor until the desired depth is reached. This does come with extra costs because a suction pile will have to be brought along. Furthermore a drag embedment anchor is usually not used for permanent moorings but certain designs can be used as such and the same can be said for vertical load anchors. A deadweight anchor can also be decommissioned but because of its size and weight its very expensive and thus it is considered as not decommissionable. The summary table is made for the most general case of each anchor design.
Lastly the efficiency of the different anchor types is listed. Here the drag embedment anchor and vertical load anchor are listed in category 1 meaning they are the most efficient weight to bearing capacity anchor. This is because they are more deeply embedded in the soil and thus get their bearing capacity from deeper soils that are stronger. The pile anchor, suction pile and torpedo anchor are in class 2 meaning because they get their bearing capacity mostly from the friction with the soil close to the mudline. Finally the deadweight anchor is in class 3 because it gets most of his capacity from his weight. Later on the efficiency increases a little but is still by far the worst weight to bearing capacity ratio.
The anchor that is used for a multiline anchor concept will experience multidirectional loading as will be explained in section A.6 and thus the chosen anchor concept has to be able to cope with this aspect. The anchor types that are in consideration when keeping in mind this specification are: pile anchor, suction pile, deadweight and torpedo anchor. The deadweight anchor is to inefficient and thus will not be chosen. Although it is proven that the pile anchor can be installed in deeper waters, it still comes with to many difficulties and thus the pile anchor will not be chosen. The torpedo anchor is patented by Petrobas and thus will not be used in this thesis. This leaves the suction pile anchor as the best candidate for the thesis on the design of multidirectional anchor system for floating offshore wind farms. This thesis is also conducted in cooperation with SPT Offshore who have considerable knowledge on suction piles.

Table A.3: Summarizing the different anchor concepts

	DEA	Deadweight	Pile Anchor	Suction Pile	Torpedo	VLA
Permanent mooring	no	yes	yes	yes	no	no
Decommissioning	yes	no	no	yes	yes	yes
Multidirection	no	yes	yes	yes	yes	no
Precise positioning	no	yes	yes	yes	yes	no
Deep water	yes	yes	no	yes	yes	yes
Efficiency	1	3	2	2	2	1

A.6. The Multiline Anchor Concept

Several floating offshore wind turbines with multiple mooring lines all connected to their own anchor currently exist and are being installed at sea. The amount of mooring lines and anchors differ from project to project ranging from three to six lines. When looking at an array of FOWT, which will be the next step in commercializing the FOWT-sector, a decision can be made to connect multiple lines from different FOWT to one anchor but keeping the amount of mooring lines the same. By doing this the amount of anchors and geotechnical site investigations needed for a floating offshore wind farm can be reduced significantly [13].
The geometric design of offshore wind farms is traditionally determined by economic considerations that a directly related to the power production of these FOWT. When multiple wind turbines are in a row the wake effects have to be considered and accounted for when positioning the wind turbines and should also be accounted for when choosing a multiline anchor lay-out. When the distances between turbines have to be increased because of these wake factors the mooring lines that are connected to the anchors also need to in-

crease in length which carries considerable costs. These wake effects will be considered in the base of design and thus for now only the geometries of multiline anchor concepts will be considered and later scaled to the right distance.
The general practice is to use 3 mooring lines per FOWT but when using more mooring lines the reliability of the system increases also with respect to the broken line criterion. Using more lines could also make smaller anchor sizes possible. This will increase the costs because of the increase in the amount of mooring lines but the smaller anchor size will decrease the costs of the anchor.

There are multiple geometries that can be utilised such as the square or the hexagonal unit cells and the

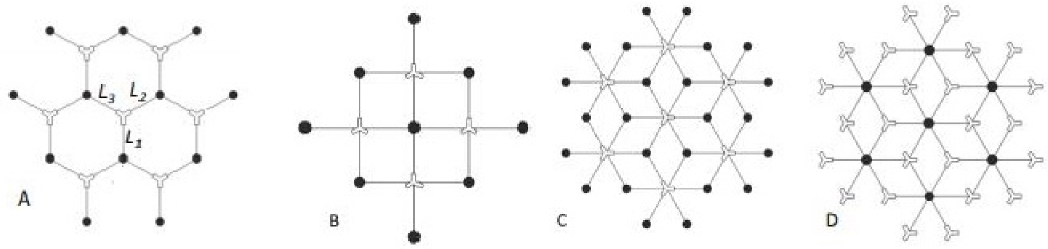

Figure A.12: Multiline concepts. Courtesy: Casey Fontana [13]

amount of lines per anchor or per FOWT can differ. In a research done by Casey Fontana [13] a few options are given and the are shown in Figure A.12. The first concept, A, having 3 mooring lines per FOWT and 3 mooring lines per anchor with a hexagonal shape. The second concept, B, using a squared approach with 4 mooring lines per FOWT and 4 mooring lines per anchor. The third concept, C, has 6 mooring lines per FOWT but only 3 mooring lines per anchor. Because of this the efficiency goes down compared to the first two concepts. The last concept has 3 mooring lines per FOWT but 6 mooring lines per anchor.
In another paper by Casey Fontana [15] a comparison is made in the amount of anchors used between three different cases. The three cases looked at are the cases that have 1, 3 or 6 mooring lines connected to each anchor. The reduction in amount of anchors is shown in a graph in Figure A.13.

This approach to the mooring system, where one anchor shares mooring lines with multiple FOWT does

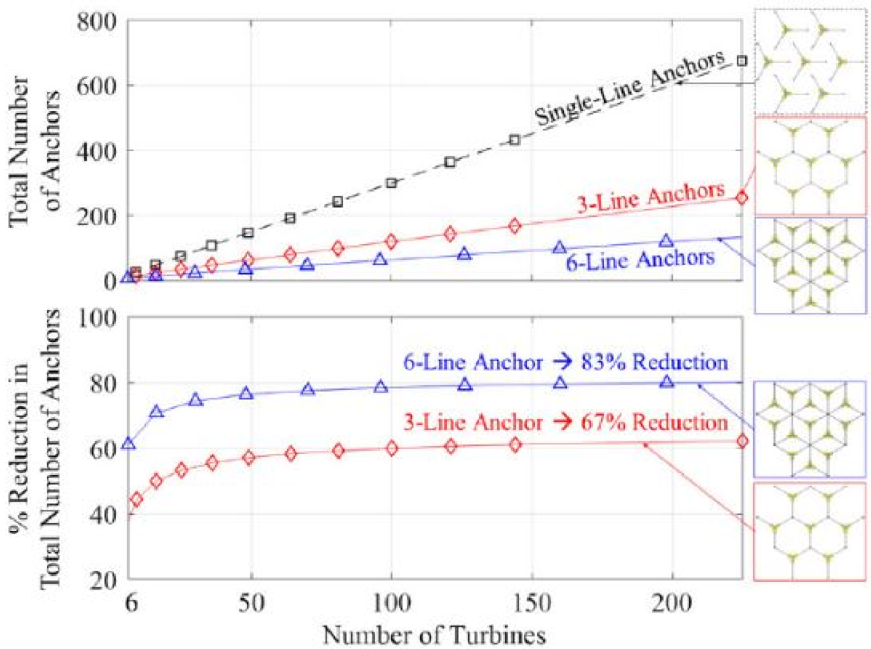

Figure A.13: Total number of anchor reduction. Courtesy: Casey Fontana [15]

come with some setbacks. The loads acting on the anchor differ in magnitude and direction depending on where the waves and wind are coming from. When each anchor is only connected to one FOWT the force direction will have one direction in which the net force will work but now this net force vector will change direction. Not every anchor is equipped against these multi-directional loading conditions and thus this should be taken into account when working with a multiline anchor system [13][15].

A.7. Anchor forces

When trying to calculate the net force the different mooring lines emit onto the anchor it is easiest to start at a catenary system where parts of the mooring line are on the seafloor leading to only horizontal forces (XY-direction in Figure A.14). It is also not taken into account that the connection point to the anchor is below the mudline which still results in some vertical force. The multiline force on one anchor when 3 mooring lines are connected to the anchor, is shown on vector basis in Figure A.14.
Another approximation made is that the platform motions are small compared to the mooring line lengths.

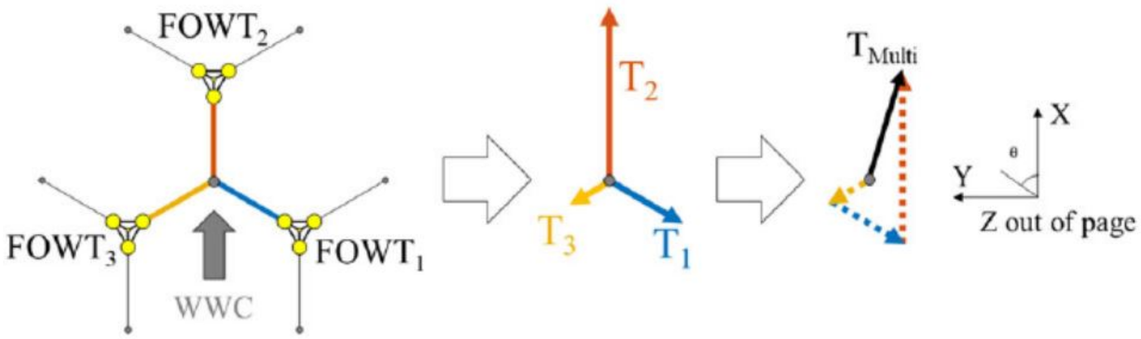

Figure A.14: Multiline net force on a single anchor. Courtesy: Casey Fontana [13]

This means that the changes in force direction, due to the movement of the platform, are so small that the lines connected to the 3-line anchor apply tensions at 120° from one another. Taking these approximations/simplifications into account the following formula's can be setup for the multiline tension force for a 3 line anchor:

$$T_{\text{multi}}(t) = \sqrt{T_{\text{multiX}}(t)^2 + T_{\text{multiY}}(t)^2} \tag{A.1}$$

$$T_{\text{multiX}}(t) = T_2(t) - \cos 60\,[T_1(t) + T_3(t)] \tag{A.2}$$

$$T_{\text{multiY}}(t) = \sin 60\,[T_3(t) - T_1(t)] \tag{A.3}$$

The 6-line vectors are shown in Figure A.15 and each line applies tension at 60° from one another. This results in the following formula's:

$$T_{\text{multiX}}(t) = T_2(t) + \cos 60\,[T_4(t) + T_6(t) - T_1(t) - T_3(t)] - T_5(t) \tag{A.4}$$

$$T_{\text{multiY}}(t) = \sin 60\,[T_3(t) + T_4(t) - T_1(t) - T_6(t)] \tag{A.5}$$

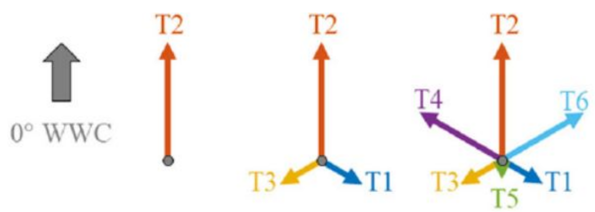

Figure A.15: Multiline vector forces for 1- ,3- and 6-line anchor for 0° wind, wave and current (WWC). Courtesy: Casey Fontana [13]

A.7.1. Multiline anchor force comparison

In the research done by Casey Fontana [15] the multiline anchor net forces are calculated under dynamic load cases (DLCs) and one Survival Load Case (SLC) that are based on data from the VolturnUS project. The load cases are: DLC 1.2 wind dominated, DLC 1.6 wind-and-wave dominated and SLC the wave dominated

extreme case. The simulation software used is the NREL's FAST (fatigue, Aerodynamics, Structures and Turbulence) Code v8. It is a fully coupled aero-hydro-servo-elastic simulator capable of predicting motions in the time domain [21]. In the FAST simulation the option MoorDyn was chosen which is a lumped-mass mooring model that simulates mooring line and the anchor force dynamics. This model takes into account the: mooring line axial stiffness and damping, weight and buoyancy forces and Morison's equation. What is not included in the MoorDyn simulation but is added afterwards are the friction forces the catenary system has with the seabed.
The system that is looked at in the paper is the NREL 5MW reference turbine with an OC4-DeepCwin semi-submersible floating system and a catenary mooring configuration in 200m waterdepth. The peak forces for the 3 different systems are shown in Figure A.16.

What can be noted is that the 3-line anchor would require a less strong anchor than the single line anchor

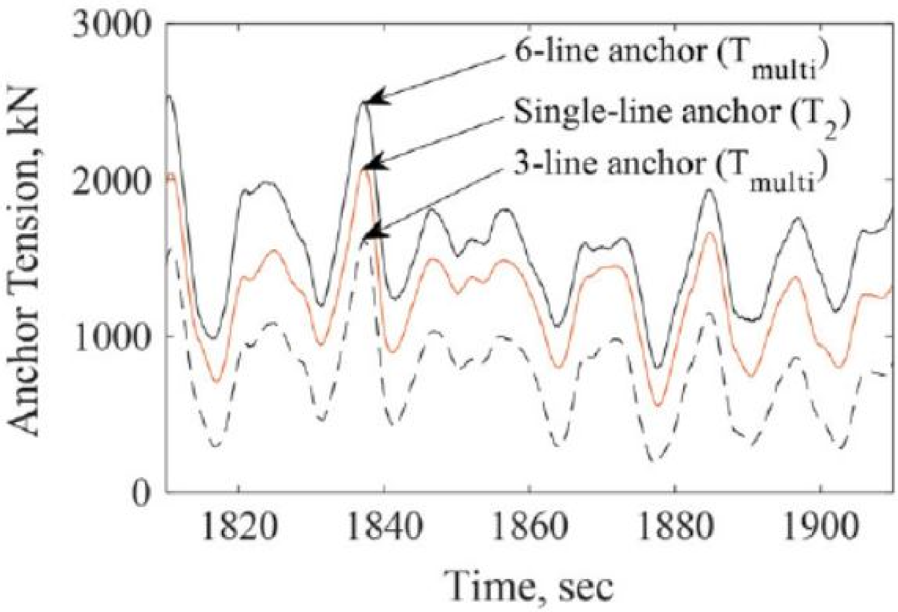

Figure A.16: Comparison of peak force event DLC 1.2 with 0° WWC. Courtesy: Casey Fontona [15]

but that a 6 line anchor would require a stronger anchor. This can be contributed to the fact that when having 3 lines, T_1 and T_3, have a component in the negative X direction and thus they cancel out some of the force that is projected on the anchor by T_2. When looking at a 6-line anchor not only more FOWT contribute to the overall forces on the anchor but also the forces T_2, T_4 and T_6 have a contribution in the positive X-axis and those are the biggest forces. These add up and because there are more FOWT on the same anchor this adds up to a bigger force on the anchor than the 3-line system and a bigger force than the single line system.
In the same study done by Casey Fontana [15] the directionality of the multiline anchor force is looked at and what can be concluded is that the multiline anchor will be subjected to loading from any direction over the course of its design life. This conclusion stems from the fact that the net force on the anchor is aligned with the direction of the environmental load. Furthermore force direction reversals within a single force cycle are present in extreme cases and thus an anchor with axisymmetric strength is required when working with multiline anchor systems.

A.7.2. Floater force comparison SPAR vs Semi-submersible

In a research conducted by K. Balakrishnan [4] the 5MW NREL turbine SPAR system is simulated using FAST v8, the same simulation system as described in the section before. The same load cases and Wind Wave Current (WWC) directions are used as in the research done by C. Fontana [15] and the anchor tension forces between the two systems are compared. Both systems can be seen in Figure A.17. In this figure you can clearly see the difference in depth these two structures will have.

When comparing the anchor force loads it can be noted that the SPAR system has a lower maximum anchor

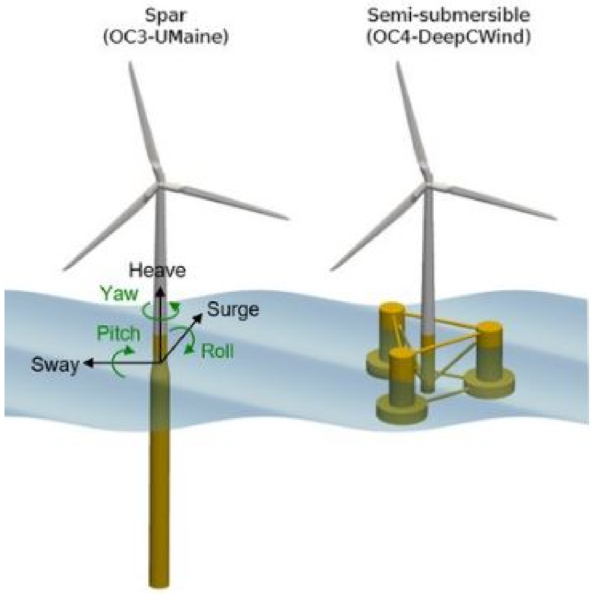

Figure A.17: The NREL 5MW turbine 1) SPAR 2) Semi-submersible. Courtesy: NREL[20]

tension force, a lower mean anchor tension force and a lower standard deviation of anchor tension force. From this it can be concluded that when using a SPAR system the anchors needed would be smaller than those needed for a semi-submersible structure [4]. The maximum anchor tension force is shown in Figure A.18. Furthermore it can be seen that the difference between SPAR and semi-submersible is biggest in the Survival Load Case (SLC). This can be contributed to the fact that the semi-submersible does have a bigger area that interacts with the waves and win and thus has a bigger contribution in the wave dominated load case. The DLC 1.2 case is wind dominated and has a smaller difference in maximum anchor force than the other two. There is still a small difference that can be contributed to the bigger size of the structure above the water.

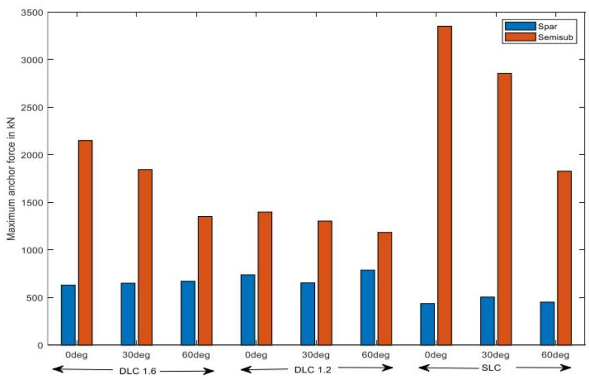

Figure A.18: Maximum anchor tension force in 0°, 30°, 60°WWC for all load cases [4]

A.7.3. Floater Forces 15MW Wind Turbine

The following graph is taken from a study conducted by the University of Maine on the NREL 15MW semi-submersible wind turbine generator [1]. In this study the reference turbine uses three catenary mooring lines that are connected to their own anchor. In Figure A.19 the FAIRTEN values are the maximum fairlead tensions that are connected at the platform's three outer columns 14m below sea water level. The ANCHTEN values are the maximum anchor tension values subjected by a catenary mooring system at 200m depth. These values are lower because the catenary system has weight that adds extra force and the friction between the chain and the seafloor also reduces the force on the anchor. The simulation software used are FAST and MoorDyn softwares described earlier. Additionally WAMIT v6 is used to solve the first-order hydrostatics, diffraction and radiation problems. It also solves the second order wave forces and produces a Quadratic Transfer Function (QTF) from which the hydrodynamic coefficients, added mass and wave-radiation damping, are produced. These are needed to simulate the motions equation of the semisubmersible turbine. The viscous damping model was calculated using the OpenFOAM, an open-source computational fluid dynamics code.

What can be taken from this research is that the UMaine VolturnUS-S Reference Platform for the IEA Wind

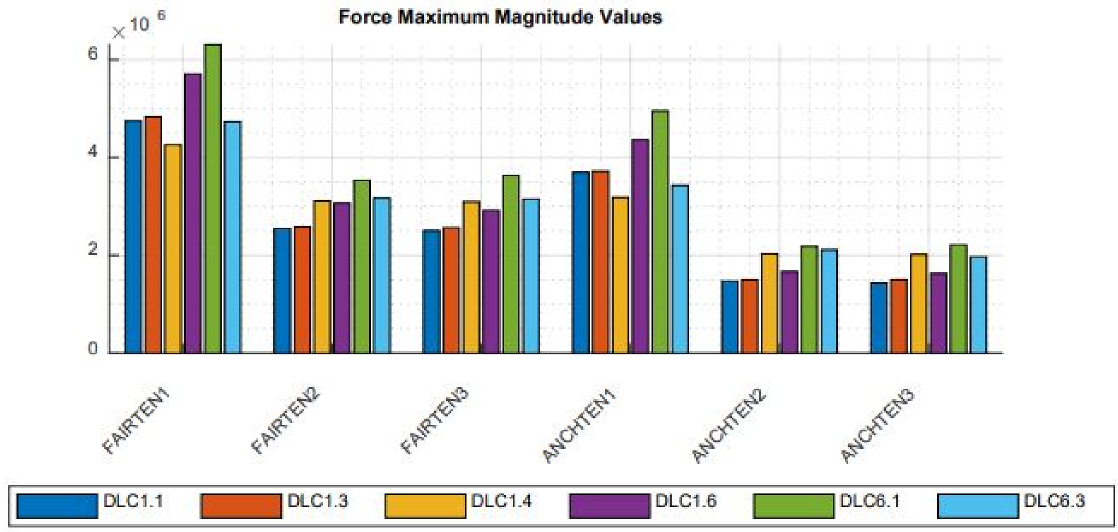

Figure A.19: Force maximum Magnitude Values. Courtesy: NREL and University of Maine [1]

15-MW Offshore Reference Wind turbine has a peak platform pitch angle that is less than 6°and a maximum peak acceleration during DLC 6.3 of $1.5 m/s^2$. Furthermore the blade deflections due to the pitch angle are also not excessive and the surge-sway offset off 25m also does not exceed boundaries. Lastly the tensions in the fairleads are not higher than the breaking strengths of the chain. All of these findings conclude in the fact that the configuration in this research could be a configuration used in the future and thus is a good validation for calculated anchor values.

A.8. Multiline Ring Anchor

When using a multiline system multiple anchor lines are connected to one anchor which leads to the connection problem. Normally an anchor is designed with one connection point and for suction piles this connection point is halfway between the mudline and the lip, as can be seen in Figure A.4. This is done to increase the static bearing capacity of a suction pile as explained in subsection A.5.4. When now trying to connect multiple catenary lines to an anchor more uplift is created because more lines exert a vertical force on the pile and they all add up together. Normally one would assume almost only horizontal forces because of the catenary system but now this changes. A suction pile is well equipped against a combined vertical and horizontal load so this is not expected to be a big problem.

When connecting different anchor lines to one suction pile one could include a couple of extra pad-eye's where the anchor lines connect to the suction pile but this would increase the chance of buckling and would require a thicker suction pile or local stiffeners. There is another solution: in a study done by J. Lee [24] a Multiline Ring Anchor (MRA) is used as an anchor point for a multiline system with up to 6 mooring lines. This MRA is installed using a suction pile and the left embedded in the soil. Depending on the soil condition and the used mooring configuration the depth of embedment is decided. Because the bearing capacity is still mostly dictated by friction it is not as efficient as plate anchors (DEA or VLA) but because it is situated in deeper and thus stronger soils the efficiency is up compared to suction piles, pile anchors and torpedo anchors. MRA could be used as inspiration in connecting the different mooring lines to the suction pile anchor. By using the lay-out and strengths of the described MRA a multiline suction pile could be made more efficient and stronger.

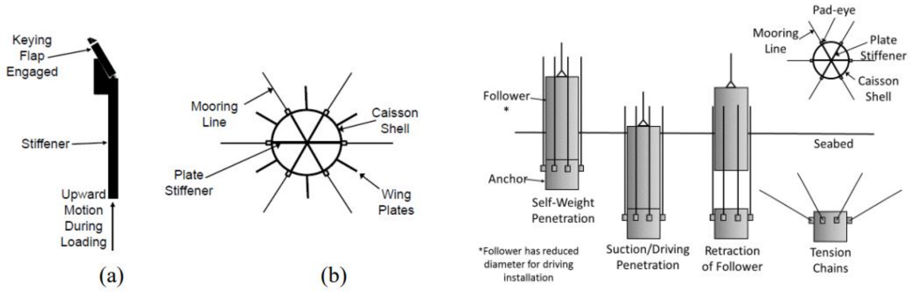

Figure A.20: Overview of an MRA and strategies for enhancing load capacity of MRA with a)keying flaps and b) wing plates and the installation procedure of an MRA using a suction pile. Courtesy J. Lee [24]

A.9. Concluding remarks and discussion of the Literature research

This thesis will conduct research on a suction pile multiline anchor system for a floating 15MW semi-submersible wind turbine. The first mooring configuration will be a catenary system. However, later in the research it will be compared to a taut or a semi-taut system. The multiline system consisting of three mooring lines per anchor and three mooring lines per FOWT will be the most probable system, because it has advantages over a 1-line or a 6-line system. The most important advantage is that it has lower loads than both the 1-line and 6-line systems. Although, if the broken line criterion destabilizes the system too much, the 6-line system could be reconsidered as a possibility.

From this scope, we can state the research question of this thesis: "What is the most effective design of a multiline suction pile anchor system for a 15MW semi-submersible floating offshore wind turbine?".

The DNV guidelines that will be used are listed in the table below. From these guidelines, multiple load cases are explained that have to be used to calculate the anchor forces. These load cases describe the wind-wave-current (WWC) distributions for different situations. Because this thesis will not be making a representative model of a floating offshore wind turbine to calculate the forces on the anchor, these will have to be taken from literature or calculated by means of scaling.

Since only one paper was found on the description of the anchor forces for a 15MW floating semisubmersible

Table A.4: DNV Guide Lines applicable for this thesis

Code	Title
DNVGL-ST-0119	Floating wind turbine structures
DNVGL-ST-0126	Support structures for wind turbines
DNVGL-ST-0437	Loads and site conditions for wind turbines
DNVGL-OS-E301	Position mooring
DNVGL-OS-E302	Offshore mooring chain
DNVGL-OS-E303	Offshore fibre ropes
DNVGL-OS-E304	Offshore mooring steel wire ropes
DNVGL-RP-0286	Coupled analysis of floating wind turbines
DNVGL-RP-E303	Geotechnical design and installation of suction anchors in clay
DNVGL-SE-0422	Certification of floating wind turbines

wind turbine [1] there is need for more data to be obtained or calculated. Another problem that arises from this paper is that there are only graphs that describe the maximum anchor forces but no exact values are given. In order to define these values more exact, a data set will be requested from the University of Maine. If this is not possible, more exact values will be obtained by scaling and comparing these results to the found values from the paper [1], as described earlier. The problem that now arises is that there are multiple maximum, mean and standard deviation values for each load case that have to be considered. These make comparing the different floater forces a complicated task. Adding the multiline anchor system, asks for the addition of directionality and phase when describing the dynamic system. This will only further complicate finding the

maximum, mean and standard deviation values exerted on the anchor.
In the next stage of the thesis, the Base of Design (BoD) will be further elaborated on by choosing soil data. It is likely that more than one data set will be chosen, since this provides the opportunity to make a more general and robust design. The suction pile will be designed according to design standards supplied by the company SPT Offshore in compliance with the DNV guidelines.

B
Appendix

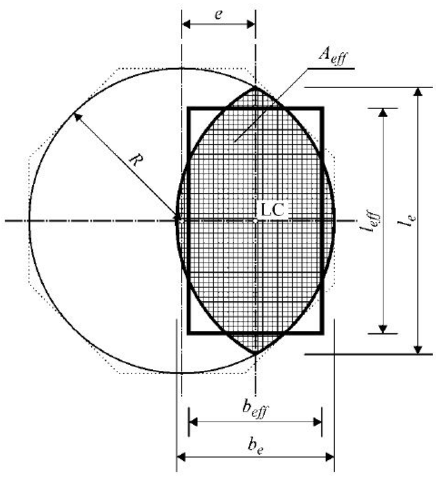

Figure B.1: Effective area of a circular foundation. Courtesy: DNVGL-RP-C212 Offshore Soil Mechanics and Geotechnical Engineering

B.1. Effective foundation theory

The effective foundation area theory has to be used when a moment is introduced in the suction pile anchor. In there is no moment thus the formula's are not used in the report. It is important that they are readily available for this thesis research thus the formula are shown below. In these formula's the effective foundation may also be represented by a rectangular with the dimensions b_{eff} and l_{eff} as shown in Figure B.1.

$$e = \frac{M_{base}}{V_{base}} \tag{B.1}$$

$$A_{eff} = 2 \cdot \left(R^2 \cdot arccos\left(\frac{e}{R}\right) - e \cdot \sqrt{R^2 - e^2}\right) \tag{B.2}$$

$$b_e = 2 \cdot (R - e) \tag{B.3}$$

$$l_e = 2R \cdot \sqrt{1 - \left(1 - \frac{b_e}{2R}\right)^2} \tag{B.4}$$

$$L_{eff} = \sqrt{A_{eff} \frac{l_e}{b_e}} \tag{B.5}$$

$$B_{eff} = b_e \frac{l_{eff}}{l_e} \tag{B.6}$$

C

Appendix

In this appendix the data for the normally consolidated clay layer is shown. First the undrained analysis is performed and the last table shows the undrained which is performed for the 45 degree angle taut mooring line.

Main parameters	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
Depth [m]	200	200	200	200	200	200	200	200	200
Height [m]	18.25	20.69	24.16	17.97	22.66	25.30	18.73	24.61	24.85
Diameter [m]	3.65	4.14	6.36	3.59	4.62	7.23	3.75	5.86	8.57
h_{side} [m]	12.16	13.79	16.11	11.98	15.11	16.86	12.49	16.41	16.56
D_{inner} [m]	3.64	4.12	6.33	3.59	4.61	7.21	3.74	5.85	8.55
D_{outer} [m]	3.66	4.15	6.37	3.60	4.63	7.24	3.75	5.87	8.58
Thickness [mm]	14.60	16.55	25.44	14.38	18.50	28.91	14.98	23.44	34.27
Embedment (h/D)	5.00	5.00	3.80	5.00	4.90	3.50	5.00	4.20	2.90
Density (ρ) [kg/m3]	1760	1760	1760	1760	1760	1760	1760	1760	1760
Submerged unit weight (γ') [N/m3]	6500	6500	6500	6500	6500	6500	6500	6500	6500
s_{u0} [N/m2]	1000	1000	1000	1000	1000	1000	1000	1000	1000
s_{u1} [N/m2]	17057	19208	22264	16816	20939	23261	17481	22657	22864
s_{u2} [N/m2]	33114	37415	43529	32633	40879	45523	33961	44315	44728
Adhesion factor (α)	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Weight plug [MN]	12.17	17.74	48.93	11.63	24.26	66.18	13.16	42.32	91.33
Weight suction caisson [MN]	0.98	1.97	7.88	1.33	2.67	10.70	2.41	4.84	19.35
Weight total [MN]	13.15	19.71	56.82	12.96	26.94	76.88	15.57	47.16	110.68

Free Body Diagram forces	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
V_{side} [MN]	1.86	3.36	6.99	2.22	4.48	8.69	2.50	6.67	9.94
H_{side} [MN]	6.22	9.05	18.91	5.95	12.10	23.54	6.72	18.07	26.92
H_{base} [MN]	0.35	0.50	1.38	0.33	0.69	1.87	0.37	1.20	2.58
V_{base} [MN]	1.25	1.83	5.47	1.20	2.51	8.21	1.36	4.55	16.60
M_{base} [MNm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_{LRP} [MN]	6.57	9.55	20.29	6.28	12.79	25.41	7.10	19.26	29.50
V_{LRP} [MN]	4.09	7.16	20.34	4.75	9.66	27.59	6.27	16.06	45.89
M_{LRP} [MNm]	-81.98	-135.20	-338.02	-77.21	-198.39	-444.22	-90.93	-325.88	-510.00

Effective Area	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
e [m]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_{eff} $[m^2]$	10.46	13.45	31.76	10.15	16.79	41.03	11.02	26.97	57.65
B_e [m]	3.65	4.14	6.36	3.59	4.62	7.23	3.75	5.86	8.57
L_e [m]	3.65	4.14	6.36	3.59	4.62	7.23	3.75	5.86	8.57
B_{eff} [m]	3.23	3.67	5.64	3.19	4.10	6.41	3.32	5.19	7.59
L_{eff} [m]	3.23	3.67	5.64	3.19	4.10	6.41	3.32	5.19	7.59

Uniform strength profile	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
N_c	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14	5.14
s_{ca}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
d_{ca}	0.42	0.42	0.40	0.42	0.42	0.40	0.42	0.41	0.38
i_{ca}	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
V_{base} (undrained) [MN]	2.88	4.19	11.40	2.75	5.71	15.36	3.11	9.90	21.01

Linear strength profile	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
k	1760	1760	1760	1760	1760	1760	1760	1760	1760
$k * B_{eff} / s_{u0}$	5.69	6.45	9.92	5.61	7.21	11.27	5.84	9.14	13.36
F_{smooth}	1.44	1.55	3.01	1.43	1.71	4.38	1.46	2.49	8.21
F_{rough}	1.93	2.30	9.68	1.90	2.88	19.89	1.99	6.51	58.95
s_{cv}	-0.04	-0.02	0.28	-0.04	0.01	0.59	-0.03	0.16	1.42
$s_{ca,new}$	-0.04	-0.02	0.28	-0.04	0.01	0.59	-0.03	0.16	1.42
$i_{ca,new}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H_1	0.35	0.50	1.38	0.33	0.69	1.87	0.37	1.20	2.58

Smooth	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
$s_{u2,new}$	1843	2040	4469	1825	2314	6783	1877	3591	13545
$d_{ca,new}$	2.35	2.39	1.26	2.34	2.30	0.87	2.36	1.60	0.43
$q_{u,smooth}$ $[MN/m]$	0.15	0.17	0.22	0.15	0.19	0.25	0.15	0.21	0.36
V [MN]	1.57	2.28	6.84	1.50	3.13	10.26	1.70	5.69	20.75
ROUGH									
$s_{u2,new}$	2470	3019	14346	2424	3897	30803	2559	9409	97266
$d_{ca,new}$	1.75	1.61	0.39	1.76	1.36	0.19	1.73	0.61	0.06
$q_{u,rough}$ $[MN/m]$	0.15	0.17	0.28	0.15	0.19	0.45	0.16	0.25	1.40
V [MN]	1.60	2.35	8.90	1.53	3.27	18.31	1.73	6.62	80.83

Applied forcing	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
H_{mean} [MN]	2.10	1.41	2.82	1.90	1.27	2.55	2.41	1.61	3.23
V_{mean} [MN]	0.98	1.97	7.88	1.33	2.67	10.70	2.41	4.84	19.35
H_{max} [MN]	4.49	3.77	5.38	4.05	3.41	4.86	4.72	3.97	5.66
V_{max} [MN]	2.09	5.27	15.06	2.84	7.15	20.44	3.50	11.90	33.99
Safety factor	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35

Normally consolidated	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
L/D	5	5	3.8	5	4.9	3.5	5	4.2	2.9
a_{VH}	5.5	5.5	4.3	5.5	5.4	4	5.5	4.7	3.4
b_{VH}	2.83	2.83	3.23	2.83	2.87	3.33	2.83	3.10	3.53
$N_{p,fixed}$	11.65	11.65	11.32	11.65	11.64	11.15	11.65	11.49	10.70
VH-envelope	0.99	0.29	0.10	1.01	1.00	1.00	1.00	1.00	1.01
Factor consolidated	0.06	0.05	0.04	0.06	0.05	0.04	0.06	0.04	0.04
Constant	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
a_{VH}	7	7	6.4	7.00	6.95	6.25	7.00	6.60	5.95
b_{VH}	2.25	2.25	2.55	2.25	2.28	2.63	2.25	2.45	2.78
$N_{p,fixed}$	11.30	11.30	11.06	11.30	11.27	11.02	11.30	11.12	10.89
VH-envelope	1.00	0.36	0.15	1.00	1.00	1.00	1.00	1.00	1.00
Factor constant	0.94	0.95	0.96	0.94	0.95	0.96	0.94	0.96	0.96
Final VH envelope	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
a_{VH}	6.91	6.92	6.31	6.91	6.88	6.15	6.91	6.52	5.84
b_{VH}	2.28	2.28	2.58	2.28	2.30	2.66	2.28	2.48	2.81
VH-envelope total	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Drained Analysis	1-line	3-line	6-line
Depth [m]	200	200	200
Height [m]	16.59	19.96	24.25
Diameter [m]	3.32	4.75	8.36
s_{u0} [N/m2]	18750	18750	18750
s_{u1} [N/m2]	33353	36318	40086
s_{u2} [N/m2]	47956	53886	61422
Weight [N]	2	5	19
V_{side} [MN]	6.0	11.3	26.5
H_{side} [MN]	6.6	13.0	32.2
V_{LRP} [MN]	8.4	16.1	45.9
H_{LRP} [MN]	6.6	13.0	32.2
a_{VH}	5.50	4.70	3.40
b_{VH}	2.83	3.10	3.53
Factor consolidated	0.562	0.516	0.468
Constant			
a_{VH}	7.0	6.6	6.0
b_{VH}	2.3	2.5	2.8
Factor constant	0.438	0.484	0.532
Final VH envelope			
a_{VH}	6.16	5.62	4.76
b_{VH}	2.58	2.79	3.13
VH-envelope total	1.00	1.00	1.00
FINAL VALUES			
h [m]	18.73	24.61	24.85
D [m]	3.75	5.86	8.57
L/D	5	4.2	2.9
VH-envelope total	1.00	1.00	1.00

D
Appendix

In this appendix all the installation and removal data is summarized and stated. These can be used when needed. Furthermore the data for the weight calculation is also stated.

Free Body Diagram forces	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
D [m]	3.65	4.14	6.36	3.59	4.62	7.23	3.75	5.86	8.57
L [m]	18.25	20.69	24.16	17.97	22.66	25.30	18.73	24.61	24.85
t [mm]	15	17	25	14	18	29	15	23	34
S_{u0} [N/m2]	1000	1000	1000	1000	1000	1000	1000	1000	1000
S_{u1} [N/m2]	17057	19208	22264	16816	20939	23261	17481	22657	22864
S_{u2} [N/m2]	33114	37415	43529	32633	40879	45523	33961	44315	44728
Selfweight penetration depth [m]	9.18	12.43	20.39	10.89	13.75	22.33	14.56	16.52	27.72
Penetration resistance [MN]	3.60	5.22	10.88	3.45	6.96	13.54	3.89	10.38	15.54
Suction [bar]	2.53	2.43	0.95	2.10	2.57	0.70	1.36	2.07	-0.67
REMOVAL PRESSURE [bar]	5.42	6.51	6.94	5.73	6.99	6.90	6.78	6.80	6.87

Free Body Diagram forces	**25 degrees**			**35 degrees**			**45 degrees**		
	1-line	3-line	6-line	1-line	3-line	6-line	1-line	3-line	6-line
D [m]	3.65	4.14	6.36	3.59	4.62	7.23	3.75	5.86	8.57
L [m]	18.25	20.69	24.16	17.97	22.66	25.30	18.73	24.61	24.85
t [mm]	15	17	25	14	18	29	15	23	34
Steel weight [kg/m3]	7850	7850	7850	7850	7850	7850	7850	7850	7850
Volume shell [m3]	3.05	4.45	12.28	2.92	6.09	16.61	3.30	10.62	22.92
Weight shell [kg]	23970	34950	96387	22909	47794	130362	25918	83358	179902
Volume topplate [m3]	0.15	0.22	0.81	0.15	0.31	1.19	0.17	0.63	1.98
Weight topplate [kg]	1203	1755	6367	1150	2448	9349	1301	4982	15571
Weight shell + topplate [kg]	25173	36705	102754	24059	50242	139711	27219	88340	195473
Weight girders [kg/m]	250	250	250	250	250	250	250	250	250
Weight girders [kg]	2737	3104	4769	2696	3468	5421	2809	4395	6426
Dry weight SPA [kg]	27910	39808	107523	26755	53710	145132	30029	92734	201899
Dry weight SPA [ton]	27.91	39.81	107.52	26.76	53.71	145.13	30.03	92.73	201.90
Subm weight SPA [kg]	24255	34595	93442	23251	46677	126126	26096	80590	175459
Subm weight SPA [MN]	0.24	0.34	0.92	0.23	0.46	1.24	0.26	0.79	1.72
Subm ballast [ton]	75.68	166.28	710.04	112.38	225.94	964.36	219.25	412.56	1797.14
ballast [ton]	87.08	191.33	817.04	129.32	259.99	1109.68	252.29	474.73	2067.95