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Design optimization of the mooring system for a floating offshore wind turbine foundation

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Abstract

[EN]

This report presents a study about the modeling and optimization of different mooring systems for Floating Offshore Wind Turbines (FOWT) for different water depth level. This study was proposed by Principle Power Inc. (PPI), designing the mooring system for its patented WindFloat foundation. Extended analysis on the anchor types, mooring lines and mooring configurations are presented in this thesis in order to select the best and most economical option for the WindFloat technology. The mooring system proposed consists on a catenary configuration with a drag embedment anchor and combination of two types of mooring lines, synthetic rope and chain.

With this configuration, a total of nine mooring systems for different water depths are designed and optimized according to the rules and guidelines of the two certification bodies, Bureau Veritas (BV) and American Bureau of Shipping (ABS). The software OrcaFlex v9.8e is used to satisfy the certification body requirement of using a time-domain simulation tool. The same metocean conditions, soil type, FOWT foundation, wind turbine and line pretension are considered for all the designs.

As a result of this study, shallow mooring designs presented heavier chains than deep waters, driving their mooring costs. On the other hand, deep waters designs have longer mooring lines, making this parameter their cost driving. These facts lead to a minimum range between shallow and deep waters. This minimum range is from 60 m to 80 m water depth.

Keywords: FOWT; WindFloat; Principle Power; Mooring system; Water Depth.

[PT]

Esta tese apresenta um estudo sobre a modelação e optimização de diferentes sistemas de ancoragem para *Floating Offshore Wind Turbines* (FOWT), e para diferentes profundidades do mar. Este estudo foi proposto pela empresa *Principle Power Inc.* (PPI), para projetar o sistema de ancoragem para a sua plataforma flutuante, *WindFloat*. Uma análise dos diferentes sistemas de ancoragem, materiais dos cabos e configurações é aprestado para selecionar a melhor opção para a tecnologia *WindFloat*. O sistema de ancoragem sugerido consiste numa catenária de cabos com uma âncora de arraste e dois tipos de materiais diferentes para os cabos de ancoragem, corda sintética e correntes.

Com esta configuração, um total de nove sistemas de ancoragem para diferentes profundidades foram projetados e otimizados seguindo as normativas e diretrizes de duas sociedades classificadoras, *Bureau Veritas* (BV) e *American Bureau of Shipping* (ABS). O programa OrcaFlex v9.8e é usado como ferramenta de simulação. As mesmas condições meteorológicas, leito de mar, plataforma flutuante, turbina eólica e pretensão dos cabos foram consideradas para todos os projetos.

Como resultado do estudo, verificou-se que os sistemas de ancoragem para águas pouco profundas apresentaram correntes mais pesadas do que para águas profundas. Para além disso, os sistemas de ancoragem para águas profundas têm cabos mais compridos, conduzindo a sistemas mais caros. Esses factos criam um custo mínimo entre águas pouco profundas e profundas. Sendo que o mínimo se encontra desde os 60 m até os 80 m de profundidade.

Palavra-chave: FOWT; WindFloat; Principle Power; Sistemas da ancoragem, Profundidades do mar.

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Acronyms Definitions

ABS: American Bureau of Shipping
AHV: Anchoring Holding Vessel
BL: Breaking Load
BV: Bureau Veritas
DEA: Drag Embedment Anchors
DNV GL: Det Norske Veritas and Germanischer Lloyd
DPA: Dynamically Penetrated Anchor
ESS: Extreme Sea State
FOWT: Floating Offshore Wind Turbine
GE: General Electric
HMPE: High Modulus Polyethylene
HMTW: Horizontal Motion induced by Turbulent Wind
MBL: Minimum Breaking Load
ML: Mooring Line
MOSS: Maximum Operating Sea State
PL: Proof Load
PMC: Platform Mooring Connector
PPI: Principle Power Inc.
ROV: Remotely Operated Underwater Vehicle
SF: Safety Factor
TLP: Tension Leg Platform
UHC: Ultimate Holding Capacity
UPC: Ultimate Pull-out Capacity
VLA: Vertical Load Anchors

1. Introduction

The offshore wind industry plays a key role across the renewable energy and maritime industry [1]. Offshore wind turbines are becoming larger and more powerful, and being deployed in deeper waters. They can be mounted on a fixed bottom base such as monopiles, jackets or tripods (see Figure 1). However, the economic feasibility of these technologies suffer some disadvantage for water depths larger than 60m [2]. At sites with high water depths, the concept of floating offshore wind turbines (FOWT) seems to be an appropriate economic solution. FOWTs are mainly composed by a turbine, floating foundation and mooring system.

Floating foundations concept can be divided in three main different technologies, tension leg platforms (TLP), semi-submersible platforms and spars (See Figure 1). WindFloat is a semi-submersible foundation designed and proven by Principle Power Inc. (PPI). PPI works as a technology service provider for the offshore deep water wind energy market.

The mooring system hardware and installation incurs a significant cost for floating structure projects. The mooring systems for FOWTS have been benefited from the offshore oil and gas experience, as described in [3-5]. However, there are still several unknowns regarding the FOWT technology and site parameters, such as wave excitations and water depths. Highlighting a report from EWEA in 2013 [1], "it is recommended that more research must be done on mooring and anchoring systems for wind turbines". This thesis present the most common anchor technologies, mooring lines and mooring configurations in order to select the best and most economical combination for the WindFloat technology .

Furthermore, water depth has long been recognised by the offshore wind industry as a key parameter in mooring system design [6]. However, there is no project research for FOWTS about the driving hardware costs parameters depending on water depths. In this thesis, the mooring system is designed for different water depths satisfying the statements from the certification bodies, Bureau Veritas (BV) [7] and American Bureau of Shipping (ABS) [8]. Different mooring configurations are studied and analysed to select the best option for WindFloat structure.
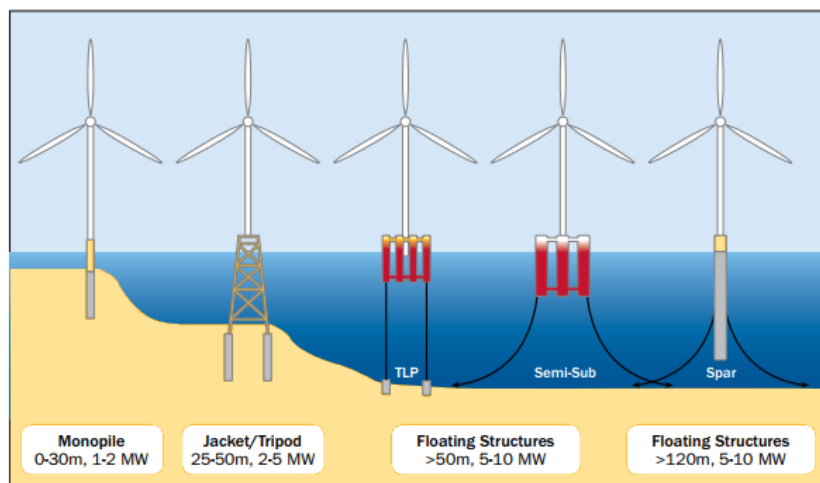
Figure 1 Offshore wind foundations [1]

1.1   Objectives

The purpose of the project is to identify which parameters drive the mooring system design depending on the water depth for a WindFloat foundation, optimizing the mooring system according to the statements of the certification bodies, BV and ABS. Different anchor types, anchor installation procedures, mooring lines and mooring configurations are analysed to select the best option for the WindFloat technology. The hardware costs are considered to identify the cheapest water depth mooring design.

1.2   Scope

This study focuses in the design and optimization of different mooring systems for nine different water depths: 50 m, 60 m, 70 m, 80 m, 100 m, 120 m, 200 m, 250 m and 400 m.

In order to be accurate in the design, the mooring systems have to follow some of the statements imposed by the certification bodies, BV and ABS. They present three different main studies. Intact conditions case, damaged case and fatigue analysis. The purpose of the project is not to define nine designs to satisfy all the certification bodies' requirements, therefore, only the intact case study will be considered as a guideline to design the mooring system.

The mooring system design is strongly dependent on a large number of variables. Therefore, some parameters must be fixed to be able to compare the mooring designs. The metocean data, type of soil, floating foundation, wind turbine, anchor size, line pretension and some mooring line sizes and materials must be fixed for all water depths. This is more detailed explained in Assumptions subchapter from section 5, Methodology.

FOWTs have a very innovative and recent market, being very competitive and sensitive. This fact compromises the necessity of publishing some values in an extra document named: "Design optimization of the mooring system for a floating offshore wind turbine foundation. Confidential Parameters". In addition, some results are presented as a function of a reference case. The aim of this project is to identify the trends on the design depending on the water depth.

The costs analysis of the study is only focused on the hardware costs of the main parts of the mooring system, the anchors and the mooring lines.

2. Platform and Wind Turbine

The semi-submersible floating platform considered is a WindFloat. The WindFloat is a floating foundation for offshore wind turbines with a simple, economic and patented design made by Principle Power Inc.

The WindFloat is made of steel. The geometry consists in three columns forming a triangle, where the turbine is set on the centre of one of the columns. This design enables the structure to be fully assembled onshore and then moved offshore to its final location. This fact reduces significantly the installation cost of the platform when is compared to fixed foundations as monopile or jacket type. These fix bottom foundations require offshore installations and heavy lift operations that involves significant vessel capabilities and high installation costs.

In October 2011. Principle Power installed a full-scale 2 MW WindFloat prototype 5 km off the coast of Aguçadoura, Portugal. It was assembled and commissioned onshore before being towed about 400 km along the Portuguese coast. This was the first time that an offshore wind turbine has been mounted and dismounted on a floating structure.

The static and dynamic stability of the WindFloat foundation provides sufficiently low pitch, roll and heave motions performance enabling to be used for offshore wind turbines. The heave stability is achieved because the patented water entrapment plates at the base of each column. This plates entrain water resulting in large added-mass component. The sharp edges of the plates increase the viscous damping.

For the performance of the pitch and roll motions, the WindFloat has a patented hull-trim system, also known as active ballast, which distributes water ballast between the three columns of the WindFloat. The purpose is to change the centre of gravity and compensate the variable turbine thrust force due to the low frequency changes in wind speed and direction. This system is closed-loop, so no water moves out or in of the system, Figure 2 presents a scheme of the WindFloat showing the ballast system and heave plates.
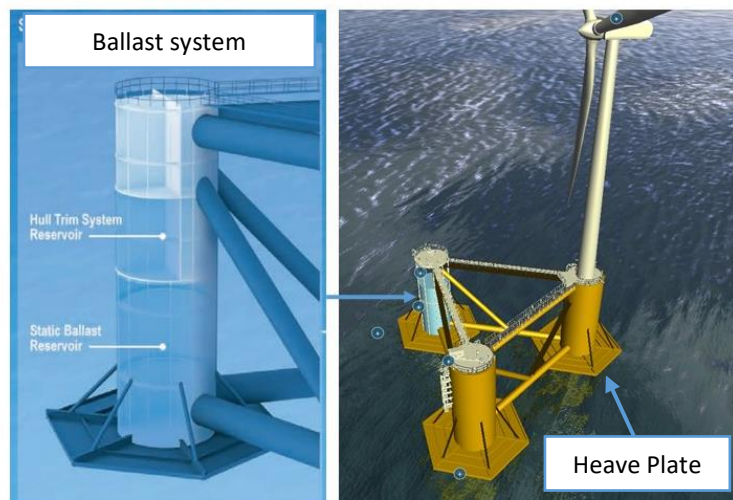
Figure 2 WindFloat Platform and ballast system [9]

The Wind turbine used for this study is from General Electric (GE). The turbine has been designed following class I-B IEC-61400-1/IEC-61400-3 [10]. Its rated power is 6 MW with a rotor diameter of 150m. The tower is tubular made of steel. The hub height is 100m. The rotor is a direct drive permanent magnet. The rated speed is at 11 m/s and the cut in and cut off are 3 m/s and 25 m/s respectively [10].The power control system of the turbine includes a variable speed blade pitch control. The turbine also has a nacelle yaw control to avoid misalignments with the wind and a drivetrain control to maintain a constant power output. This turbine, according to GE, is developed for all offshore conditions. The turbine characteristics in upwind are summarised in Table 1.

Table 1 Turbine characteristics

Class I-B IEC-61400-1/IEC-61400-3	
Rated Power	6 MW
Rotor Diameter	150 m
Hub Height	100 m
Rated wind speed	11 m/s
Cut in wind speed	3 m/s
Cut off wind speed	25 m/s

This turbine has been already used for the Merkur wind farm, which is a German 396MW offshore wind farm composed by 66 Haliade 150-6MW wind turbines and foundations of grounded monopiles. Figure 3 shows the inside of the Haliade Offshore wind turbine provided by General Electric and a wind turbine from the Merkur project.
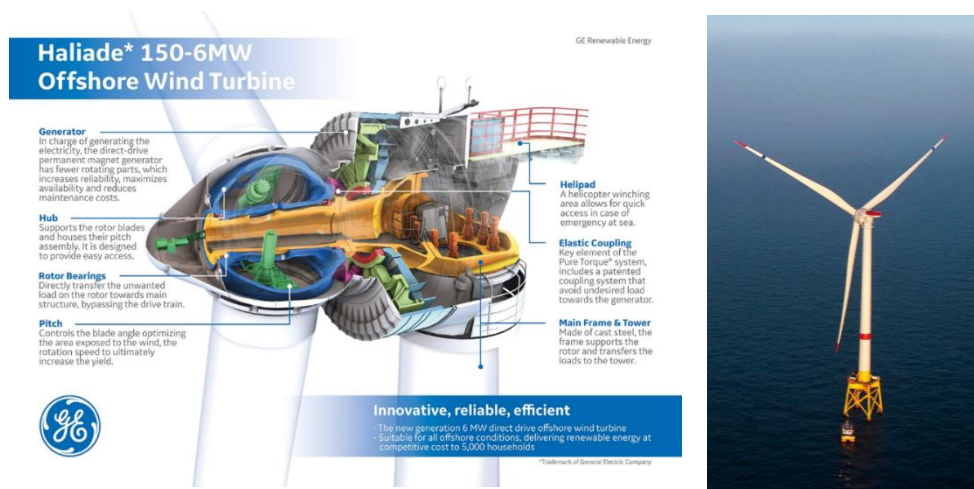
Figure 3 Wind turbine Haliade 150-6MW by GE [10]

3. Mooring System

This chapter explains the different parts of the mooring system, starting from the different types of anchors, their applications and installation procedures. The mooring lines subchapter explains the variety of materials that can be found nowadays in the mooring industry. Each subchapter finishes with a table summary where anchors and line types are compared.

At the end of the chapter the two main mooring configurations are presented, the catenary and the taut system, explaining the advantages and drawbacks of each one. In addition, a table summary explains which are the best anchors and line types for each configuration, concluding on the best option selected for the analysis of this project.

3.1 Anchors

Nowadays, different types of anchors are presented in the offshore industry. In this chapter, the most common anchors are presented explaining its design and installation procedure. The anchors are divided as:

- Deadweight anchor
- Drag embedment anchor
- Anchor piles:
  - Driven Pile
  - Suction Pile
  - Torpedo Pile
- Vertical load anchor (VLA)
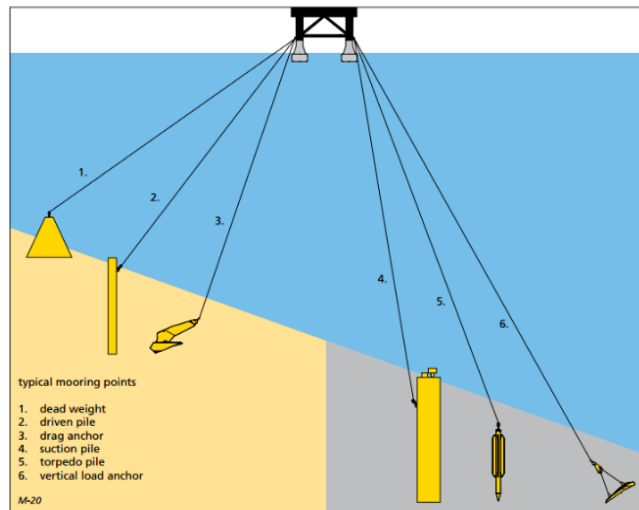
Figure 4 presents the studied anchors depending on the water depth commonly installed.

Figure 4 Anchor types [15]

The most common guidelines in order to select the best anchor type for mooring system are:

- Holding capacity: The size and type of the anchor will depend on the required anchor holding capacity.
- Soils: The anchor size depends on the soil. Some anchor types cannot be installed in hard clays.
- Weight: Heavy anchors will have more expensive manufacture costs. Also, large and heavy anchors would need larger and stronger vessel decks and cranes for their installations, increasing their costs.
- Equipment: Depending on the anchor type, different equipment would be necessary to install the anchor, making the installation procedure a cost driver.
- Directionality: Drag embedment anchor can hold only horizontal loads, meanwhile VLA and piles provide high multidirectional capacity.

Seafloor soils are hard to classify since usually they are a composition of different particles (micro and macro levels) and irregular. The most commonly used soil classification standards (ASTM D-2487, BS 5930 and ISO 14688) were reviewed by Thusyanthan [11], concluding that soil classification are useful for anchor selection. However, in a real project, in situ tests are required.

Soil, in general, can be classified as clay, silt, sand, gravel and cobble, based on the particles size of the soil. Sand, gravel and cobble have similar behaviour that can be classified as sand. Clay behave quite differently. On the other hand, the behaviour of silt depends on the percentage of the finer content and it can behave like clay or sand. Figure 5 shows this classification based on British Standard (BS) certification society.

Figure 5 Seabed Soil Classification according to BS 5930 [11]

In general, the soil types encountered in anchor design are sand and clay, with a grain diameter from 0,1 μm to 2 mm [4].

Clay type soils are generally characterised by its consistency, mainly related by the undrained shear strength. This is the result of friction and interlocking among particles. Due to interlocking the soil can contract or expand when it is subject to shear strain. If soil expands its volume, the density would decrease and the strength should decrease making the clay soft. On the other hand, if the volume contracts, the density increases and the clay would be harder [12].

There are some discrepancies between standard societies about clay classification. Table 2 shows how the clay is classified with different criteria from American (ASTM) and British (BS) standards.

The undrained shear strength values (S_u) are usually derived in the laboratory. The values can also be estimated in situ, from standard penetration tests or cone penetration tests.

Table 2 Clay Type Based on ASTM and BS [15]

Consistency of Clay		Shear Strength [kPa]	
		ASTM D-2488	BS CP-2004
Soft	Very Soft	0-13	0-20
	Soft	13-25	20-40
Medium	Firm	25-50	40-75
	Stiff	50-100	75-150
	Very Stiff	100-200	150-300
Hard	Hard	200-400	300-600
	Very Hard	>400	>600

The anchor type selection is subject to the soil condition. The anchor types considered in this study can be installed in the following soil types:

- Deadweight: all kind of soils
- Drag anchors: soft clay, medium clay, hard clay, sand
- Driven Piles: soft clay, medium clay, sand
- Suction Piles: soft clay, medium clay
- Torpedo Piles: soft clay, medium clay
- VLAs: soft clay, medium clay

3.1.1 Deadweight

The deadweight is the simplest anchor. It consists of a heavy object placed on the seafloor to resist vertical and/or horizontal loads. The holding capacity comes mainly from the weight of the anchor and partially from the friction between the anchor and the soil.

Usually they are fabricated from concrete and steel. They are commonly used because they are inexpensive to manufacture and available for any type of seafloor and loading conditions. Compared with other anchors, for holding the same loads, they are the heaviest anchors. This fact makes them the most inefficient anchors regarding holding capacity - weight ratio. Therefore, they may require heavy lift capabilities for installation, driving the installation costs.

They are not the most economically option for a FOWT since the ultimate holding capacity is usually high due to the turbine thrust force. Thus they are usually installed for light ships. Although, on very hard seafloors, they might be the only reasonable anchoring option. They are usually installed for mobile or semi-permanent moorings. However, they can also be found for permanent moorings where the long-term characteristics of the soil are not known in detail [13].

3.1.1.1 Deadweight Design

Deadweight anchors are built according to individual requirements, depending on the design criteria. Therefore, they are not off-the-shelf equipment. Their geometry can be more or less complex. The simplest types like sinkers or squat clumps are typically used for lower-level requirements, where the size and weight may be easy to handle. On the other hand, more complex geometries are manufactured when the loads are high. The aim of a complex geometry is to increase the friction coefficient between anchor and soil, thus the holding capacity-weight ratio improves. Although the design costs would become more expensive, the installation would be cheaper since less vessel capabilities would be needed. Figure 6 shows some deadweight geometries used nowadays, going from simpler to more complex types.
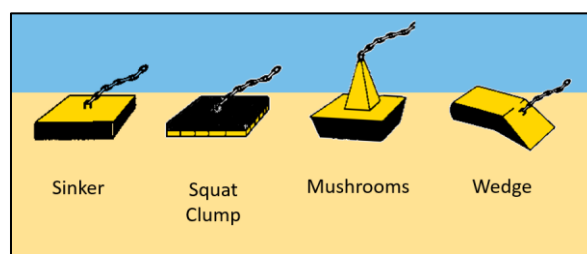
Figure 6 Types of Deadweight anchors

3.1.1.2 Deadweight Installation Procedure

Deadweight anchors are the easiest to install. Depending on their weight, an anchor handling vessel (AHV) or a vessel crane is needed to transport the anchor to the desired place. Monitoring the procedure, the AHV deploys slowly the anchor until it touches the seabed.

Due to its inefficient relation between holding capacity and weight, the deadweight anchors are usually very heavy. Therefore, the installation costs are driven by the AHV capacity to transport and deploy the anchor.

3.1.2   Drag Embedment

The drag embedment anchor (DEA) is the most common type of anchoring system available nowadays. This can be illustrated by the fact that more than 6000 anchors were sold by Vryhoft Anchors VB, one of the worldwide leading DEA suppliers, in the last 40 years [14].

This anchors are designed to penetrate either partly or fully in the seabed, where the holding capacity is mainly generated by the resistance of the soil in front of the anchor. It is very well suited for resisting large horizontal loads, but it does not perform well for large vertical loads. Hence they are a good solution when combined with the catenary mooring system, as presented in the chapter about Mooring Configuration.

3.1.2.1 Drag Embedment Design

A large number of anchor types has been designed, depending on the fluke, area, shank and stabilisers. These parameters are shown in Figure 7.
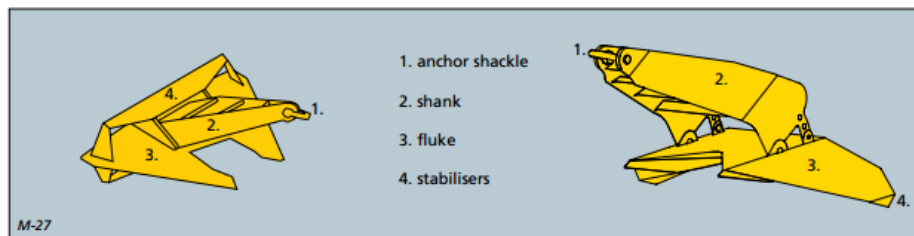
Figure 7 Parts of the drag embedment anchor [15]

The geometry and the weight of the anchor has to be design in order to support the ultimate holding capacity (UHC). This holding capacity is governed by two main parameters; the fluke area which is limited by the strength of the anchor design and the penetration into de seabed. The seabed penetration is soil type dependent; the anchor would need deeper piercing into the seabed for soft clays, where the shear strength is low and less resistant, than hard clays. The seabed penetration also depends on the DEA geometry and applied load.

Vryhof is one of the most important anchor manufactures of the world and Stevpris MK6 is one of its last drag embedment anchors, launched in 2004. Figure 8 represents the ultimate holding capacity (UHC) of this anchor depending on the seabed type and anchor weight. This figure also shows the installation drag and penetration distances. As it can be observed, for the same anchor size, hard clays seabed provides more holding capacity and less drag and penetration into the seabed than soft clays.
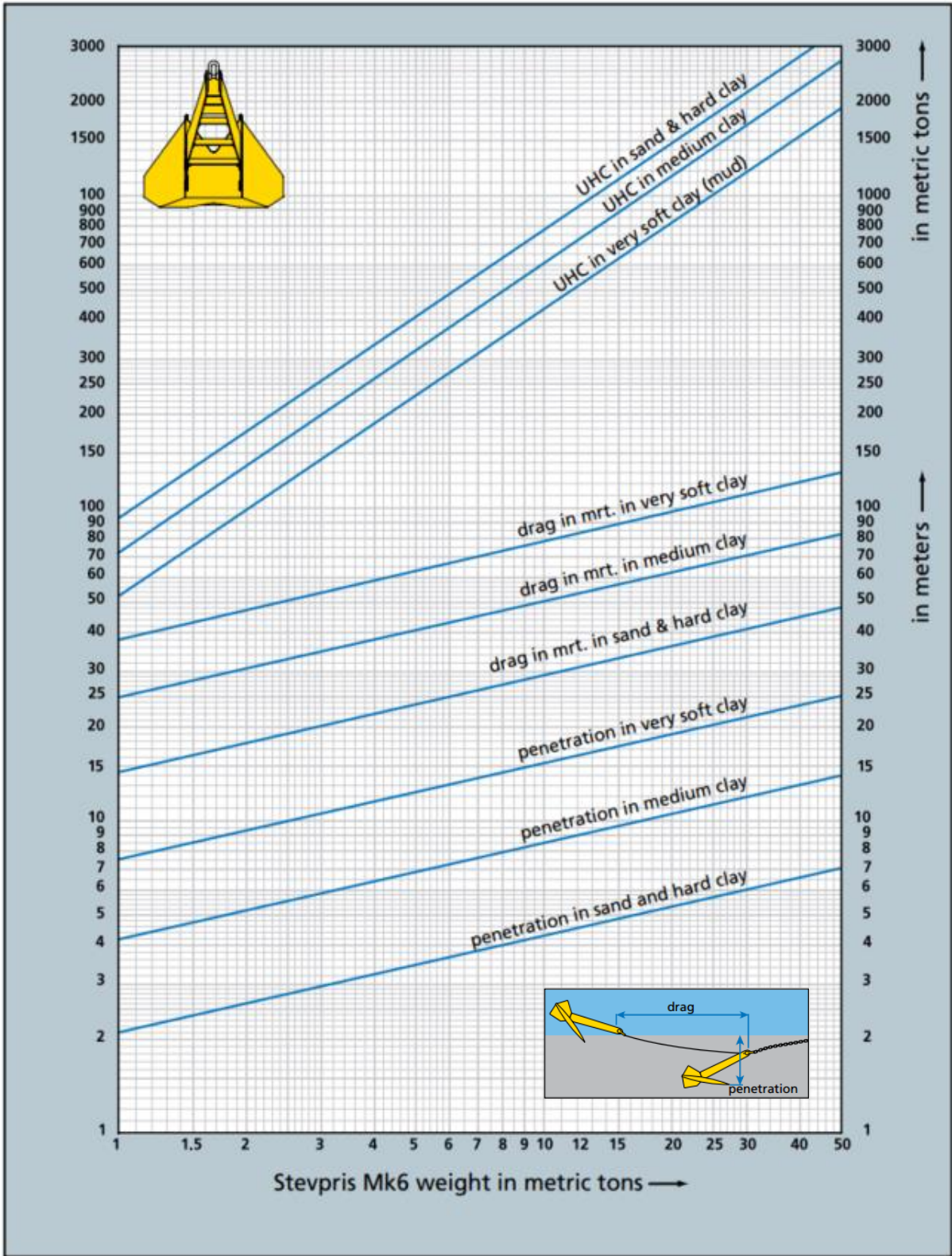
Figure 8 UHC of drag embedment anchors [15].

3.1.2.2 Drag Embedment Anchor Installation Procedure

The simplest installation procedure for permanent drag embedment mooring systems is to lower the anchor to the seabed using the mooring line. When the anchor is nearly on the seabed, the Anchor Handling Vessel (AHV) may start moving slowly forward to ensure that the anchor embeds correctly on the seabed without spinning, using a tracking electronic device. Figure 9, top.

Alternatively, to ensure a good embedment, the anchor can be connected with a temporary installation bridle or wire rope to the rear of the anchor. The AHV lower the anchor overboard while paying out the mooring line and the bridle simultaneously. Figure 9, bottom.
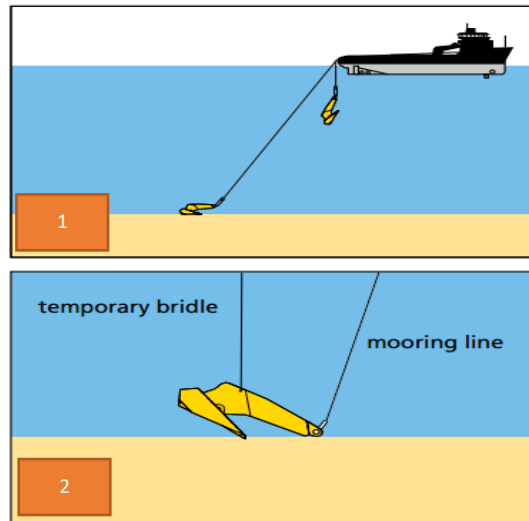
Figure 9   Seabed deployment for drag embedment anchor system [15]

The method used to determine the drag anchor's final position is usually tracking measurable data from an electronic device. This device consists of a transponder on the anchors and a read-out computer that translate the received data. Sometimes, depending on the water depth, a deep-water transducer is necessary.

After the correct position is confirmed, the AHV moves forward to move the anchor that starts to dig into the seabed and it starts to increase its holding capacity. During this pull in, the tracking device reports the load on the anchor and depth and drag length until final penetration according to the criteria that satisfies the mooring system design in terms of position and holding capacity.

Once the anchor is embedded at the desired penetration, it should be test loaded to ensure adequate holding capacity, detect possible damages in the mooring line components and ensure the mooring line's catenary shape is formed. For permanent drag anchors moorings, the mooring line should be test loaded to at least 80% of the maximum storm load determined by a dynamic mooring analysis for the intact condition [16] (Section 7.4.3) The load case is defined in Certification Requirements chapter. The duration of the test load should be at least 15 minutes [16].

The proof load is the driving installation cost of the drag embedment anchors. The AHV is usually used to pull the mooring line from the recent installed anchor. Therefore, large vessels with high bollard pull capabilities are required to pull the installed system.

3.1.3 Anchor Piles

Anchor piles are very effective in many soils, however, due to the installation process they are some of the most expensive anchors. They are used for taut mooring systems and TLP since they can hold vertical and horizontal loads.

These anchors consist in a cylindrical pile made of steel. Depending on the design and embedment mode, the main anchor piles can be divided in: driven, suction and torpedo piles. The next subchapters present the main differences between these three anchors and its installation procedure.

3.1.3.1 Driven and Suction piles

Driven piles are relatively long, slender and open-ended steel columns. These anchors are usually installed by impact hammering, vibrating or pushing into the seabed. Driven piles are an ancient technology almost exclusively used for offshore markets. Its successful performance during the past encouraged their use against other technologies. However, the installing operation difficulties increase for deep water depths.

Other similar technology is the drilled piles. They are installed by drilling a hole in the soil typically using an auger. Then concrete is placed in the hole to form the pile. These technology have been used in offshore only when pile driving was not possible, like in calcareous sediments seabed.

Suction pile anchors are caisson foundations. They are penetrated into the seabed to a target depth by pumping out the water, creating under-pressure inside the pile and forcing the anchor into the seabed. They consist in a stiffened cylindrical shell with a cover plate at the top and open bottom.

The suction pile concept was first developed in the early 90' in 10-200 m water depth for a catenary anchor lines [17]. However, the first suction pile combined with taut leg mooring line was taken in Brazil in 1997 for Petrobras.

The soil characteristic is the main issue for the suction pile anchor. They can be used in soft or medium clay but not in sand or hard clay since the water can flow through the ground during installation, making the suction very difficult and unfeasible.

Driven and Suction Anchor Piles Design

The main parameters for anchor piles design are; anchor type, type of mooring, anchor load direction, soil type, anchor dimension ratios and anchor padeye location. In this chapter this parameters are dimensioned for a pre-FEED design according to ABS guidelines [18].

The mooring is connected to the anchor through the padeye. Usually, depending on the application, the padeye of the mooring line connection can be at the top, for TLP, or at the intermediate level, for taut systems, see Figure 10. The location for taut systems is assumed to be:

- Driven pile: 50% L from the pile top
- Suction Pile: 70% L from the pile top
- Torpedo piles: on the top of the pile

The mooring line under the seabed maintains an inverse or reverse catenary shape, as it can be observed in Figure 10. This shape reduces the horizontal load on the top of the pile increasing its lateral capacity [19].

Figure 10 Driven and Suction anchor pile geometric variables.
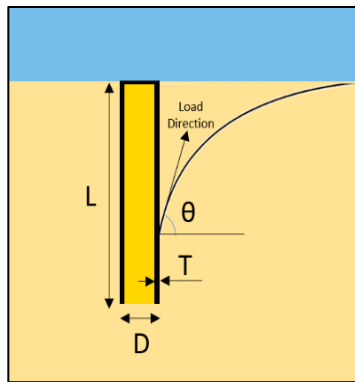
Table 3 Anchor piles L/D and D/T ratio [18].

Pile anchor	Soil type	L/D	D/T
Driven Pile	Soft Clay	30	30
	Medium Clay	30	30
	Hard Clay & Sand	40	25
Suction Pile	Soft Clay	6	150
	Medium Clay	6	150

The dimension ratio changes depending on the soil and mooring system. Table 3 shows the most common ratios between L/D and D/T, where L is the length, D the diameter and T the wall thickness of the pile as shown in Figure 10.

As it can be observed in the table, the driven piles have a higher ratio between L/D making these piles slender and heavier. Suction piles are usually smaller, however, they have thicker walls since they must resist under-pressure forces inside the pile.

Depending on the seafloor and the dimensions of the anchor pile, the UHC of the driven and suction pile can be computed following Equation (1) [18]:

$$D = c(UHC)^d,\qquad\qquad(1)$$

where UHC is the required pile ultimate holding capacity in kN and c and d values are soil and anchor type dependent found in Appendix A – Anchor Design.

For all anchor piles designers, the soil characteristics should be relied on sampling and laboratory testing instead of in-situ testing, taking into consideration that measured properties of soil samples differs from deep waters in-situ values.

Depending on the type of mooring, the load directions may be horizontal and/or vertical. In many cases, the optimal utilization of the pile anchor capacity is achieved when the direction of the maximum loading at the padeye (θ on Figure 10) is approximately 35-45 degrees from the horizontal direction.

When the angle θ is higher than 40º the holding capacity is axial and the anchor is usually used for TLP systems. On the other hand, when the uplift is lower than 40º, most of the holding capacity is lateral and the anchor is commonly used for taut configurations. Figure 11 presents how the load capacity changes from axial to lateral depending on the load direction.
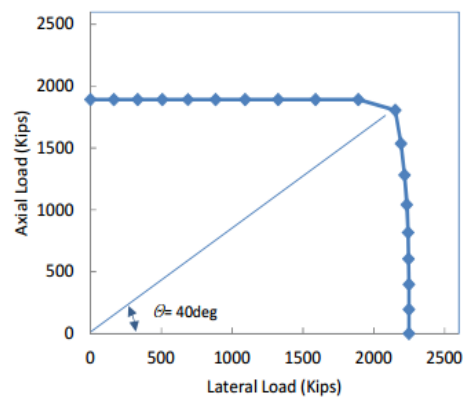
Figure 11 Typical pile anchor ultimate holding capacity envelope [18].
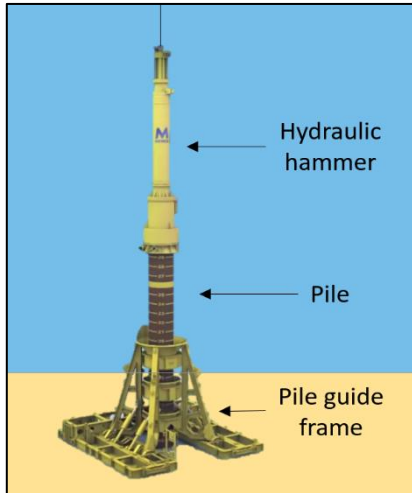
Figure 12 Driven Pile Installation

Driven piles are usually installed with a subsea pile guide frame. This device allows the hammer to drive vertically the pile into the seabed. First the pile guide frame is slowly lowered to the required position by a crane vessel or AHV with A-frame or crane. Thereafter the pile is also lowered and set inside the guide, as it can be observed in Figure 12. The pile is penetrated into the seabed due to its own weight. Once the pile does not self-weight penetrate, it is ready to be driven into the seabed. The hammer is lowered and set on top of the pile. The hammer usually use steam, diesel fuel or hydraulic power as a source of energy. Figure 12 illustrates a hydraulic hammer.

Dynamic loads due to hammer impact during pile installation will induce fatigue damage on both padeye and pile contour welds. This fact requires an extra analysis for a given hammer type and efficiency, pile penetration and soil resistance.

Specific equipment is required in order to demonstrate that the pile self-weight penetration, the pile orientation, driving records and final penetration are within the ranges established during pile design and driving analysis. Contrary than DEAs, the full intact storm load case is not required for a test load. However, the mooring and anchor design should define a minimum acceptable level of test loading. This test loading should ensure the mooring line's inverse catenary is sufficiently formed to prevent slacking during storm conditions. Another function of the test loading is to detect sever damage to the mooring component during installation [16](Appendix E.7.4)

Suction Piles Installation

The installation of suction piles can be managed from a crane vessel or launched over an AHV. When the suction pile is correctly positioned and oriented, the crane lowers the pile slowly until the pile penetrates into the seafloor due to its own weight. This self-weight penetration is approximately two-thirds of the pile length. [20]. Once the own weight penetration stops, the water pump attached at the top of the suction pile starts to apply negative pressures, also called suction pressure. The applied suction pressure is defined by its upper and lower limits [20].The lower limit is dictated by the soil resistance corresponding to the pile penetration. If the suction pressure is lower than this value, the vertical downward load is lower than the soil resistance, therefore the pile cannot penetrate into the seabed. However if the suction pressure is too high the soil inside the pile becomes unstable. Consequently the pile is filled with soil and the installation becomes incomplete.

All this procedure requires specific instrumentation such as measurements of the water pressures inside and outside the pile, pile penetration depth, elevation of the soil surface and tilt angle of the pile. These measurements are displayed and recorded by a data logger. In addition, in order to guide and secure the installation, a remotely operated underwater vehicle (ROV) technology is mandatory.

The test load required for suction piles is the same as driven piles. The test load should ensure that the mooring line's inverse catenary is formed.

As offshore exploration moved to water depths of around 3000m, new technologies came up in order to reduce installation costs and facilitate the construction. In this scenario, torpedo anchors have proven to be a reliable alternative. These anchors can be classified as a dynamically penetrated anchors (DPA) group, since they are dynamically penetrated to the soil by the free-fall velocity caused by gravity. Torpedo anchors are the most applied of the DPA. They have been developed and patented by the Brazilian company Petrobras in 1996 and they have installed more than 1000 torpedo piles [21].

DPA consist of a pile with stabilizing fins, conical tip, ballast and an omni-directional chain attachment on the pile top. Once in place, they behave in the same manner as a conventional installed anchor pile. The ballast is necessary to prevent unacceptable vertical tilt angles after penetration in the soil. The ballast is inserted into the bottom portion of the pile to keep the centre of gravity low. They are usually made in cast iron.

The fin size is a geometrical parameter that depends on the use and the needed holding capacity. Torpedo piles with large fins have higher lateral pile capacity. The vertical capacity is a combination of pile weight and soil adhesion to the external surface. Therefore, large fins increase the external surface and the anchor can hold higher vertical loads. Figure 13 shows a scheme of a torpedo pile anchor.
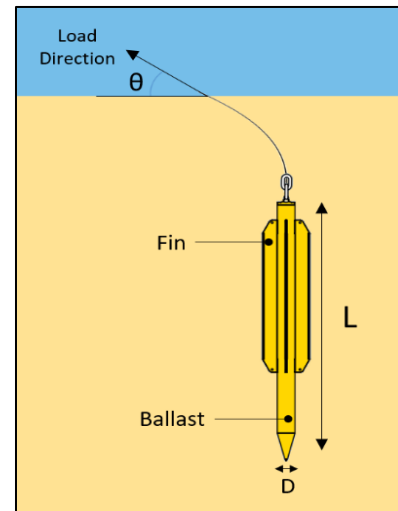
Figure 13 Torpedo Anchor Scheme

Torpedo piles Design

Torpedo piles are designed specifically for a given load and soil conditions. However, over the time, some torpedo sizes have been standardized. T-24 is typically used for pipes restraint, T-43 for mobile anchor systems and T-98 for permanent anchors [21]. "T" indicates the dry weight of the anchor in metric tonnes. Depending on the depth, the torpedo size would change.

For smaller torpedo piles, such as the T-24, it might be held 122 m above the seafloor while the heavier T-98 requires only 30.5m. The lighter torpedoes are installed in deeper waters since less weight is needed to reach the terminal velocity[1] to penetrate the seafloor.

---

[1] The terminal velocity is the maximum speed reached for an objected when is dropped in a fluid. The gravity force and the drag resistance force will equal, making the object fall at constant velocity. The aim of torpedo anchors is to reach the seafloor with the terminal velocity since they would have the maximum kinetic energy possible to pierce the seabed.

The methodology of installation of the torpedo pile consists of a vertical launching from the vessel until the seabed. The vessel used is typically an AHV. The construction of the torpedo anchor allows them to be easily deployed over the stern positioned over the target zone. The installation starts from the anchor lift from the AHV at zero velocity and facing the desire position. Then the anchor is left free and it falls until it reaches the seabed.

The mooring line can be held by the AHV itself while the anchor is lowered by an installation line. Once the anchor is well penetrated into the seabed, the installation line can be recovered. As it is shown in Figure 14.
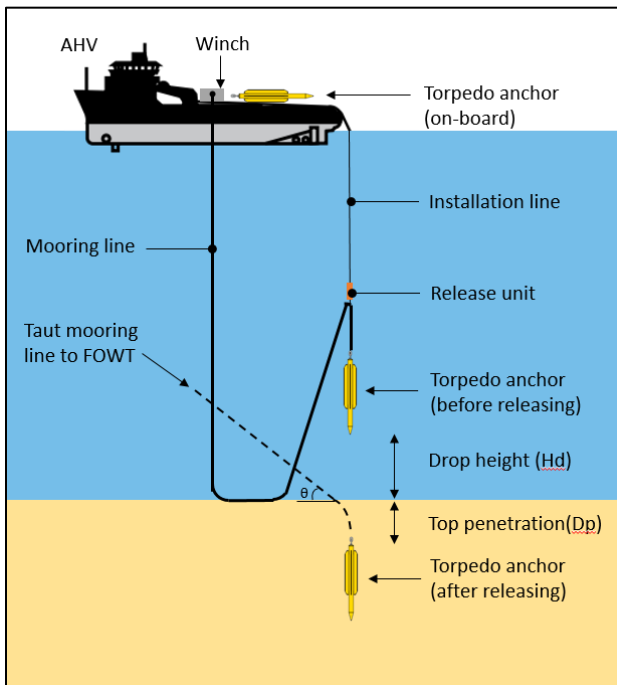
Figure 14 Torpedo Anchor installation procedure

During the fall, the pile travels almost freely, only dragging the mooring line. It is obvious that the object must have a minimum directional stability to arrive vertical at the bottom. The pile is considered unusable when its vertical angle exceeds the limits. Typically the limit is when the pile axis is at 3º from the vertical [22]. If for any reason the installation is unacceptable for the pile tilt or the position is out of tolerance, the pile can be recovered and be re-installed.

After the gravity installation, the top penetration (Dp) is typically about 9 to 15 meters below the mudline. Once the mooring line is loaded, as the other pile anchors, the chain under the seabed forms an inverse or reverse catenary shape to increase its lateral capacity.

3.1.4 Vertical Load Anchors

VLAs are relatively modern development regarding offshore industry. They consist of an anchor fluke or pate that is connected with wires to the angle adjuster (Figure 15).
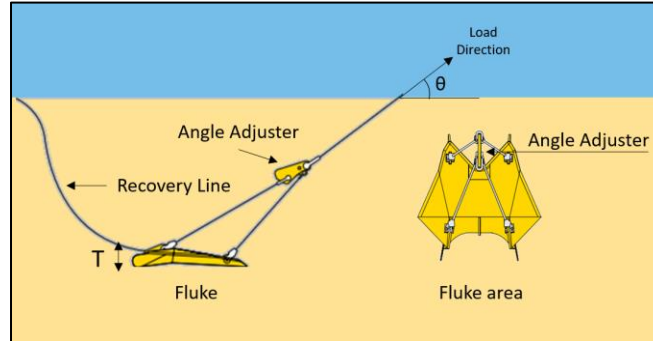
Figure 15 VLA Scheme

The VLAs, are installed in a similar way than drag embedment anchors, penetrating the anchor into the seabed with a horizontal load, however, VLAs need deeper penetration. Once the anchor is at the desired penetration a change on the fluke angle enables them to hold vertical and horizontal loads. The VLA gets its high holding capacity when the fluke is oriented nearly perpendicular to the applied load [16]. They can also have a line for recovery.

3.1.4.1 VLA Design

For VLA, the ultimate holding capacity is often defined as the ultimate pull-out capacity (UPC), which is the load for the soil around the anchor reaching failure. At UPC the plate anchor starts moving through the soil. The model Stevmanta VLA made by Vryhof is taken as a reference. According to its manual [15], the Ultimate Pull-out Capacity (UPC) follows Equation (2):

$$UPC = N_c \cdot S_u \cdot A, \tag{2}$$

where,

- N_c is the bearing capacity. It is the ability of the soil to support the foundation loads. This parameter is correlated with the angle of internal friction. Usually Nc= 10 [15].
- S_u is the undrained shear strength of clay (kPa). The parameters are presented in Table 2.
- A is Fluke area (m²).
- UPC is the ultimate pull-out capacity in KN.

As it can be observed in the equation, the UPC is function of the clay type. The soil data should be based on reliable test data sampled and laboratory tested. Therefore, the soil study is the most complex and expensive part of the VLA's design.

3.1.4.2 VLA Installation

As is it observed in the design procedure, VLA are strongly dependent on the seabed type and penetration depth. The installation equipment must be adequate to ensure the anchor reaches the required penetration depth. A direction change on the fluke angle enables the VLA to hold vertical loads. There are different installation procedures to install VLA anchors. The two most efficient methods, based on the fluke angle change, are:

- Single line installation using the shear pin angle adjuster
- Double line installation using the fixed angle adjuster

The single line installation requires only one AHV. The VLA with the shear pin angle adjuster is deployed by gravity to a predetermined position. As the same way as DEA, when the anchor is on the seabed, the AHV starts paying out the installation or mooring line. The line tension increases and the VLA starts to embed into the seabed. A ROV can optionally be used to inspect the position and orientation of the anchor.

When a predetermined installation load has been reached with the AHV, the shear pin in the angle adjuster breaks. As it can be observed on Figure 16, breaking the angle adjuster (represented with a red dot) the angle position of the fluke changes. This angle change adapt the anchor to hold vertical loads and increases the holding capacity by three times [15].

The double line installation requires two AHV. AHV1 deploys the VLA into the seabed. It tensions and embeds the anchor through the installation line until the design penetration depth. AHV2 is connected to the VLA through a mooring line to the angle adjuster. Once the anchor is penetrated to the design depth, AHV1 is disconnected from the anchor and AHV2 starts to pull and increase the mooring line tension. This fact changes the angle of the fluke. If AHV2 cannot generate enough bollard pull, AHV1 can be connected in tandem to generate additional tension. Both procedure can be optional inspected by a ROV.

At the end of both installation procedures, VLAs anchors must be tested as the same way of a DEA [16], explained in 3.1.2.2 Drag Embedment Anchor Installation Procedure section.
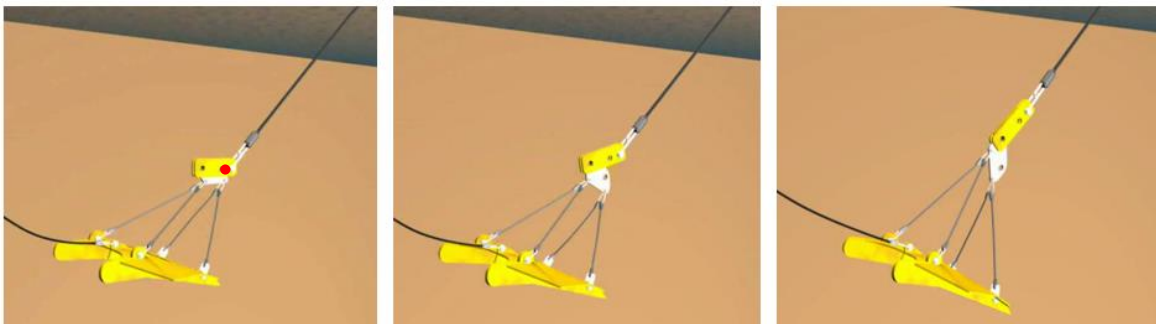
Figure 16 Angle change system for VLA installation with a shear pin angle adjuster

3.1.5   Anchor Summary

Different technologies has been developed in order to satisfy the offshore mooring system needs. Each technology have their advantages and drawbacks. This chapter compare the different anchors, in their design and installation costs.

Figure 17 shows the required weight for different anchor systems depending on the UHC and seabed type. The assumptions and procedures followed to compute this analysis are described in Appendix A – Anchor Design. The plot is represented in logarithmic scale.
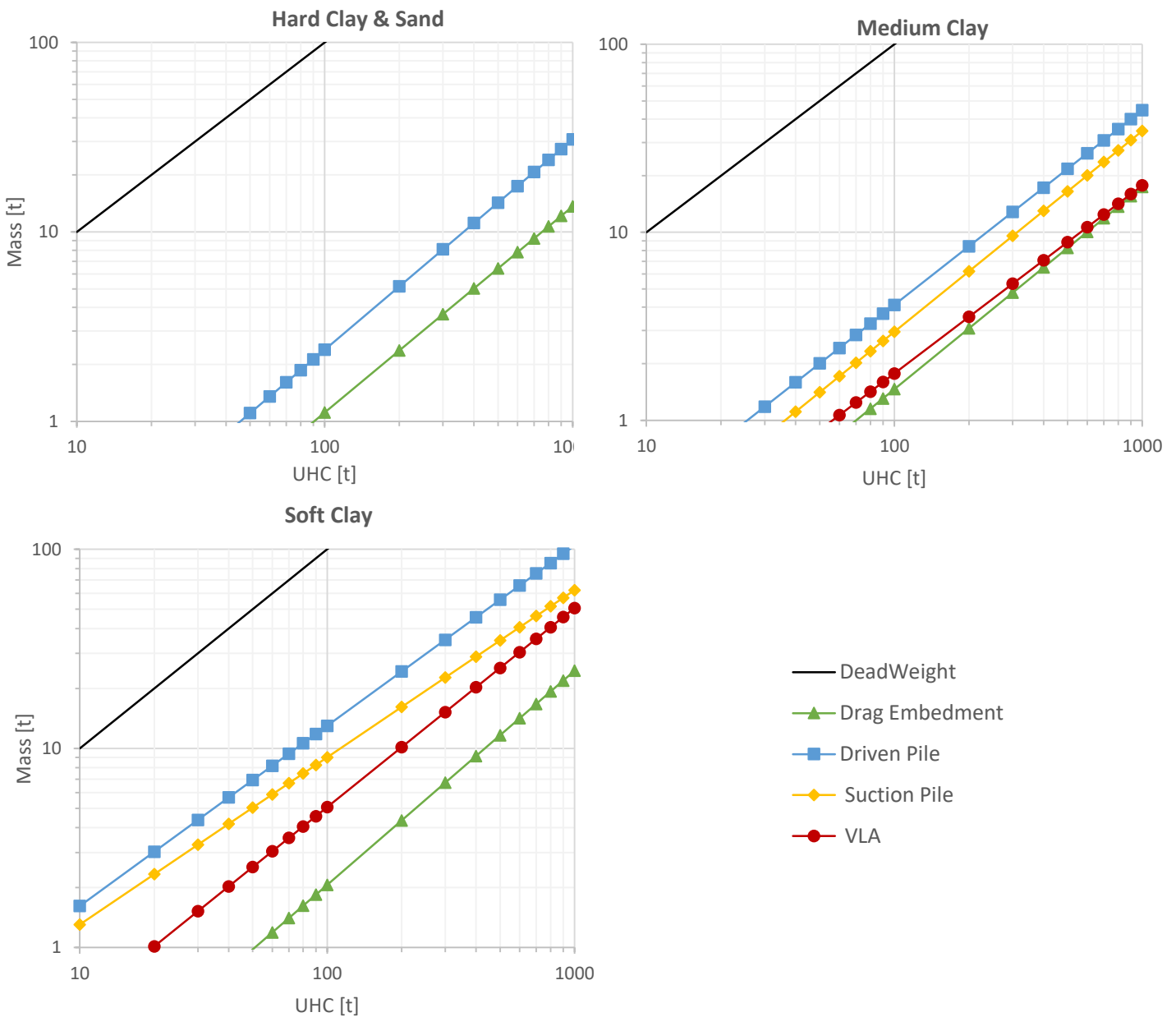
Figure 17 Anchor design analysis depending on UHC and soil type

Figure 17 only compares the weight of the anchor, not the fabrication procedure nor the engineering work behind the design. However, it can be a good indicator to compare holding capacity-weight rations and anchor hardware costs. As the graph shows, the deadweight anchors are the most inefficient for all types of clay. Drag embedment anchors have the best performance holding capacity-weight. However, DEAs can only hold horizontal loads.

If vertical direction load becomes important in the anchor selection, the best anchor type would be the VLA, since they need less material. Driven piles are larger than suction piles since they do not have the un-pressure holding capacity effect. Besides the weight costs, the engineering design for VLA and suction piles are more expensive since they require more accurate soil investigation that other technologies.

The anchor weight is not only important for the design costs. The weight also drives the installation costs since heavier anchors require stronger and larger vessels and cranes. Figure 18 shows the worldwide available number of AHV depending on their maximum bollard pull. In order to realize this study different AHV providers had been analysed. The bollard pull is an important parameter to consider in the installation test load. For example, the test load for DEAs must be at least 80% of the maximum storm load determined by a dynamic mooring analysis for the intact condition.
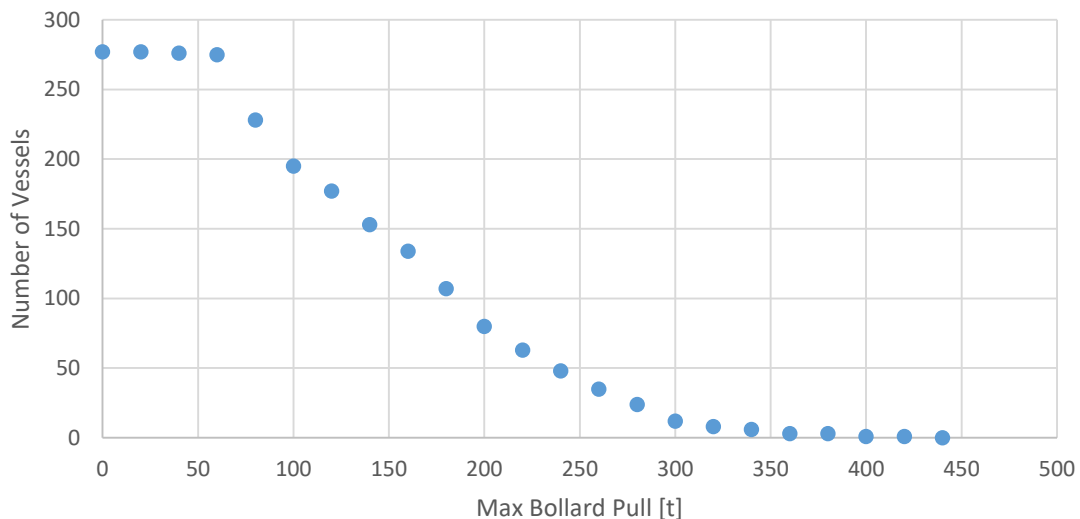
Figure 18 Number of vessels per bollard pull

Analysing the figure above, the number of vessels available depending on the maximum bollard pull decreases logarithmically from 80 t to 350 t with a correlation coefficient of $R^2 = 0,9906$. Anchors with UHC less than 80t would have almost the same AHV rental installation. Almost all the vessels could pull an anchor test load of 80 t or less.

On the other hand, if the UHC of the anchor is over 350 t, only 3 vessels could pull the anchor test load, increasing significantly the installation cost. Between 80 t and 350 t, the number of vessels decrease logarithmically, thus a small increase in the anchor UHC, the vessel availability would decrease substantially. This graph shows the importance of designing an efficient anchor. Not only the design costs matter, but the installation must be considered in order to decrease the costs.

Finally, Table 4 summarises the main characteristics of the different anchor types presented over this chapter. The table is divided into colours, depending on the characteristics, where green means a good performance or cheap cost and red means poor performance or expensive. The site investigation shows the level of importance of each item, listed as low, high or not applicable (NAN). Low rating means a low impact or not necessary investigation in order to design the anchor, making the site investigation cheaper and corresponding to green box.

Table 4 Anchors summary

		DeadWeight	DEA	Piles	VLA
Soil Type	**Soft Clay**	Good	Good	Good	Good
	Medium Clay	Good	Good	Good	Good
	Hard Clay	Good	Good	Bad	Bad
	Sand	Good	Good	Good for Driven	Bad
	Hard Rock	Good	Bad	Bad	Bad
Site Investigation	**In-Situ Strength**	Low	Low	High	Low
	Laboratory Strength	High	High	High	High
	Dynamic Response	NAN	Low	High	High
Load Direction	**Omnidirectional**	Performs well	Inadmitible	Performs well	Performs well
	Horizontal	Performs well	Performs well	Performs well	Performs well
UHC/Weight Ratio		Lowest	Highest	Low	High
Installation Costs		Expensive for high UHC	Cheapest	Expensive	Expensive

3.2 Mooring Lines

This section presents different materials generally used for mooring lines. The materials commonly used in the mooring market are: steel chain, steel wires and synthetic ropes. The material parameters lead the decision of choosing the most appropriate material, depending on: the mooring configuration, the stiffness, weight and minimum breaking loads (MBL). A summary table is presented at the end of this section.

3.2.1 Chain

Chain has a wide range of experience in offshore mooring systems. It is durable, easy to inspect and it is cost effective. However it is heavy and it can be difficult to deploy safely. Its abrasion resistance and the catenary effect due to the weight are important and beneficial considerations in the mooring design. The chain can be available in different type, size and grades, depending on the application, fatigue and strength needs.

The types can be studlink or studless. The studs provide weight and stability to the link, facilitating the process of laying down the chain while handling. By removing the studs, the weight is reduced and the fatigue life is increased. The studless chain is more commonly used for permanent moorings.

The size is specified by the nominal diameter "D". It can go from less than 1 inch (25,4mm) to more than 7 inches (177,8mm) of diameter. Figure 19 shows the dimensions of a common stud less chain.

The grades are associated with different strength and durability characteristics of the steel. Table 5[2] presents the proof load (PL) and break load (BL) data for a small range of available chain grades. As it can be observed there is a great change between grade RQ3 and R5, where the breaking loads can increase more than a factor of 1,5.
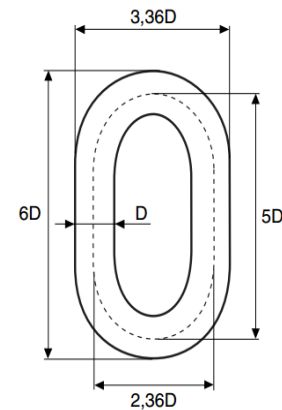
Figure 19 Stud less chain dimension [7]

Table 5 Proof load and Breaking load for different grades chain [15]

diameter	Proof load								Break load					Weight	
	R4-RQ4		R3S		R3	RQ3-API	R5		R4-RQ4	R3S	R3	RQ3-API	R5		
	stud	studless	stud	studless	stud	studless	stud	stud	studless	stud and studlless					stud	studless
inches	kips	kips	kips	kips	kips	kips	kips	kips	kips	kips	kips	kips	kips	lbs/ft	lbs/ft
4	1798	1590	1498	1448	1299	1165	2089	1856	2281	2073	1856	1756	2664	152	139
4 1/8	1899	1679	1582	1529	1371	1231	2206	1960	2409	2189	1960	1855	2813	162	148
4 1/4	2001	1770	1668	1612	1445	1297	2325	2066	2538	2307	2066	1955	2965	172	157
4 3/8	2105	1862	1754	1696	1521	1365	2446	2174	2671	2427	2174	2057	3119	182	166
4 1/2	2211	1955	1843	1781	1597	1433	2570	2283	2805	2549	2283	2160	3276	192	176
4 5/8	2319	2050	1932	1868	1675	1503	2695	2394	2941	2673	2394	2265	3435	203	186
4 3/4	2428	2147	2023	1956	1753	1574	2821	2507	3080	2799	2507	2372	3597	214	196
4 7/8	2538	2245	2115	2045	1833	1645	2950	2621	3220	2926	2621	2480	3761	226	206
5	2650	2344	2209	2135	1914	1718	3080	2736	3362	3055	2736	2589	3926	238	217

[2] To have Table 5 units in international system:
kips are kilo pounds. 1kip = 4,4482 kN = 4448,2 N
lbs/ft are pound per foot. 1 lbs/ft=1,48 kg/m

Chain is a good option for catenary mooring lines to interact with the seabed due to its abrasion resistance and touchdown areas due to its high linear density. However, chain has low fatigue and corrosion resistance. In order to consider the corrossion effect in the process of designing the mooring line, the chain may be greatly oversized. This extra dimensionalization of the chain is designed to ensure a good performance of the line. The certification society imposes the corrosion dimensionalization regulations of the chain. This can be found in NR 493 [7] Secc 3, Chapter 9 for BV and [16] for ABS. When a chain is broken or damaged it can be easaly repaired using a connecting link.

3.2.2   Wire Rope

Wire ropes are designed for a wide range of applications in the construction industry such as buildings, bridges, cranes, elevators and mooring systems. In the marine environment the rope finish may be bright or galvanized for protection to avoid corrosion. In order to select the wire rope some parameters may be taken into account such as tensile strength, abrasion, bending fatigue or flexibility, crushing effect and corrosion.
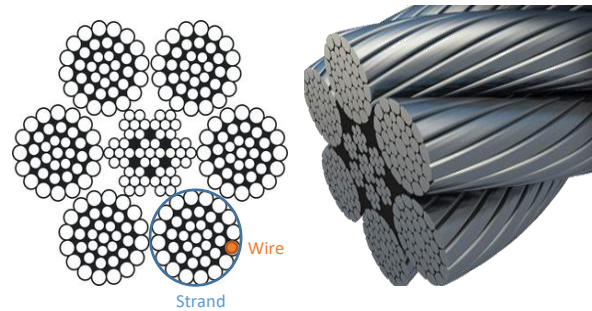
Figure 20 6x19 wire rope
(6 strands with 19 ropes per strand)

The wire ropes are identified primarily by the number of strands in the rope and the number of wires for each strand. The strands are made of metal, usually steel, twisted into a helix, as it can be observed in Figure 20. The helically shape improves resistance and conforms the strands in their position to avoid the crushing effect.

The crushing is the effect of external pressure on a rope, which damages it by destroying the cross-section shape of the rope, its strands, the core, or all three. Usually 6 strand ropes have greater crush resistance than 8 or 19 strand ropes.

The number of strands and wires in each strand are governed by the required tensile strength and the bending fatigue. For example, for a typical 6-strand wire rope, the strands provide 90% of the tensile strength [23]. Properties like fatigue resistance and abrasion resistance are directly affected by the design of strands and wires. As a general rule, a rope that has strands made up of a few large wires will be more abrasion resistant and less fatigue resistance than a rope with the same strands, but made up of a lot of small wires.

The wire ropes are lighter solutions with higher stiffness than chains, however they are hard to deploy and they have torque limitations to take into account when the rope is designed.

3.2.3 Synthetic Rope

Synthetic ropes within the maritime sector are relatively modern. From 1970's, oil exploration moved to deeper waters and mooring sytem using wire ropes or chains became significantly more difficult and expensive to install. Therefore, cheaper options appeared such as synthetic ropes. With this revolution in the mooring lines market, a lot of industries innovated in materials and fibers construction to improve the ropes performance. Different factors involve the selection of the appropriate rope:

- Tensile strength to satisfy the platform loads.
- Linear density which is usualy near to the neutral buoyancy i.e. similar to water density.
- Type of construction. Depending on the construction, the rope would be more or less firm and abrasion resistance. The cnstruction is not a critical property, but depending of the application, would change the durability and life of the rope. There are different types of constructions. The most common are 3-strand twisted, 8-strand braided or 12-strand braided. See Figure 21.
- Elongation properties which are driven by the elastic properties of the material. The typical materials can be divided in two:
  - High Young modulus: High Modulus Polyethylene (HMPE) and Aramid
  - Low Young modulus: Polyester, Polypropylene and Nylon.
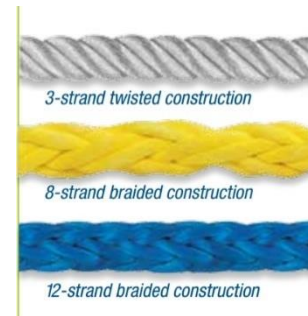
Figure 21 Type of synthetic rope [32]

Materials with high elongation (low Young modulus) like nylon, deforms significally when the tension is applied. This deformation, named elongation, provides energy absorption and restoring force in the line. On the other hand, low elongation ropes (high Young modulus) provide a better control in the platform position but less restoring force. Figure 22 presents different synthetic ropes with their elongation at the breaking load.

High modulus materials are good option for catenary systems, when they are combined with chain. Since the restoring force is obtained from the catenary shape produced by the chain weight and the high modulus rope contribuites to have a position control of the platform. However, for taut systems the best option would be low young modulus synthetic ropes or wire ropes since the system is tensed and the restoring force came from the stored energy caused by the elongation of the material.

HMPE 3.6%
Aramid 4.6%
Polyester 18.0%
Polypropylene 22.0%
Nylon 28.0%
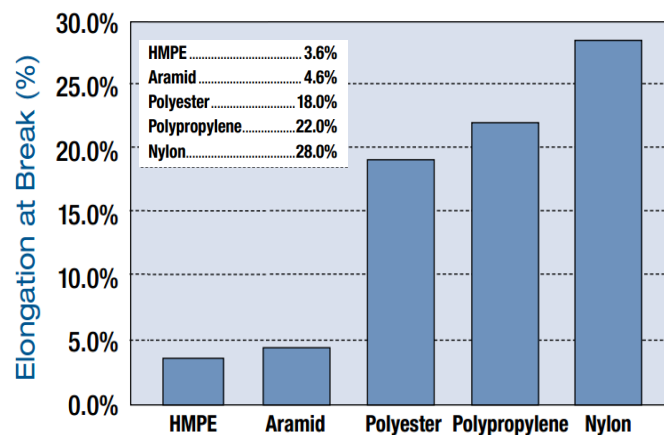
Figure 22 Fiber elongation at breaking tension [32]

Creep consists on a slow deformation that occurs when the rope is loaded over a long period of time. This effect is mostly non-reversible. All synthetic fibers exhibit some degree of creep, however not all the irreversible elongations are due to creep. Typically when the rope suffers creep, the rope would have to be retensioned again as the elongation has increased and thus the tension decreased. This is one of the most important issues for synthetic ropes into permanent mooring lines.

The design of the synthetic rope must consider the creep effect. In addition, when the rope is installed in the mooring, testing loads may be applied to elongate permanently the rope untill the designed length.

3.2.4   Mooring Line Summary

Table 6 shows the summary of the differnet mooring line materials. The table compares chain, galbanized steel wire rope and synthetic ropes. The level of significance of the line characteristics depends on the mooring configuration.

Table 6 Mooring line summary

	Chain		Galvanized Wire Rope	Synthetic Rope		High Modulus
	Studless	Studlink		Low Modulus		High Modulus
				Polypropylene Nylon	Polyester	Aramid HMPE
Linear Density	High	High+	Low-Intermediate	Polypropylene Buoyant Nylon: Low	Low	HMPE: Buoyant Aramid: Low
Abrasion/ UV/ Marine growth resistance	High	High	High	Low	Intermediate	Intermediate+
Fatigue Resistance	Intermediate	Intermediate+	High	Low	High	Very High
Elasticity	Low	Low	Low-Intermediate	High	Intermediate	Low
Installation	Easy	Easy+	Intermediate	Hard++ due contact and creep	Hard+ due to contact and creep	Hard due to seabed contact
Reparation	Easy with shackle	Easy with shackle	Change all section	Change all section	Change all section	Change all section
Costs	Cheap+	Cheap	Intermediate	Cheap	Intermediate	Expensive

3.3 Mooring Configuration

Several types of mooring configuration can be installed on a floating platform. The most common mooring configurations in the offshore market are the catenary and taut-leg. These different configuration dictates the type of FOWT, type of anchor and line materials. For instance, the anchor loads from a catenary system are horizontal, where DEA can be installed. On the other hand, the taut leg system has omnidirectional loads in the anchor point. Where it is strongly recommended to use VLA or pile anchors, being these last ones more expensive.

These configurations will be explained in detail in this section, showing its advantages and drawbacks and concluding on which is the best combination of anchor, line material and mooring configuration for the WindFloat platform.

3.3.1   Catenary System

In this configuration, the mooring lines form a catenary shape, as it is shown in Figure 23. The lines can be divided in two segments. The suspended line, connected to the floating structure and freely hanging in the water. And the lying on the seabed segment that finishes applying horizontal loads on the anchor.

The stiffness produced by a catenary configuration is due to its geometric change. In equilibrium position, a large segment of the mooring line will lie on the seabed. When moved away from its equilibrium position, the
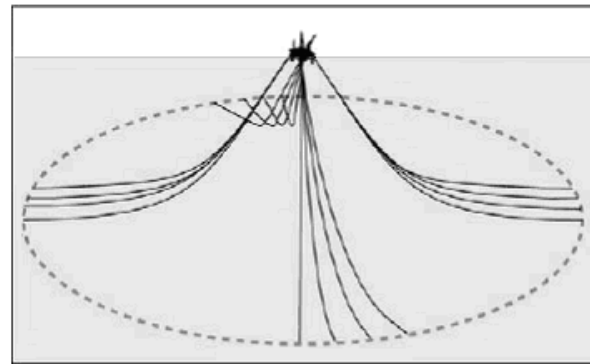
Figure 23 Catenary mooring system

suspended line length of the mooring line will increase. This effect increases the weight force of the line and originates a restoring force back to equilibrium position. In order to increase the damping coefficient of the mooring lines, the force originated by the line weight is usually increased, installing heavier chains or adding clump weights in the seabed touch point section.

This system could be assessed with different combination of materials as: only chain, chain and nylon rope, chain and polyester rope or chain and HMPE. The aim of mixing materials is to increase the weight in the touching seabed section by the chain and reducing it in the suspended line by the fibre. The characteristics of the suspended line changes while deepening of the fibre. For low elastic fibres, high elongation, the damping of the mooring would be not only geometric but elastic. On the other hand, when the suspended line is made by a high elastic fibre, the line does not significantly elongate and the motion control on the FOWT is increased. Fibre does not resist abrasion well and they must avoid any contact with the seabed.

The mooring line that is suspended in the water will take a catenary shape. The catenary curve has a scaled rotated graph of hyperbolic cosine shape. Figure 24 represents one catenary mooring line. In this figure, X is the distance between anchor and fairlead, x is the distance between touchpoint and fairlead, and ls is the suspended line length.
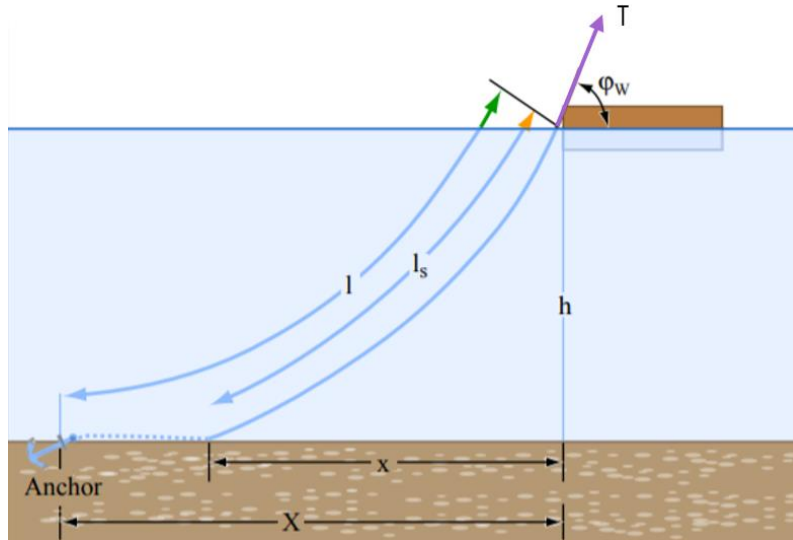
Figure 24 Definition of catenary system

Neglecting the hydrodynamic forces and assuming an inelastic cable, the catenary shape equations can be written as Equation (3), where water depth is h in meters, the mooring line weight is W in t/m, the applied horizontal load to the mooring line at the fairlead is T_H in tonnes and the length of the suspended mooring line is ls in meters:

$$l_s = h \cdot \sqrt{\left(\frac{2T_H}{Wh} + 1\right)}. \qquad (3)$$

The horizontal distance (x) between the fairlead and the touchdown point of the mooring line on the seabed can be computed following Equation (4):

$$x = \frac{T_H}{W} \cosh^{-1}\left(1 + \frac{Wh}{T_H}\right). \qquad (4)$$

The distance between the anchor and the fairlead can be geometrically computed following Equation (5):

$$X = l - l_s + x. \qquad (5)$$

Therefore, combining Equation (3) and Equation (4) in Equation (5) , the distance between the anchor and the fairlead can be finally computed from Equation (6):

$$X = l - h \cdot \sqrt{\left(\frac{2T_H}{Wh} + 1\right)} + \frac{T_H}{W} \cosh^{-1}\left(1 + \frac{Wh}{T_H}\right). \qquad (6)$$

As it can be observed in the equation above, the catenary configuration has non-linear relationship between tensions and motions.

Finally, in order to have the surge restoring line force, T_H is isolated from Equation (6) and derivate in function of X. The surge restoring force from a catenary mooring system is found in Equation (7):

$$C_{11} = \frac{\partial T_H}{\partial X} = W \left[\frac{-2}{\sqrt{\left(1 + 2\frac{T_H}{Wh}\right)}} + \cosh^{-1}\left(1 + \frac{Wh}{T_H}\right) \right]^{-1}.$$

(7)

As it can be observed, the restoring force strongly depends on the weight of the line, therefore one of the aims of the catenary system is to increase the weight when the line is tensed. The most economic option is to increase the weight only in the seabed touchpoint. Therefore, when the environmental load moves the FOWT, the weight is lift up, increasing the weight of the suspended line. The gravity line force increases and the restoring force increases.

3.3.2   Taut System

The Taut leg system has the mooring lines pre-tensioned until they are taut, see Figure 25. The mooring lines terminates with an angle at the seabed, usually between 30 and 45 degrees. This means that the anchor is loaded by horizontal and vertical loads. The most common anchor type for this configuration is the suction pile anchor, although VLA or driven and torpedo piles can be also used.

Comparing the taut line system with the catenary, the taut system restoring forces is originated by the axial elastic stretching of the mooring line rather than its weight. Hence, polyester ropes are a very good option since they have a low young modulus.
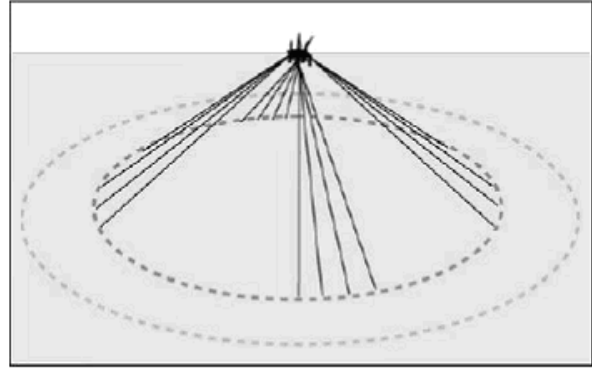
Figure 25 Taut mooring system

The main advantages compared with the catenary system are the motion control and shortness of the mooring lines. However, the anchors have to support vertical loads. Suction piles or VLA anchors are more expensive than DEA. This fact of using shorter lines but more expensive anchors makes the taut mooring configuration more expensive for shallow or deep waters but cheaper for very deep waters.

Figure 26 shows a taut mooring line for a FOWT, where h, X and ls are presented before, in Figure 24.

34
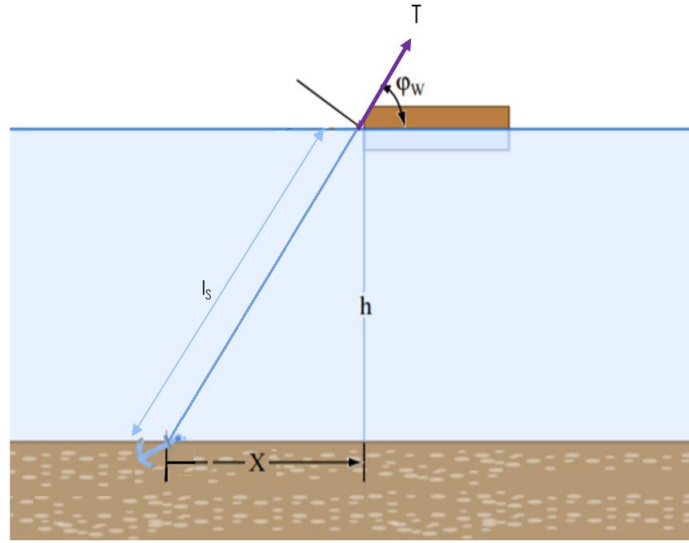
Figure 26 Definition of taut system

In equilibrium, the line only suffers the pretension load (T_0). However, platform motions appear when environmental loads are applied. The tension in the fairlead becomes a combination of both the pretension load (T_0) and the loads originated by the motion (T_L). Considering the line elasticity and neglecting the weight, the total tensions can be written as Equation (8), where A is the line section area, E is the young modulus, L_0 is the ls without external load and ΔL is the length increment of the line originated by its elasticity.

$$T = T_0 + T_L = T_0 + \frac{AE}{L_0}\Delta L. \tag{8}$$

The horizontal component of this tension is presented in Equation (9)

$$T_H = T_0 \cos\varphi + \frac{AE}{L_0}\Delta L \cos\varphi. \tag{9}$$

The horizontal distance between the anchor point and the fairlead (X) can be written as the combination of both length, the L_0 and ΔL, as it is shown in Equation (10)

$$X = l_s \cos\varphi = (L_0 + \Delta L) \cos\varphi \tag{10}$$

The surge restoring line force (C_{11}) can be obtained combining Equation (9) and Equation (10) and deriving T_H as function of X. If small displacements are assumed, the surge restoring force is approximated by Equation (11).

$$C_{11} = \frac{\partial T_H}{\partial X} \approx \frac{AE}{L_0} \tag{11}$$

35

As it can be observed in Equation (11), the restoring force of a taut mooring system is proportional to the Young modulus. However, too high modulus material would suffer too high tension. Therefore, the best line options for taut systems are low young modulus synthetic ropes, like polyester or polipropilene or wire ropes.

Comparing both restoring forces, the catenary configuration in Equation (7), and the taut mooring system in Equation (11), the principle restoring force comes from different line parameters. The catenary system is weight restoring force dependent. While the taut systems restoring force depends of the Young modulus line. In addition, the increment in tension originated by the FOWT motions is non-linear for the catenary mooring while it is linear for the taut configuration under the assumption of small displacements. Different studies support this theory [24] and [25].

3.3.3   Mooring Configuration Summary

Table 7 shows the main differences between catenary and taut configuration explained over this chapter, presenting also the most common anchor types and mooring lines for each configuration.

Table 7 Mooring Configuration Summary

	Catenary	Taut
Restoring Force	Geometric change and line weight	Line Stretch
Line length	2-3 times water depth	1,3-1,5 water depth 1,0 water depth for TLP
Anchor type	Drag embedment anchor	Piles and VLA
Most common Line types	Chain Chain + Synthetic rope	Low modulus synthetic ropes Wire rope

Concluding and analysing the different anchors, mooring lines and mooring configurations presented over this chapter, the most feasible option for the WindFloat technology for a water depth range between 50m and 400m is the catenary configuration with a drag embedment anchor and a mooring line combination of synthetic rope and chain.

For shallower water depths than 50m, the most feasible option would be a catenary configuration with DEA and only chain line, since increase the line weight would decrease the mooring costs. On the other hand, for deeper water depths than 400m, the most feasible option would be a taut configuration with VLA or suction piles and polypropylene line. This configuration should be analysed since decreasing the length of the line would decrease the mooring hardware costs, but installing VLA or suction piles would increase the anchor installation costs.

4 Certification Requirements

Requirements, rules and guidelines are published by classification societies in order to design a safety mooring system. These requirements are for oil and gas offshore floating platforms with particular specifications for FOWTs. American Bureau of Shipping (ABS), Det Norske veritas and Germanischer Lloyd (DNV GL), or Bureau Veritas (VB) are the main offshore classification societies.

In this project, Bureau Veritas is used as a guideline to design the mooring lines of the FOWT. The specifications are divided in environment, load cases and analysis. According to the scope not all the specifications will be followed, since the main objective is not to analyse in detail the design of the mooring. It is rather to have a robust design to satisfy the basic criteria and its efficiency to be compared with other water depths.

This chapter will resume the guidelines from Bureau Veritas. These guidelines can be found in the Rule note NR 493 [7] for the classification of mooring systems for permanent and mobile offshore units. For the specific rules for FOWT, the guidelines are layout in rule note NI 572 [26]. There is some discrepancies between the different societies. In this chapter, a comparison between BV and ABS is presented. The ABS guidelines are found in the guide Floating Offshore Wind Turbine Installation (FOWTI) [8].

4.1 Environment

The environment is divided into three different excitation loads: waves, wind and current. BV describes how to select, analyse, apply and discretise the metocean data in order to design a robust mooring line. The environment definition is the same for BV and ABS, with one exception. BV describes two types of sea states: normal and extreme. ABS guidelines adds a survival sea state. The sea states definitions are explained further on.

4.1.1 Waves

Waves are designed by the parameters of a wave energy spectrum. The spectral wave can be defined by the significant wave height (Hs), mean zero up-crossing period Tz or spectral peak period Tp, mean wave direction and the spectrum model. The spectrum model can be a JONSWAP, Pierson-Moskowitz, Ochi Bubble, Torsethausgen, among others.

The significant wave, Hs, can be defined in two different ways, depending on how the sea state is defined.

When the sea state is defined by statistical measures of the wave heights, the Hs is defined by the average height of the highest third of the zero up-crossing waves ($H_{1/3}$). Figure 27 shows a graph where the waves height frequency is plotted, the Hs is the average of the highest one third, shown in the figure.
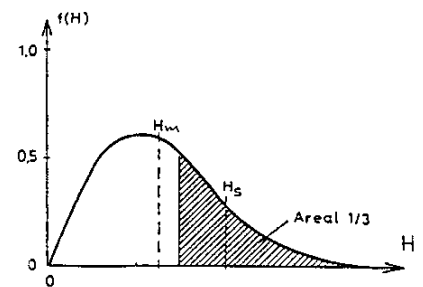

Figure 27 Example of the probability density function of the wave heights H

When the wave height frequency follows a Rayleigh distribution, the Hs or $H_{1/3}$ can be approximated by the Equation (12) where H_m is the average wave height, also shown in the previous graph.

$$H_{1/3} \approx 1{,}6H_m \qquad (12)$$

On the other hand, when the sea state is defined by spectrum model, Hs is given by H_{mo}. The model wave height derived from numerical analysis of the spectrum is found in Equation (13) where m0 is the variance of the free surface.

$$H_{m0} = 4\sqrt{m0} \qquad (13)$$

In deep water H_{m0} and $H_{1/3}$ are matching, but in shallow waters Hm0 may be less than H1/3. The relation between the maximum wave high (H_M) with the significant wave high (Hs), when the wave heights follows a Rayleigh distribution, can be described in Equation (14).

$$H_M = 1{,}86H_s \qquad (14)$$

According to BV, the mooring system design must fulfil the requirements through two different sea states, with different Hs, Tp, spectrum model parameters and directions. These two different seas states are: the normal sea state with a 1 year return period[3] and the extreme sea state with 50 years return period. This data must be determined from a certified metocean database. ABS guidelines defines a survival sea state with 500 years return period.

For more information about the waves environmental conditions, see Rule Notes NI 572 [26] App3 Secc. 3, for BV and FOWTI guide [8] Chapter 4, section 3 for ABS.

4.1.2   Wind

Wind conditions are to be site specific and are essentially represented by wind velocity profile V(z), standard deviation of wind speed σ1, and direction change θ. In addition, as wave conditions, wind is divided in two categories; normal wind for 1 year storm return period and extreme wind for 50 year storm return period.

The wind velocity profile is the description of the average wind speed as a function of the height above the still waterline, given by Equation (15).

$$V(Z) = V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha}, \qquad (15)$$

Where, z is the hight over the sea level and α is the wind shear exponent which depends on the conditions:
- α=1/7=0,14 for normal conditions, with return period of 1 year
- α=1/9=0,11 for extreme conditions, with return period of 50 years.

---

[3] The return period is an estimation of the likelihood of having the sea state. It is the inverse of the probability that the sea state will be exceeded in one year. For example, a sea state with a return period of 50 years means there is 1/50=0,02 or 2% probabilities that this seas state will occur in one year. On the other hand, the sea state with a return period of 1 year has a 100% of chances to happen per year.

There are two different loads generated by the wind, the steady loads and the dynamic loads. The steady loads are usually in the tower and structure. Depending on the study the blades can be considered as steady or dynamic, if the turbine is parked the blades are considered as steady wind loads. On the other hand, when the turbine is working, the wind load will be the thrust force generated by the turbine, considered as dynamic load. The steady wind loads may be computed from the Equation (16).

$$F_w = 0,5\rho C_s S_w V_w^2, \tag{16}$$

where,

- ρ is the air density, in kg/m^3. Generally ρ=1,222 kg/m^3
- S_w is the projected area of the structural element on a plane normal to the direction of the force/wind, in m^2
- V_w is the mean wind speed at the considered elevation, in m/s.
- C_s is the shape coefficient, where Table 8 is used in absence of data.

Table 8 Shape coefficient Cs

Shape	C_s
Spherical	0,4
Cylindrical	0,5
Rectangular	1,5
Large flat surface	1,0
Wires	1,2
Exposed beams and girders under deck	1,3
Small parts	1,4
Isolated shapes (crane, beam, etc...)	1,5
Clustered deckhouses or similar structures	1,1

The dynamic load is the thrust generated by the rotor. To calculate this thrust force, Equation (17) is used:

$$F_T = 0,5\rho C_T S V_{hub}^2, \tag{17}$$

where,

- ρ is the air specific mass, in kg/m^3.
- S is the swept area of the blades, in m^2
- V_{hub} is the mean wind speed at hub height, in m/s
- C_T is de thurst coefficient of the turbine.

For parked conditions the wind loads are only steady loads on the tower, platform structure and blades. In working conditions, the steady loads are on the tower and platform structure, the dynamic loads are considered as the thrust force generated by the turbine.

For more information about the wind conditions, see Rule Notes NI 572 [26] App3 Secc 2, for BV and FOWTI guide [8] Chapter 4, section 2 for ABS.

4.1.3   Current

Current conditions are to be defined for the purpose of load analysis of drag dominated structures and mooring analysis of FOWT. Also, as wave and wind conditions, two current states may be given, normal current with 1 year return period and extreme with 50 year return period. For ABS the survival sea state is also defined.

The current velocity is a vector of the sum of all the different current contributions, as wind generated current, sub-surface currents and tidal current, among others.

Generally the sub-surface currents are the driving ones. They are assumed to have the same direction than waves. Sub-surface currents profiles U(z) may be given by power law equation, Equation (18), where d is the water depth and z is the water depth from the sea level in meters. U(0) is the current speed at surface level.

$$U(Z) = U(0) \left(\frac{z + d}{z} \right)^{\frac{1}{7}}. \tag{18}$$

When the floating structure is considered slender the current loads follows the Morrison equation. According to BV, FOWT is considered as sender structure, therefore the hydrodynamic loads will follow Equation (19):

$$F_M = \frac{1}{2} \rho_w C_D D \left(v_F - \frac{d\xi_B}{dt} \right) \left| v_F - \frac{d\xi_B}{dt} \right| + \frac{\rho_w \pi D^2}{4} \left[(1 + C_M) \gamma_F - C_M \frac{d^2 \xi_B}{dt^2} \right], \tag{19}$$

where,
- ρ_w is the water density, in kg/m³.
- C_D is the drag coefficient.
- C_M is the added mass coefficient
- D is the structure diameter, or projected cross-sectional dimension of the structure, in m.
- V_F is the local fluid velocity, in m/s
- ξ_B is the local body displacement, in m
- γ_F is the local fluid acceleration, in m/s²

For more information about the current conditions, see Rule Notes NI 572 [26] App3 Secc 4, for BV and FOWTI guide [8] Chapter 4, section 4 for ABS.

Other marine conditions like tides, sea ice, water levels, marine growth, seismicity and earthquake related phenomena can be found in Rule Notes NI 572 [26] App3 Secc 4, for BV and FOWTI guide [8] Chapter 4, section 5 and section 6 for ABS.

4.2 Analysis and Design Loads

In order to design the mooring system different methods are presented in NR493 [7]; Quasi-static, quasi-dynamic and fully coupled analysis. These methods are only valid under specific assumptions. For mooring lines design for FOWT only full dynamic can be conducted [26].

Different load cases must be satisfied in order to design a safe mooring system:
- Intact conditions:
  - Maximum Operating Sea State (MOSS) with a 1 year return period sea state.
  - Extreme Sea State (ESS) with a 50 year return period sea state.
  - Survival Sea State (SSS) with 500 year return period sea state, only for ABS guidelines.
- One-line damaged
  - Sea state with 50 years return period.
  - Transient condition.
- Fatigue analysis

According to the scope, only the intact conditions are considered in this study. The purpose of this study is not to design the mooring system in detail but to have a robust and efficient design to be compared between other water depths designs. In this chapter the intact conditions are explained and compared between BV and ABS guidelines.

For BV guidelines and both sea states, n simulations of at least 3h each are to be performed, using different elementary waves representative in the whole spectrum. The design tension TD of a line in intact condition, for specified sea stated, is defined from the mean (T_M) and the standard deviation (T_S) of the n maximum values, as it is observed in Equation (20), NR 493 [7] Secc. 3, Chapter 6:

$$T_D = T_M + aT_S,$$ (20)

where a is a factor depending on the type of analysis performed and the number of simulations given. The value can be found in Table 9. For FOWT mooring design, the method must be dynamic.

Table 9 Factor a for intact conditions tension calculations

Method of analysis	Number of simulations			
	n = 5	n = 10	n = 20	n ≥ 30
Dynamic	0,60	0,30	0,10	0
Dynamic – 1 window	1,20	0,80	0,55	0,45
Quasi-dynamic	1,80	0,90	0,50	0,40
Note 1: For intermediate values of n, a is obtained by interpolation.				

For offset calculations, the same methodology as used for the tensions may be applied. The design offset O_D for the analysed condition is given by Equation (21), NR 493 [7] Secc. 3, Chapter 7:

$$O_D = O_M + bO_S, \qquad (21)$$

where, in this case, b is a factor that depends on the number of simulations, as given in Table 10.

Table 10 Factor b for intact condition offset calculations

	Number of simulations			
	n = 5	n = 10	n = 20	n ≥ 30
b	0,60	0,30	0,10	0
Note 1: For intermediate values of n, b is obtained by inter-polation.				

ABS guidelines defines that an acceptable length of global performance simulation time duration depends on many factors. Therefore, it should be determined and verified by sensitivity analysis. Recent studies indicate that, for typical floating oil and gas platforms in deeper water, five to ten 3 hour simulations with different random seed numbers (equivalent to 15 to 30 hours simulation) may be needed in order to obtain standard deviations and extreme values of the responses with good confidence [27]. Where the tension design would be the average of the maximum values from the five to ten simulations selected and verified with a sensitivity check.

In order to simplify the analysis, ABS guidelines with ten simulations of 3h are selected to design the mooring systems. In addition, this 30h simulations are simplified by a design wave, defined in Appendix B.

According to BV, in order to have representative results, the mooring line should be divided in different segments i in the finite element model, where the segment l_i should not exceed Equation (22):

$$l_i = T_p \sqrt{\frac{F_{mean}}{m_{NI}}}, \qquad (22)$$

Where, F_{mean} is the mean line tension in kN and m_{NI} is the total normal mass per unit length, in kg/m, of the line segment i. Notice that smaller length of line segments are generally necessary in the touchdown area, top chain and close to the fairlead.

In this thesis, the line has been divided in segments in the order of 1m in the suspended line, near to the touchdown area 0,5m and near to the anchor up to 20m.

4.3 Criteria

The criteria imposed by the certification societies are defined by a safety factor (SF). The SF of a mooring line component is defined in Equation (23), NR 493 [7] Secc 3. Chapter 11.1:

$$SF = \frac{BL}{T_{max}},$$

(23)

where, BL is the breaking load of the mooring line and T_{max} is the maximum tension occurring on the different mooring line tensions when the design tension is applied.

For drag anchors, the safety factor SF is defined as Equation (24), NR 493 [7] Secc 3. Chapter 11.2:

$$SF = \frac{MHP}{Ta_{seabed}},$$

(24)

where, MHP is the maximum holding capacity applicable to the mooring line and Ta_{seabed} is the tangent-to-the-seabed component of the tension line at the anchoring point when design tension is applied.

The calculated SF for the line components and drag anchors should not be lower than the given values on Table 11.

Table 11 Safety factor of line components and DEA for BV and ABS

Condition of the System (2)	BV NR 493 [7] Sec 3	ABS FOWTI [8] Sec 5	BV NR 493 [7] Sec 3	ABS FOWTI [8] Sec 5
	Line Components		Drag Anchors	
Intact (1)	1,67	1,67	1,50	1,50
Damaged	1,25	1,05	1,05	1,00
Transient	1,20	1,05	1,05	1,00
Survival	-	1,05	-	1,05

(1) For system without redundancy, BV: the safety factor is to be increase by 20%. ABS: see tables in FOWTI [8] Sec 5.
(2) For fiber ropes the SF is to be increased in the rope itself by 10% for polyester ropes and 20% for other materials in the case of BV. For ABS, all synthetic ropes have a SF of 1,82 for intact conditions and 1,43 for damaged conditions.

5   Methodology

5.1   Modelling Tools

Aerodynamic loads generated by the turbine, motions of the platform generated by waves and drift loads must be taken into account in order to design the mooring system. Therefore, the most appropriate is a time-domain simulation tool able to consider all the motions and loads. The tool used for designing the mooring system in this project is OrcaFlex.

OrcaFlex is a commercial time-domain simulation tool developed by Orcina [28] that performs hydrodynamic analysis of offshore structures. OrcaFlex is one of the world's leading software for the dynamic analysis of offshore marine systems. The algorithm is considered very powerful for computing the mooring system. The software has been developed to be very applicable to model FOWTs. The hydrodynamic coefficients of the platform are obtained from the commercial software WAMIT [29]. OrcaFlex 9.8e is used for the computations presented in this study.

5.2   Design Basis and Conventions

The station keeping system is designed to guarantee restricted motions of the FOWT, to avoid any damage under any environmental load. The FOWT is composed by the floating platform WindFloat designed by Principle Power and the Wind turbine Haliade 150-6MW by General Electric. The main characteristics are presented in chapter "Platform and Wind Turbine".

Following the reasons presented in Mooring Configuration, the station keeping selected is a mooring catenary system with a drag embedment anchor. The mooring lines are a combination of different materials; a suspended line made of synthetic rope and steel chains lying on the seabed. A heavier chain is chosen for the line sections close to the touch down area in order to enhance the effect of the catenary system.

The mooring system is composed by three identical lines, one per each column, and equally spaced around the FOWT. This fact is based on the symmetry of the platform and the omnidirectionality of the metocean data, justified in metocean section of this document.

Mooring line 1, ML1, is attached at the wind turbine column. ML2 is at the following column in anti-clock wise direction and ML3 is connected to the remaining column. The mooring system distribution is presented in Figure 28.
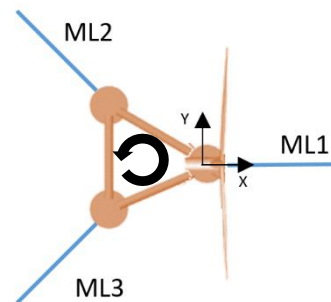

Figure 28 Mooring Lines Distribution

The general axis are set in the turbine column as shown in Figure 28. The angle conventions are in degrees and anti-clockwise from the global X-axis. The metric system used is the SI, with forces in tonnes (t).

5.3 Load Cases

Load cases are defined in the Certification Requirements chapter. Nevertheless, as it is explained in Scope, only three load cases are considered. Two cases are imposed by the certification body; the maximum operating load case and the extreme load case. The third load case is required to check the design for excessively frequent turbine shutdowns due to platform horizontal motions induced by turbulent wind (HMTW).

5.3.1 Maximum Operating Sea State Load Case (MOSS)

This load case covers a turbine operating during 1-year return period storm, shown in Metocean Data chapter. The thrust force is maximum at the rated wind speed, which makes it a design case. The Wind turbine Haliade 150-6MW has a rated wind speed at 11m/s, presented on Table 1.

The thrust value associated with the rated wind speed is shown in the confidential parameters document. This thrust force, applied at the hub height, generates a moment and a platform heel angle. To balance this moment and keep the average platform heel at +/- 1º a compensating moment is applied on the platform, corresponding to the active ballast mass.

5.3.2 Extreme Sea State Load Case (ESS)

The ESS load case is considered when the FOWT has to face a 50- years return period sea state, defined in the Metocean Data section of this document. In this case, the wind speed is over the cut off speed, hence the turbine is parked. The pitch angle of the blades is kept at 90º. The turbine has a nacelle control in order to avoid the misalignment with the wind. When the turbine is parked, the rotor is locked to avoid rotations.

Nevertheless, the wind is still producing a force due to the drag on the blades and tower. The ballast effect must be considered to make sure that the average pitch and roll angles are null to minimize structural stresses. The active ballast is simulated by a compensating momentum, applied on the platform.

5.3.3 Horizontal Motions induced by Turbulent Wind Load Case (HMTW)

The turbine has a safety system switching off the turbine in case of excessive accelerations levels at the hub or excessive misalignment between the wind and the nacelle. A turbulent wind could lead to high standard deviations in the horizontal platform motions, inducing high nacelle acceleration and misalignments. Therefore, the mooring system stiffness should reduce the horizontal platform motions, induced by the turbulent wind.

The wind considered for this load case is turbulent. The average speed of the inflow is 14 m/s at the hub height. The turbulence intensity (TI) is set to 15%. The wind profile is computed using TurbSim[4]. The wind direction is at 90º from the X-axis, as it is the most critical direction in terms of the largest horizontal motions.

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[4] TurbSim is a stochastic inflow turbulence tool developed to provide a numerical simulation of a full-field wind flow. This tool has been developed by National Renewable Energy Laboratory (NREL)
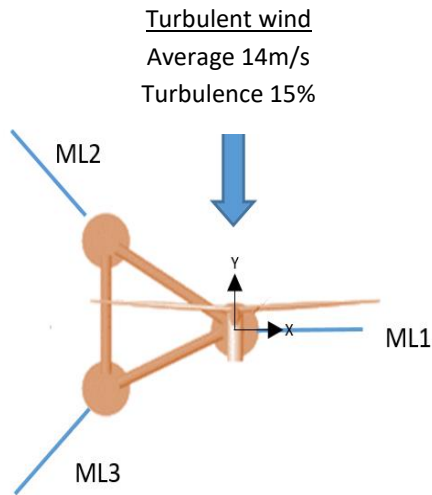
Turbulent wind
Average 14m/s
Turbulence 15%

Figure 29 Scheme of the platform and wind direction for HMTW load case

The nacelle is oriented to face the wind, providing a zero average nacelle yaw error. This configuration is illustrated in Figure 29.

The considered motion parameter in order to design the mooring system for the HMTW load case is the yaw motion standard deviation.

The simulation time is set to 30 minutes to track enough data to compute the horizontal motion standard deviation. The build-up period is set to 200 seconds.

The aerodynamic loads were simulated by using an equivalent blade drag coefficient, calibrated by PPI.

Similar to the other two load cases, an active ballast is simulated in order to compensate the momentum created by the thrust force.

In this load case, no waves nor currents excitations are considered.

5.4 Metocean Data

The metocean data are site and water depth dependent. However, the same metocean parameters are considered in the analysis and comparison of the mooring designs for different water depths. In order to study the influence of the water depth on the FOWT mooring designs, simplified metocean data sets are defined. Those conditions are omnidirectional. They are arbitrary defined in the attempt of reflecting the three main load cases: the MOSS, the ESS and the HMTW. Their corresponding metocean data are presented in Table 12.

Table 12 Metocean data for different load cases

Load Case	Turbine Condition	Hs [m]	Tp [s]	Wave Spectrum [30]	Wind Speed [m/s]	Current Speed [m/s]
		3h average			100 m above sea level	At surface
MOSS	Operating	5	10	JONSWAP	11	0,25
ESS	Parked	8	12	JONSWAP	35	0,50
HMTW	Operating	0	0	-	14 TI=15%	0

According to the Certification Requirements, the maximum loads are determined by the expected maximum load occurring in a 3h simulation. In order to test a large number of mooring configurations, a design wave is selected by isolating a representative extreme wave in a 10 minutes simulation. The procedure followed to find the design wave can be found in Appendix B.

A directional analysis is performed to determine the combination of wave, current and wind directions giving the highest loads on each mooring line. This study is carried with the extreme sea state conditions, in 50m water depth. The WindFloat platform is symmetric hence the study is only performed from 0º to 180º, every 30º. The simulation time is set at 10 minutes using the design wave described in Appendix B. The metocean data has been previously presented on Table 12.

The study is performed and analysed for the three mooring lines. The maximum loads are found in mooring line 1. Figure 30 represents the maximum anchor tension loads for ML1 and different combination of wind and waves directions. The metocean direction convection considered is provenance direction and un-clock wise from X-axis. Current and waves are considered collinear in the whole study. The anchor tension is divided by the anchor tension criteria in order to present the results as reference values. The reason is explained in the scope.
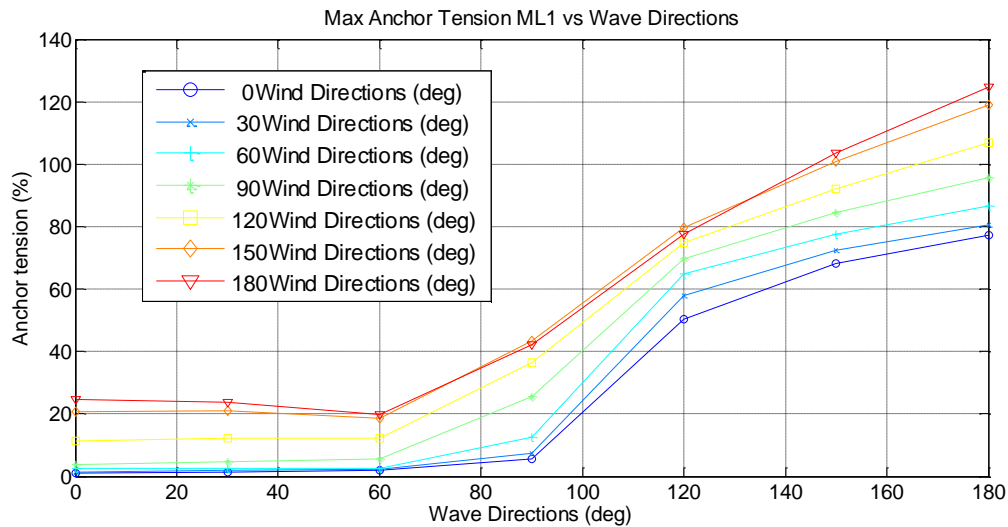

Figure 30 Directional study for ML1 and maximum operating sea state load case

Analysing the results from the directional study, the maximum loads appears when the wind, waves and currents propagation are collinear. The mooring design must be analysed with the combination of mooring line and wave-wind direction that present the highest loads. As it can be observed in Figure 30, the highest load is found in ML1 with a wave and wind propagation direction collinear at 180º.

In addition, the analysis at 0º propagation are also computed since the maximum offsets are found when the environment conditions are collinear between the two lines.

5.5 Mooring Design

Nine different designs are analysed depending on the water depth: 50 m, 60 m, 70 m, 80 m, 100 m, 120 m, 200 m, 250 m and 400 m. This chapter explains the assumptions and procedures taken into consideration in order to design and analyse the different nine moorings systems.

5.5.1 Assumptions

A large number of variables are considered in order to design a mooring system; pretensions, top angle, anchor tensions, maximum tensions, line lengths, line weights, metocean conditions, seabed type or floating platform restoring coefficients are some examples. As it has been explained in the previous chapters, the floating platform, wind turbine, metocean conditions, seabed type and basic design would be considered the same for all cases. Therefore, the mooring system design would only depend on the length, weight and pretension of the lines.

The anchor size is also considered to be the same for all water depths. As a consequence, all the cases will have the same maximum anchor tension. This anchor tension criteria is imposed by the proof load that the AHV has to pull during the anchor installation, as explained in the Drag Embedment chapter. In addition, the anchor uplift must be lower than 0.1º as imposed by BV for DEA, see chapter Certification Requirements.

The principal goal of the mooring system is to restrain platform motions to acceptable limits. The maximum motion allowance is imposed in order to avoid damages on the platform and surroundings, such as cables or other FOWTs. Floating platforms have 6 degrees of freedom; heave, surge, sway, pitch, yaw and roll. The mooring system is mainly designed to control the surge, sway and yaw motions. The ballast system and platform structure are mainly restraining heave, pitch and roll motions. The combination of both, surge and sway motions, is commonly known as offset, following Equation (25):

$$Offset = \sqrt{Surge^2 + Sway^2}. \qquad (25)$$

The top angle is the declination angle between the mooring line at equilibrium conditions and the vertical. The platform response in surge, sway and yaw depends on this parameter. For a larger top angle, the horizontal restoring force would be higher and reducing motions. However, it would reduce the catenary effect, thus the mooring system would have less damping and the anchor would issue higher tensions peaks. The nine water depth cases will have similar top angles.

Finally, as previously explained, the yaw motion standard deviation criteria is set in order to avoid switching off the turbine during operating conditions due to nacelle accelerations or misalignment for the HMTW load case.

The mooring line tensions and platform motions depend on the mooring design parameters. Table 7 shows the interaction of the outputs and the main design parameters such as pretension, heavy chain weight, suspended line and anchor chain length. The output response is presented when the design parameter increases. In addition, Figure 35 shows a sketch of the variables considered for a catenary mooring system.

Table 13 Mooring design variables interaction

|	Uplift angle	Anchor tension	Top angle	Offset	Yaw motion STD
Criteria	<0.1 deg	Confidential Parameters Document			
Increase in Pre-Tension	Increase	Increase slightly	Increase	Decrease	Decrease
Increase in Weight of Heavy Chain	Decrease	Decrease	Decrease	Increase	Increase
Increase in Length of Suspended Line	Increase	Increase	Increase	Decrease	Decrease
Increase in Length of Anchor Chain	Decrease	Decrease slightly	Indifferent	Indifferent	Indifferent
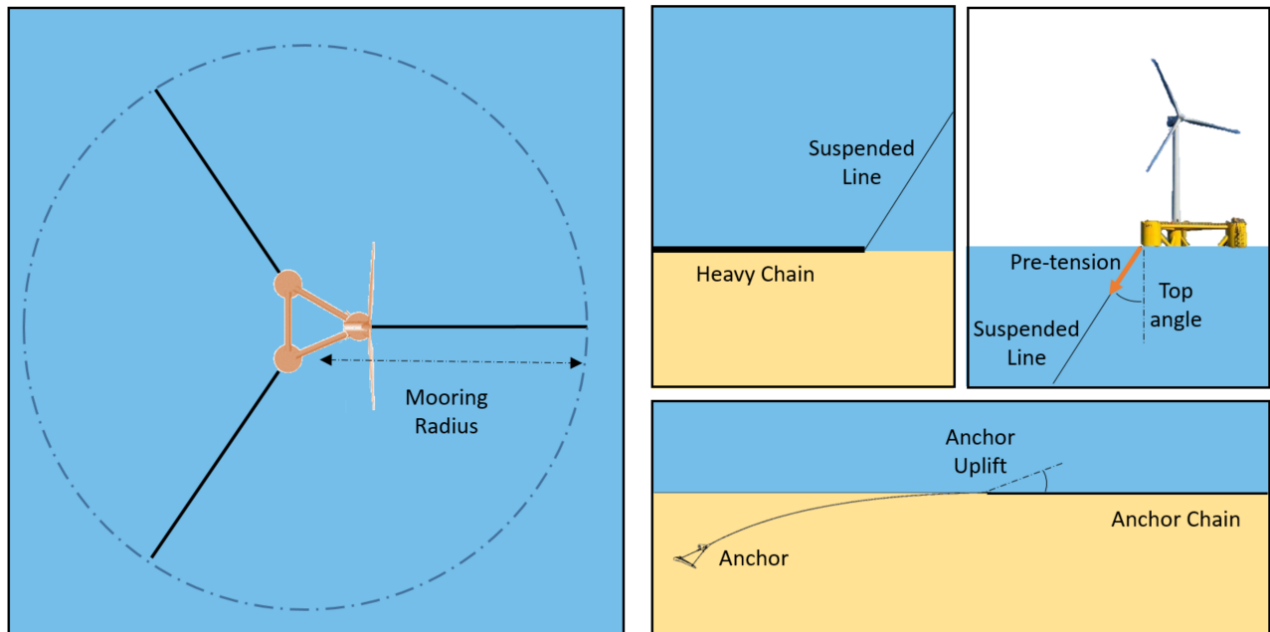
Figure 31 Design variables of a catenary mooring system

The pretension is assumed to be fixed at 40t for all water depths. The pretension value is chosen as a trade-off between platform offsets and anchor tensions. Appendix C reports the numerical results leading to this decision.

The mooring line can be divided into five sections. Some sections are assumed to be the same for all water depths in order to simplify the analysis by decreasing the number of variables. Others, like synthetic rope, is water depth dependent to ensure enough clearance between the synthetic rope and seabed. In this way, the synthetic rope would not touch the seabed in any case. The synthetic rope length follows the equation shown in the confidential parameters document.

Table 14 presents whether the weight and length is considered variable or fixed for the different five line sections. The suspended line is composed by synthetic rope and suspended chain. The heavy chain is at the touching seabed point. The middle heavy chain and the anchor chain are lying on the seabed. The organization of the line goes from the winch platform connection, where the synthetic rope is attached, until the embedded anchor, where the anchor chain is connected.

Table 14 Different sections of the mooring system studied

Mooring part	Material	Weight [t/m]	Length [m]
Suspended rope	Synthetic	Fixed	Equation
Suspended chain	Steel Chain	Fixed	**Variable**
Heavy Chain	Steel Chain	**Variable**	Fixed
Middle Heavy Chain	Steel Chain	Fixed	Fixed
Anchor Chain	Steel Chain	Fixed	**Variable**

The linear density of the heavy chain vary depending on the water depth. This change is achieved by adapting the chain size and the chain fittings.

With all the assumptions considered, the design and optimization of the water depth specific mooring system is reduced to variations of:

- The length of the suspended chain.
- The weight of the heavy chain.
- The length of the anchor chain.

5.5.2   Design Process

This section explains the procedure that has been followed to optimize the mooring system for all water depths. The procedure is shown in Figure 32.

The first step is to study a design varying the weight of the heavy chain and the length of the suspended chain for the ESS load case. The objective of this analysis is to find the best and most effective combination that satisfy 95% of the anchor tension criteria and 100% of the offset criteria in both directions (0º and 180º).

Once the design of the heavy chain and suspended chain length is set, the HMTW load case is computed in order to know whether the mooring design satisfies the horizontal motion criteria or not. If the standard deviation criteria is not satisfied, another heavy chain versus suspended chain length study is analysed. Usually, to reduce the yaw motion standard deviation, the top angle would have to increase. Table 13 shows how the design variables may change in order to achieve higher top angle values.

On the other hand, if the criteria parameters are satisfied, the anchor chain is reduced until the anchor tension is 100% of the criteria or the uplift overpass 0,1º. This would not affect the top angle of the mooring line, hence the offset and horizontal motion standard deviation due to turbulent wind would remain.

The last step is to verify if the design satisfies the criteria in the MOSS load case. If the anchor tension or the uplift overpass its criteria, larger anchor chains would be performed. On the other hand, if the platform offset criteria is not satisfied, the whole procedure would be repeated trying to increase the top angle, and therefore reducing the offsets.

The final mooring system design is the one that satisfies all the criteria for all three load cases.
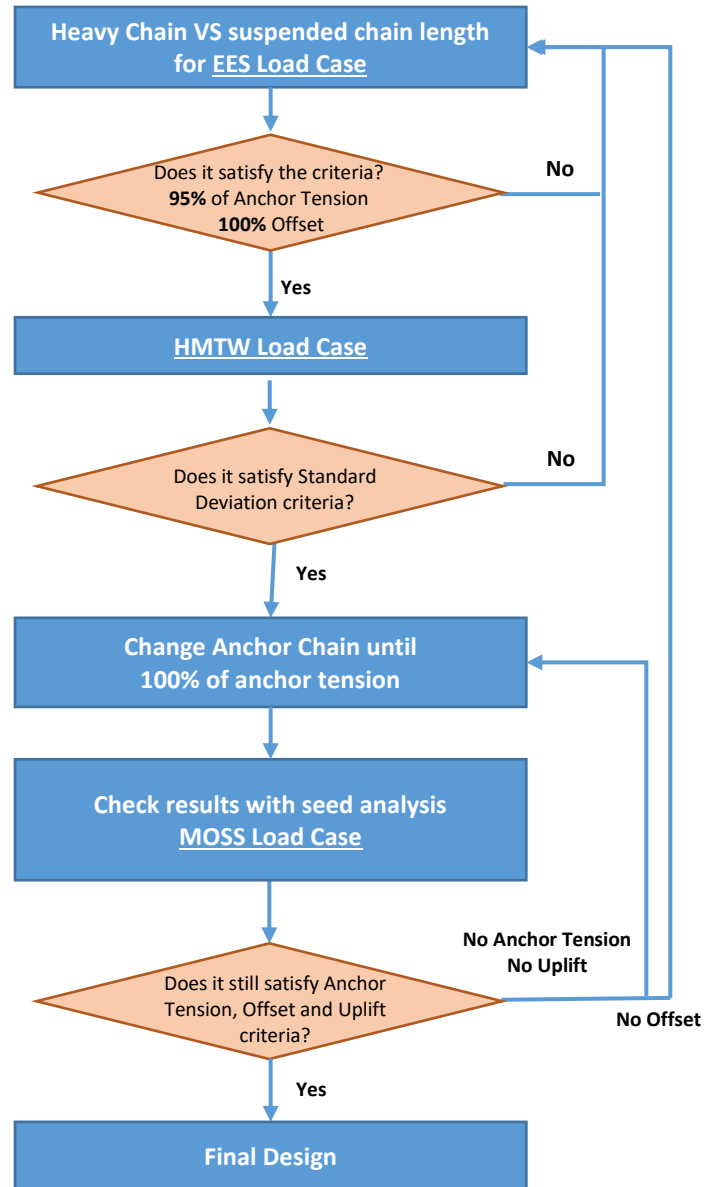

Figure 32 Scheme of the followed procedure

5.5.3   Anchor Design

As it is explained on Mooring Configuration chapter, DEA are installed in the mooring system for all water depths. The anchor size and installation cost depends on the maximum tension. As it is explained in Drag Embedment chapter, once the DEA is installed, the AHV must pull a proof load on the mooring line to verify the installation. For higher proof loads, higher capacity vessels are needed which increase the installation costs.

As a reference for this study, the anchor selected is the Stevpris Mk6. This DEA is one of the most used anchors from the most important manufacture in the world, Vrihof [15]. Figure 8, shown in chapter Drag embedment anchors, describes the correlation between Ultimate Holding capacity (UHC) and anchor weight. Therefore, the drag embedment anchor is sized using the anchor design tension and Figure 8 . A market research from different anchors sizes is performed in order to analyse the costs.

All water depths would have the same anchor size and costs, except the shallow water case of 50 m. This case has higher anchor tensions than other water depths, hence it would require larger anchors and higher proof loads, see Appendix C for clarification.

6   Mooring Optimization Results and Discussion

This chapter reports the mooring designs that would meet the designs criterias for the studied range of water depths. The results identify some trends of hardware cost when adapting the mooring design to different water depths, presented in Figure 33 and defined as follows:

- Shallow waters of 50 m, 60 m, 70 m, 80 m, 100 m
- Intermediate waters of 120 m, 200 m, 250 m
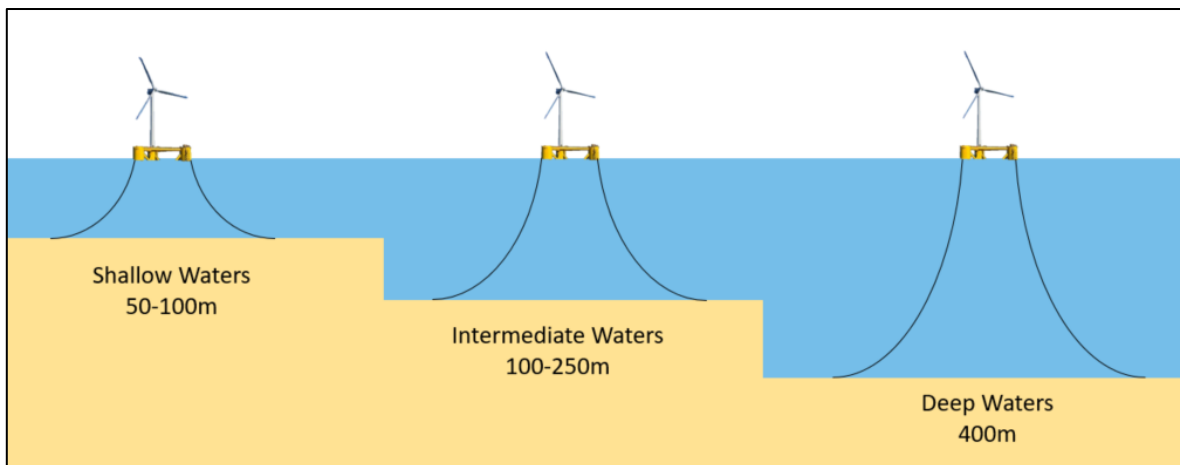- Deep water of 400 m.

Figure 33 Different water depths definitions

The mooring design subchapter presents the weight of heavy chain, length of suspended line and mooring radius for each studied water depth case. All the cases have similar top angle.

The platform motions and line tension responses, such as maximum top tensions, anchor tensions, anchor uplift and offsets are presented in mooring responses subchapter. All graphs have the criteria marked by a red line. The mooring and platform responses are performed for MOSS and ESS load cases, with an exception of the maximum top tension that is only presented by the ESS load case. This subchapter also presents the standard deviation of the horizontal motion for the HMTW load case.

As it is explained in the Scope, the purpose of the project is to identify trends of the mooring designs depending on the different water depths. For that reason, all the results discussed are represented as non-dimensional values. The non-dimensionalization of this work is computed dividing the absolute values by a reference one. The selected reference case is the 100m water depth in the ESS load case.

Finally, the hardware mooring costs of the FOWT are presented. The cost model comes from Principle Power Inc. collected data, established through manufacturer consultations. The costs are presented as a non-dimensional results dividing the absolute cost by a reference value. The reference cost is the cost associated to the 100 m water depth.
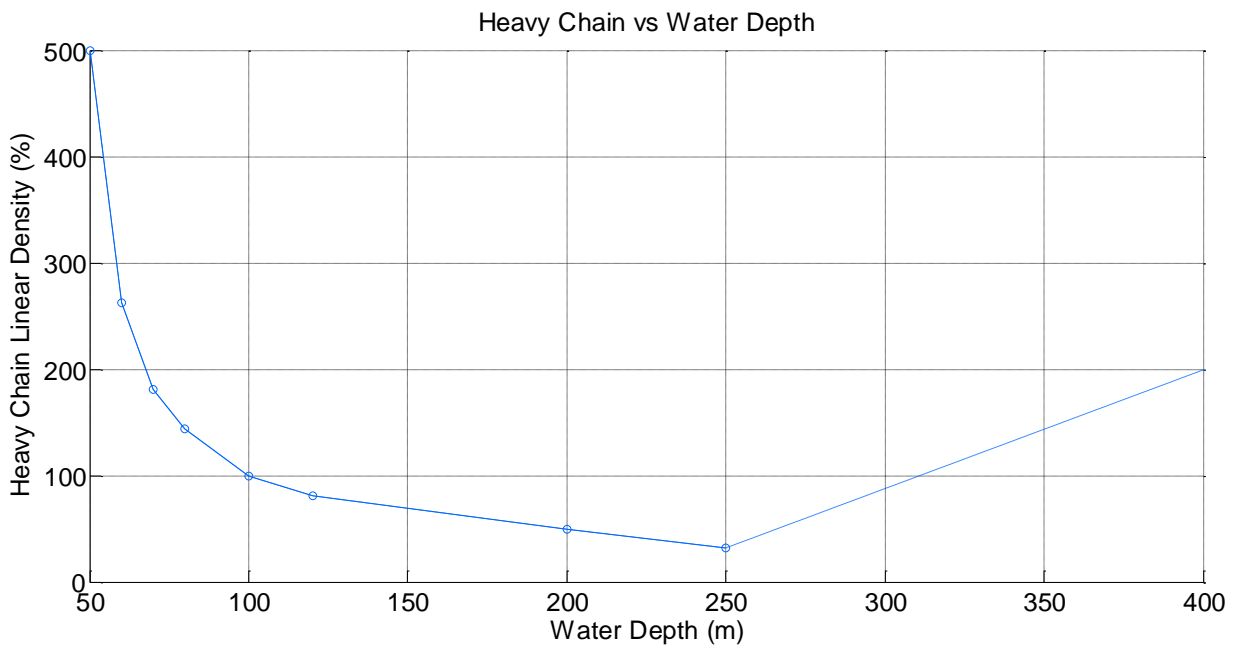
6.1 Mooring Design

Figure 34 Heavy chain for the different water depths

Figure 34 presents the heavy chain weight for the different studied water depths. The restoring capacity of a catenary system depends on the catenary shape, requiring higher gravity forces in shallow waters than deep. This fact is presented on the figure above, where shallow waters required a heavier chain to satisfy the requirements. Shallow waters' heavy chain weight increases exponentially when the water depth decreases. The shallowest case of 50m water depth has the heaviest chain. This fact makes the heavy chain the driving parameter to design the mooring line for shallow waters, since small decrease on the water depth requires heavier chains.

On the other hand, intermediate waters' heavy chain weight decreases linearly for deeper water depths. This tendency is identified until 250 m case, where it reaches the lightest point.

The deep water case of 400m required heavier chains than 250m. For light heavy chains, the suspended line is too steep (low top angles) resulting in higher motions and overpassing the requirements. Therefore, the heavy chain was increased in order to concentrate again the weight at the touch down point. This method enhances the catenary shape of the system increasing the top angle and the restoring force, being able to satisfy the platform horizontal motions criteria, presented further on Figure 42.
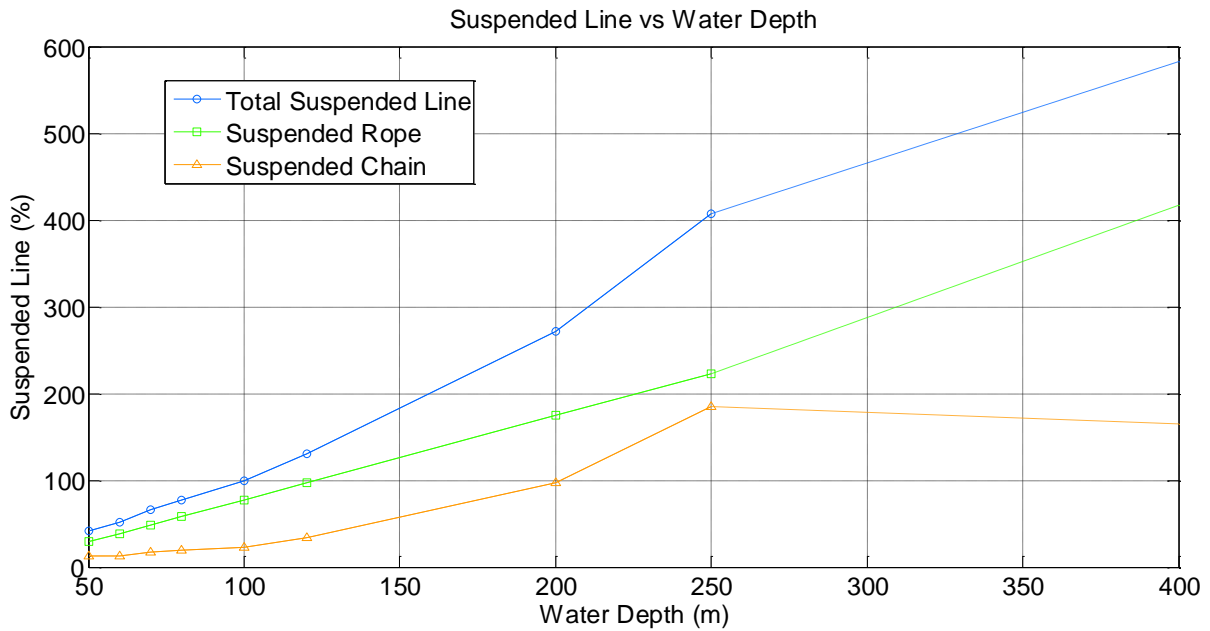
*Figure 35 Suspended line for the different water depths*

Figure 35 presents the design results of the suspended line length. This line is composed by synthetic rope and suspended chain. The objective of varying the suspended line is to adjust the top angle to increase the restoring force on the mooring line.

Contrary as the trend of the heavy chain weight, in shallow waters the suspended line length increases linearly with the water depth. On the other hand, intermediate water design's trend seems to increase exponentially.

When the heavy chain weight is increased, the top angle decreases. Therefore, in order to avoid too steep top angles and a decrease in the restoring force generated by the catenary shape of the system, the length of the suspended line has to increase. Table 13 shows the relation between those parameters.

In order to satisfy all criteria, the mooring design of the deep water case of 400m could not follow equation found in the confidential parameters document for the synthetic rope length. In consequence, the designed value was increased. Consequently, the suspended chain and the total suspended line were reduced compared to the intermediate waters trend.
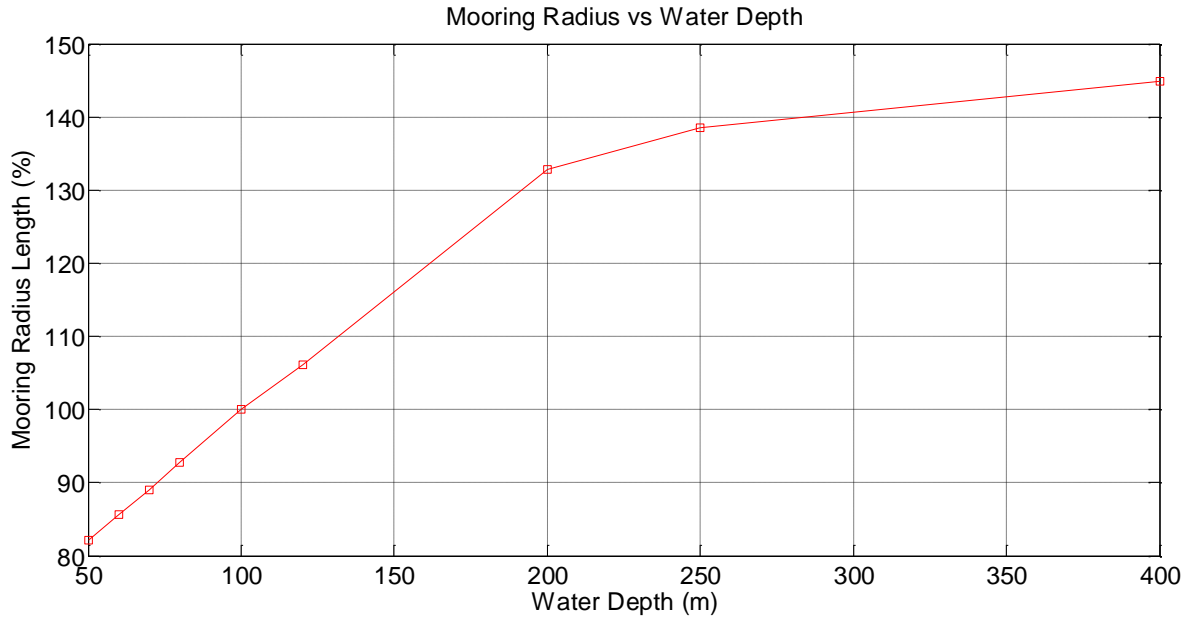
Figure 36. Mooring radius for the different water depths

Figure 36 shows how the mooring radius increase when water depth increases. The mooring radius is an important parameter to be optimized, since the site areas where the FOWT can be installed are usually limited. For shorter mooring radius, higher density of turbines can be achieved resulting in a larger energy production for a given site area.
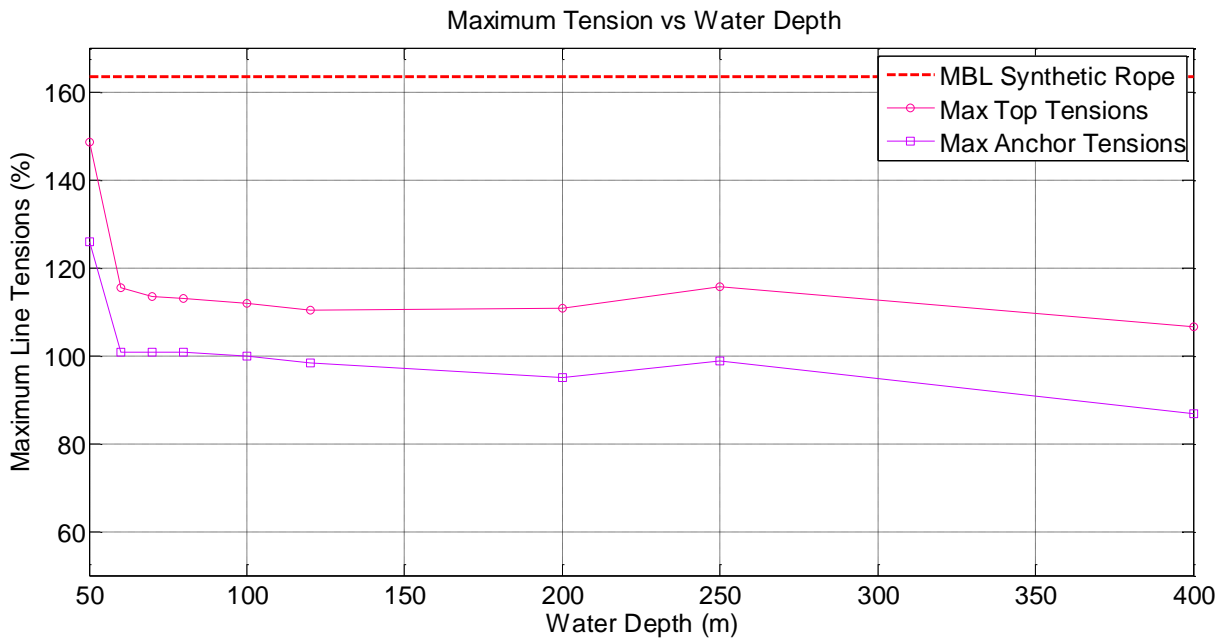
6.2 Mooring Responses

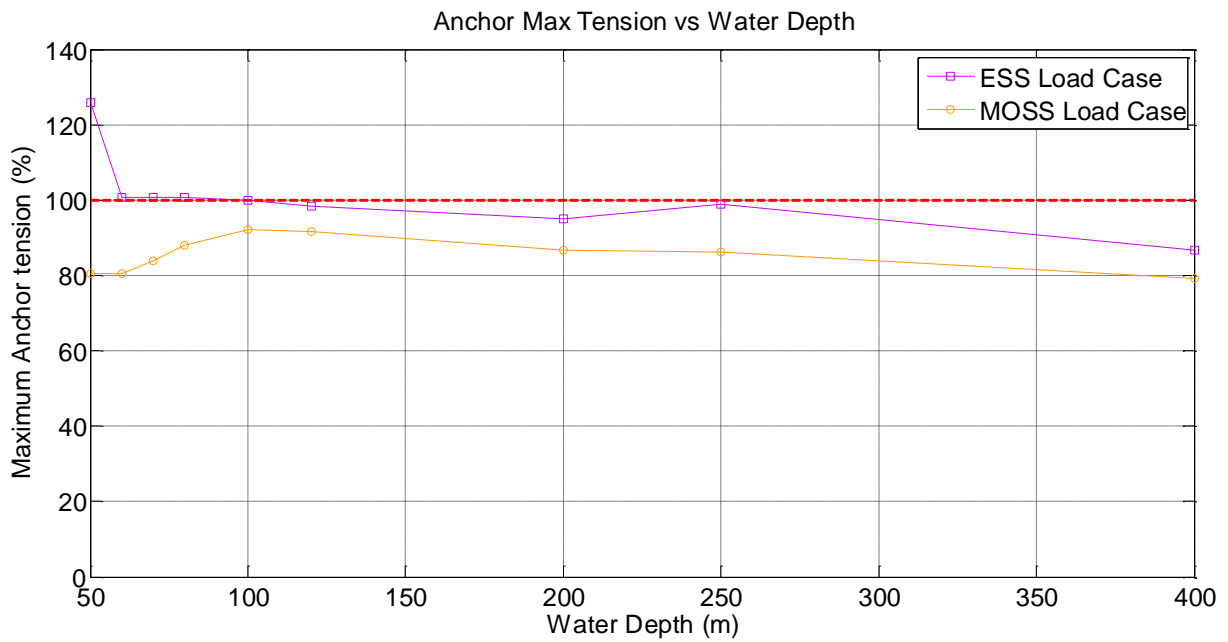*Figure 37. Maximum tensions for the different water depths*

Figure 38. Anchor tensions for the different water depths

Figure 37 presents the maximum line tensions for each water depth. The maximum tensions occur at the platform mooring connector (PMC). At this point the line is composed of a synthetic rope. The MBL limit is shown in the figure as a red line. This limit is divided by a safety factor of 2, imposed by BV, see Table 11. As it can be observed, all the maximum tensions are below this limit, therefore, the rope meets the safety requirements imposed by the standard society in terms of maximum tensions.

Maximum anchor tensions for each water depth are plotted in Figure 38. This graph has also the limit represented by a red line. The limit is the maximum anchor tension criteria used to design the mooring line. The results show how all water depth cases satisfy the criteria except the shallowest, for the ESS load case. This case faces 25% more anchor tension than the criteria imposed for the other cases. For the 50m water case and the assumptions considered, it was impossible to satisfy both criteria, offset and anchor tensions. Hence a compromise was found by applying a larger limit, the impact of this decision leads on having more expensive hardware and installation anchor costs. This is detailed explained in Appendix B.

The results obtained in Figure 38 shows that the anchor has to support higher tensions for ESS load case than MOSS. This fact satisfies the hypothesis of using ESS as the design load case.

The anchor uplifts are presented in Figure 39 for both load cases. As it can be observed, no water depth in any load case overpass the limit of 0,1º. Therefore, the DEA only holds horizontal loads.
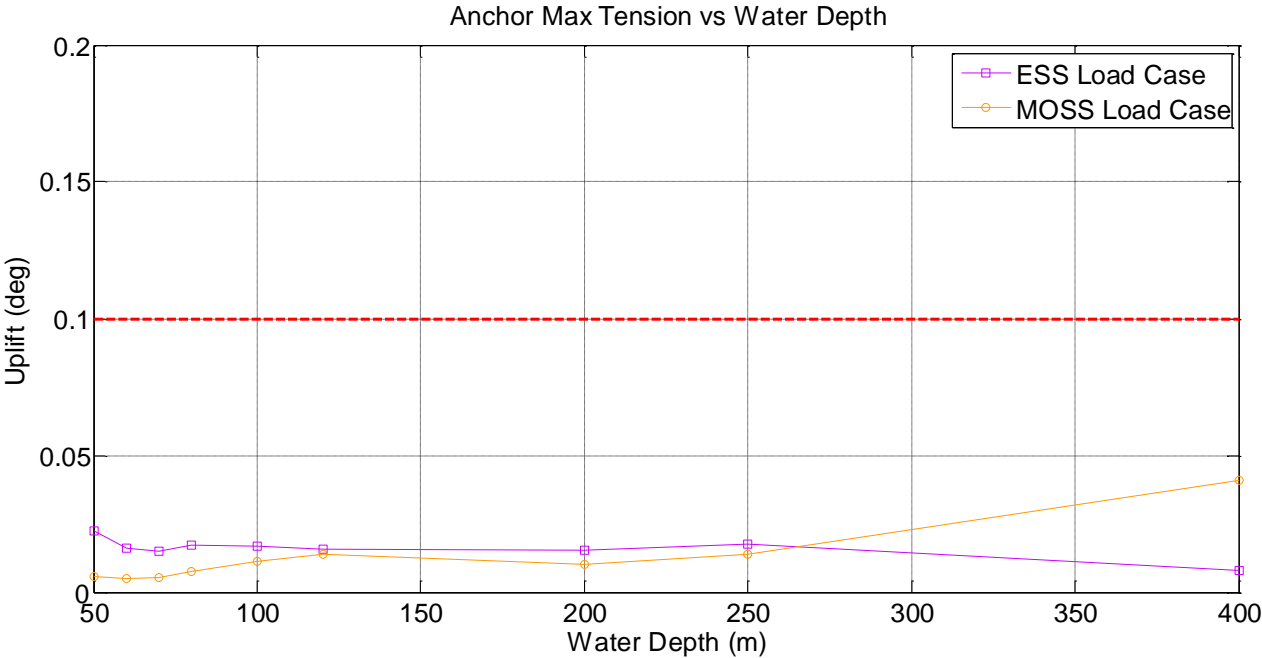

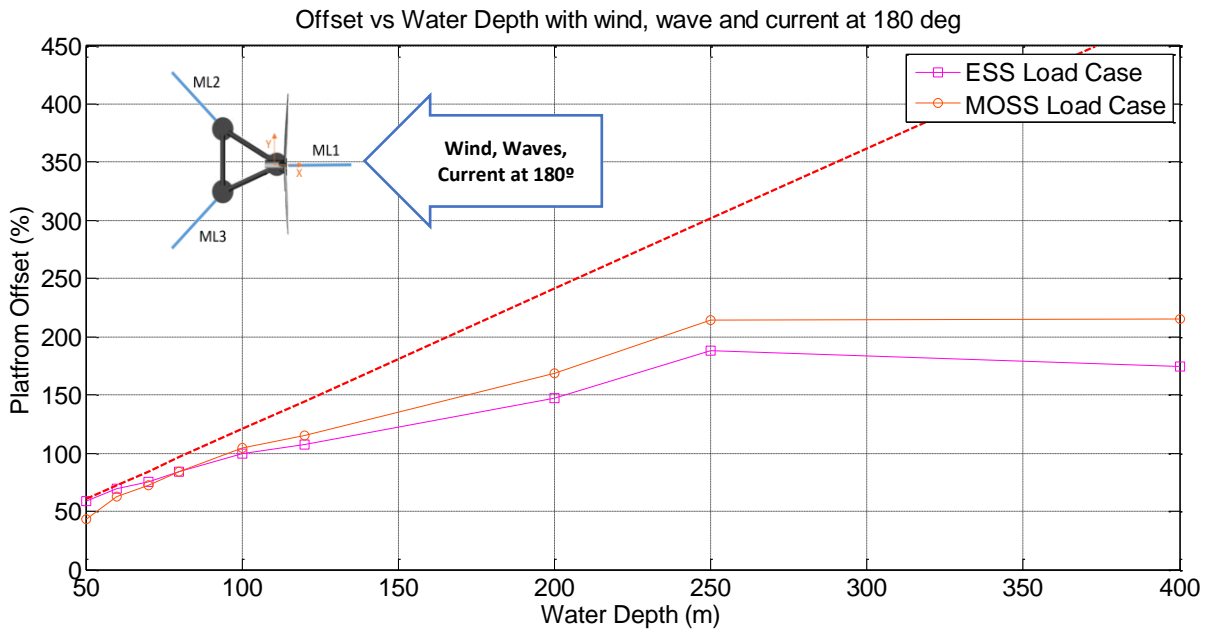*Figure 39 Uplift for the different water depths*

Figure 40 Offset for the different water depths with wind, waves and current at 180º
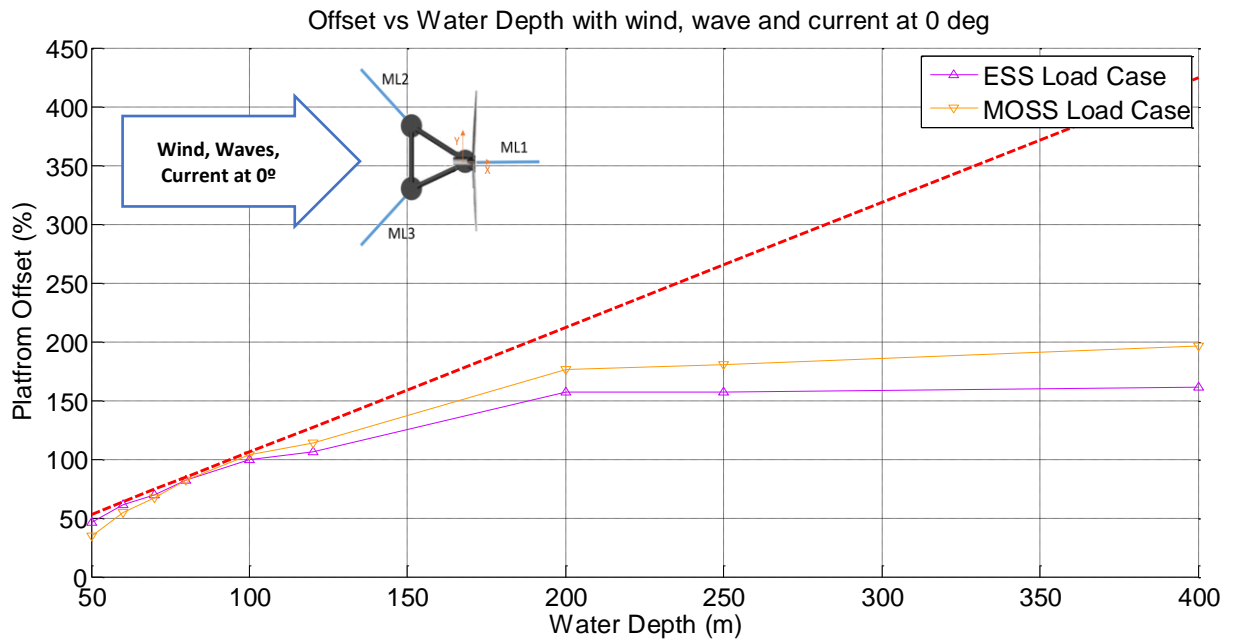

Figure 41 Offset for the different water depths with wind, waves and current at 0º

The platform offset motions were computed for both, ESS and MOSS and directions of 180º and 0º, in Figure 40 and Figure 41, respectively. The offset criteria depends on the direction and water depth. It represented as a red line. All the offset responses are below the red line, hence all the directions and load cases satisfy the offset criteria. As it can be observed in the figures above, 180º provenance sea state direction is collinear with ML1 and 0º provenance sea state direction is between ML2 and ML3.

For shallow water depth cases the motion offset values are closer to the limit than deep water cases. Therefore, the offset motions (surge and sway) were driving the mooring design for those cases. Although intermediate and deep waters have higher motions, the criteria is less restricted and do not affect the design. The platform motions for those water depths were more constrained by the yaw motion standard deviation for HMTW load case, see Figure 42.
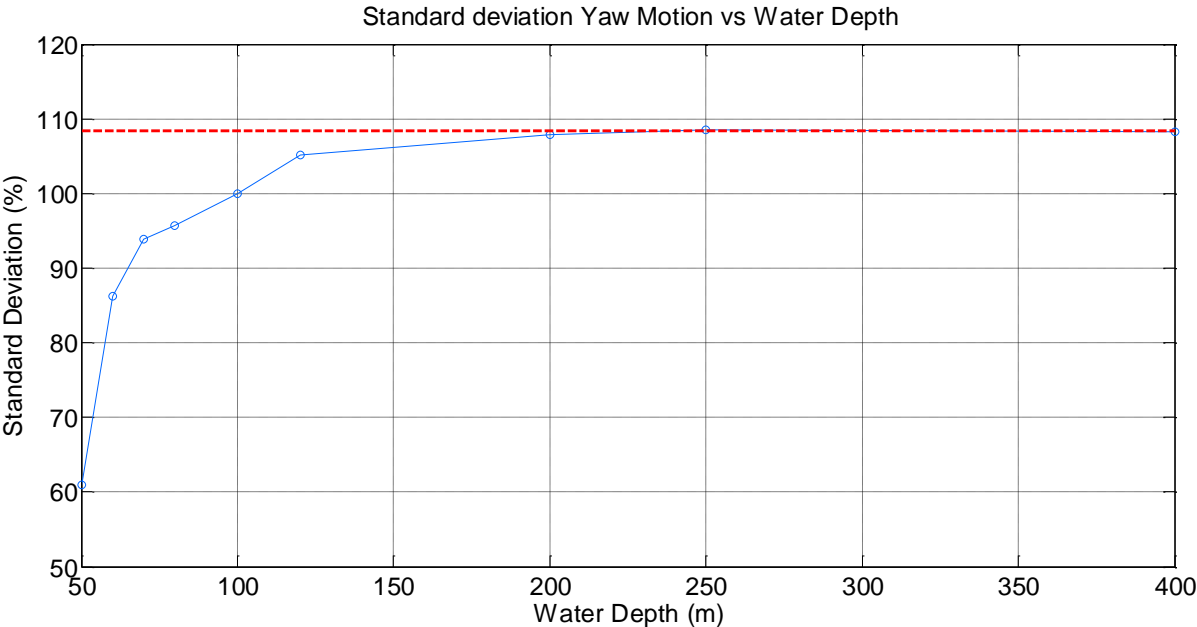

Figure 42. Standard deviation yaw motion for the different water depths

Figure 42 shows the standard deviation for the platform yaw for the HMTW load case. As a main difference from the platform offset, the standard yaw deviation criteria is constant for all water depths. This limit is represented with a red line.

The platform surge, sway and yaw motions are larger for deep water cases than shallow. However, as contrary of the offset criteria, the yaw standard deviation criteria is constant, making the intermediate and deep water cases closer to their limit than shallow waters. This fact makes the standard yaw motion deviation the design motion parameter for intermediate and deep waters.

Comparing the figure above with Figure 34, it can be observed how both graphs follow a contrary exponential trend. For high heavy chain weights, the standard yaw deviation is low. The reason is that for high values of heavy chain and same top angle, the motion damping coefficient is higher, the stiffness of the mooring system increases and the platform motions decreases.
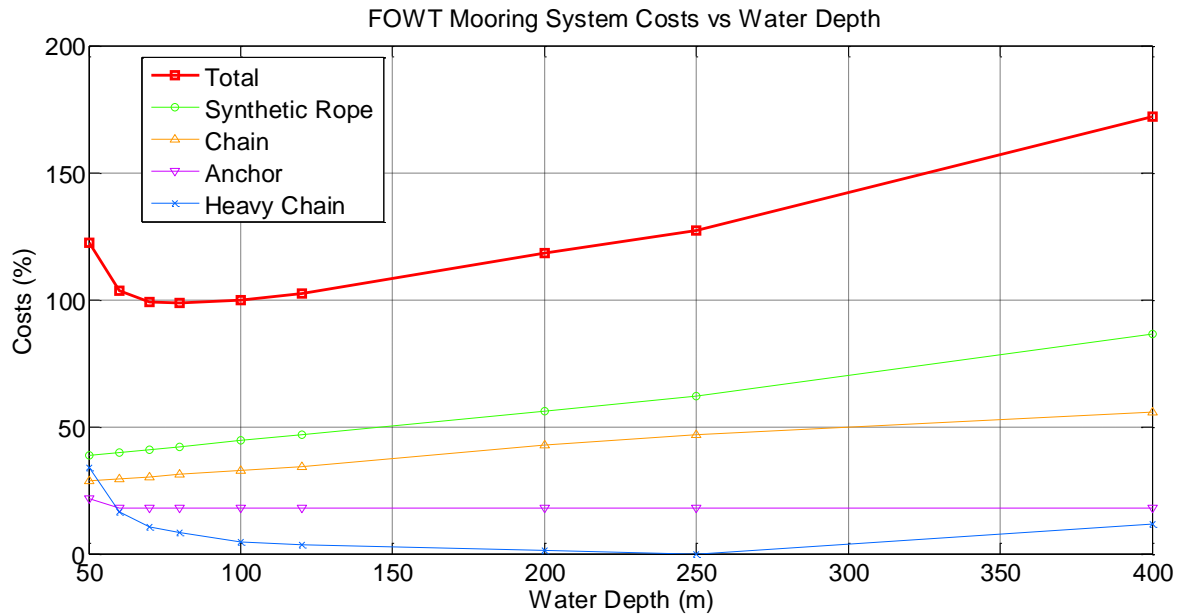
6.3 Mooring Hardware Costs

Figure 43 Hardware mooring cost for the different water depths

The mooring system costs per FOWT, for each water depth are presented in Figure 43. This graph is divided into different parts of the mooring system: synthetic rope, chains, heavy chain and anchor costs.

As it can be observed in the cost analysis, the chain and synthetic rope increases linearly with the depth. The heavy chain costs are proportional to the heavy chain weight, being more expensive for shallow waters than deeper. The anchor costs, on the other hand, are constant for all water depths since all the cases have similar anchor tensions, except the shallowest case of 50m, where the anchor tension has a higher limit.

At the end, the total cost presented in the figure above, is the sum of the costs from the different mooring system parts. As it can be observed, the trend of the total costs have a minimum range from 60m to 80 m water depth. This minimum is originated by two factors, the weight of the heavy chain driving the shallow water costs and the length of the lines driving the intermediate and deep water costs.

7 Conclusions and Suggestions for Further Studies

Nine FOWT mooring system designs have been presented and discussed in this work. These nine designs were divided into three categories; shallow, intermediate and deep waters. The main objective is to identify which parameters are driving the mooring hardware costs.

The FOWT is composed by a turbine, floating foundation and mooring system. The foundation is based on the WindFloat technology designed by Principle Power Inc. The wind turbine is a Haliade 150-6MW turbine design by General Electric. For the mooring system, different anchor types, line materials and mooring configurations have been analysed in this thesis. The most economic and reliable option for the WindFloat technology and studied depths is a catenary system with a drag embedment anchor and a combination of different line materials, synthetic rope and chain.

The design basis presented for the different cases was composed by three identical lines equally spaced. The mooring lines are composed by a synthetic rope suspended in water and chains lying on the seabed. The chains have different sizes, being lighter near the anchor. At the touch down area, the chain weight is increased in order to enhance the effect of the catenary system and increase the restoring force of the mooring.

In order to optimize and satisfy the standards of the certification bodies, the nine designs had to satisfy specific criteria for three different load cases, maximum operating sea-state (MOSS), extreme sea-state (ESS) and horizontal motion induced by turbulent wind (HMTW) load cases. For practical reasons, all designs have the same platform, turbine, seabed type, metocean conditions, and line pretension. Only three variables were water depth dependent; the length of suspended line, the weight of heavy chain and the total length of the mooring line. The tool OrcaFlex v9.7 was used to simulate and design the mooring systems.

Considering mild metocean conditions for all the study, the shallow mooring designs present heavier chains on the seabed touching point than intermediate and deep water cases. Hence heavy chain weight drives the design costs for shallow waters. On the other hand, intermediate and deep water designs have longer synthetic ropes and chains, making these parameters the cost driving ones. This leads to a minimum between shallow and deep waters. The minimum range for the considered metocean data is found from 60 m to 80 m water depth. The value of this work is not to find the single minimum value of the cost curve, but to identify the trends that shape this cost-depth curve.

FOWT mooring system designs are very site dependent. However, this study can improve the understanding of the mooring systems, making offshore floating wind technology more cost competitive. A further study and improvement of this report would be to analyse the trends of the mooring design for more severe sea states. The procedure could be the same as presented in this thesis changing another variable, the wave excitation (Hs and Tp).

8 References

[1] EWEA, "Deep water. The next step for offshore wind energy," 2013.

[2] A. J. Goupee, B. J. Koo, R. W. Kimball, K. F. Lambrakos and H. J. Dagher, "Experimental Comparision of Three Floating Wind Turbine Concepts," J. Offshore Mech. Arct. Eng 136(2), 2013.

[3] N. Baltrop, Floating structures: a guide for design and analysis, Bd. 101/98. Aberdeen: CMPT, 1998.

[4] S. K. Chakrabartui, Handbook of offshore engineering, Amsterdam: Elsevier, 2005.

[5] O. M. Failsten, Sea loads on ships and offshore structures, Cambridge: Cambridge University Press, 1990. – VIII, 328 s.

[6] Z. Lin and P. Sayer, "influence of water depth variation on the hydrodynamics of deep-water mooring characteristics," Ocean Engineering 109 (2015) 553–566, Glasgow, UK, 2015.

[7] Bureau Veritas, Classification of Mooring Systems for Permanent and Mobile Offshore Units, France: Rule Note NR 493 DT R03 E, 2015.

[8] ABS, "Floating Offshore Wind Turbine installations," USA, October 2015.

[9] Principle Power Inc., [Online]. Available: http://www.principlepowerinc.com/en. [Accessed May 2017].

[10] GE Renewable Energy, "GE's Haliade 150-6MW," 2015.

[11] I. Thusyanthan, "Seaded Soil Classification, Soil Behaviour, and Pipeline Design," Offshore-Technology conference, Houston, Texas, 2012.

[12] C. Kittel, Introduction to solid state physics 8th edition, USA, 2004.

[13] J. Ben C. Gerwick, Construction of Marine and Offshore Structures, Third Edition, San Francisco, USA: CRC Press, 2007.

[14] R. Ruinen, Application Engineer, Vryhof Anchors BV and K. aan den Ijssel, The use of drag embedment anchors in offshore, Neederlands: Ingeo Kring Vol.9 No.1, 2003.

[15] VRYHOF ANCHORS, Anchor manual, 2015.

[16] API American Petrolum Institute, Design and Analysis of Stationkeeping System for Flaoting Structures, Washington DC: API publishing servicies, 2005.

[17] S. P, "Suction Anchor piles - State of the Art," Proceedings, Mooring and Anchoring Conference, Aberdeen, UK, 1996.

[18] ABS, Offshore Anchor Data for Preliminary Design of Anchors of Floating Offshore Wind Turbines, Houston, Texas, August 2013.

[19] L. Xiong, D. J. White, S. R. Neubecker, W. Zhao and J. Yang, "Anchor loads in taut mooring: The impact of inverse catenary shakedown," Applied Ocean Research Volume 67, Pages 225-235, 2017.

[20] S. Bang and Y. Cho, "Use of Suction Piles for Mooring of Mobile offshore Bases - Task 3 Completion Report: Analysis and design methods of suction piles," 2000.

[21] I. Bob Wilde, "Torpedo pile anchors enter the GoM," Hart Energy Publishing, Houston, Texas, 2009.

[22] A. C. Fernandes, "Directional stability of the torpedo anchor pile during its installation," The IES Journal Part A: Civil & Structural Engineering. Volume 4-Issue 3: Deepwater Floating Systems, Brazil, 2011.

[23] Union, "Wire Rope User's Handbook," WireCo-World Group, 2016.

[24] V. Harnois, H. C.M. Smith, S. Benjamins and L. Johanning, "Assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems," CrossMark, Cornwall, UK, 2015.

[25] L. Johanning and G. Smith, "Station keeping study for WEC devices including complinat chain, compliant hybrid and taut arrangement," 27th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), 2008.

[26] Bureau Veritas, "Classification and Certification of Floating offshore Wind Turbines," NI 572 DT R01 E, October 2015.

[27] ABS, "Design Guideline for Stationkeeping Systems of Floating Offshore Wind Turbines," Houston, Texas, June 2013.

[28] Orcina ltd., *OrcaFlex Version 9.8e,* 2014.

[29] Wamit Inc, "User Manual Version 7.2," Wamit, Chestnut Hill, USA, 2016.

[30] IEA Wind, "Description of Laod cases for OC4, Phase II," 2013.

[31] Orcina Ltd. Daltongate, Ulverston, Cumbria, OrcaFlex User manual Version 9.8a, UK.

[32] Samson, "Rope User's Manual," Samson Ropes Techology, Ferndale, WA, USA, 2014.

Appendix A – Anchor Design

The assumptions considered to compute Figure 17 are presented, for each anchor type, in this appendix:

- Deadweight anchor is considered to have no friction with the soil. The holding capacity is weight dependent with a UHC/weight ratio of 1.

- Drag embedment anchor UHC/Weight ratio is taken, as a reference, the model Stevris Mk6 from Vyrhof shown in Figure 8.

- Driven and suction piles are considered a top covered and empty cylinders with diameter D, length L and thickness T. The relation between volume and diameter can be obtained with the ratios of L/D and D/T presented in Table 3. With this relation and combining with Equation (1) and Table 15, the UHC can be related with the volume. Finally, as suction and driven piles are usually made of steel, a density of 7100 kg/m^3 is considered to have the relation between UHC and weight.

Table 15 Design parameters for anchor piles, from $D=c(UHC)^d$

Pile anchor	Soil type	c	d
Driven Pile	Soft Clay	0.1049	0.3016
	Medium Clay	0.0528	0.3452
	Hard Clay & Sand	0.0319	0.3700
Suction Pile	Soft Clay	0.3095	0.2798
	Medium Clay	0.1260	0.3561

- VLA consider the association between the UPC and fluke area following Equation (2), where Nc=10 [15] .The soft clay study is computed using a shear strength of Su=35 and the medium clays with Su=100. These values are taken from Table 2, according to British standards (BS). The relation between UPC and volume can be computed using the fluke average thickness, T =250mm [15]. At the end, the ratio UPC/Weight can be obtained using the steel density of 7100 kg/m^3.

Appendix B – Design Wave

As explained in the Certification Requirements chapter, the sea state is defined by its energy spectrum. To generate the random sea, OrcaFlex uses a random number generator and a wave seed number specified by the user. In consequence, the same wave seed will always generate the same wave train [31].

To determine the design wave, ten simulations with the same metocean parameters have been computed during 3 hours simulations, for 10 different seed numbers. As a result, ten different train waves were generated. The goal is to find the maximum load associated to each wave seed. Figure 44 shows the average of the 10 maximum loads with the average presented in red. The design waves are defined by the seed number and time origin that results in a maximum anchor tensions, close to the average of the 10 simulations considered.

The seed analysis is carried out for the driving load case, the ESS. The study is performed for the case of 50 m water depth. Wave, wind and current are collinear at 180 degrees. As it can be observed, the design wave will be in Seed 2. The time origin was found at -2040s.
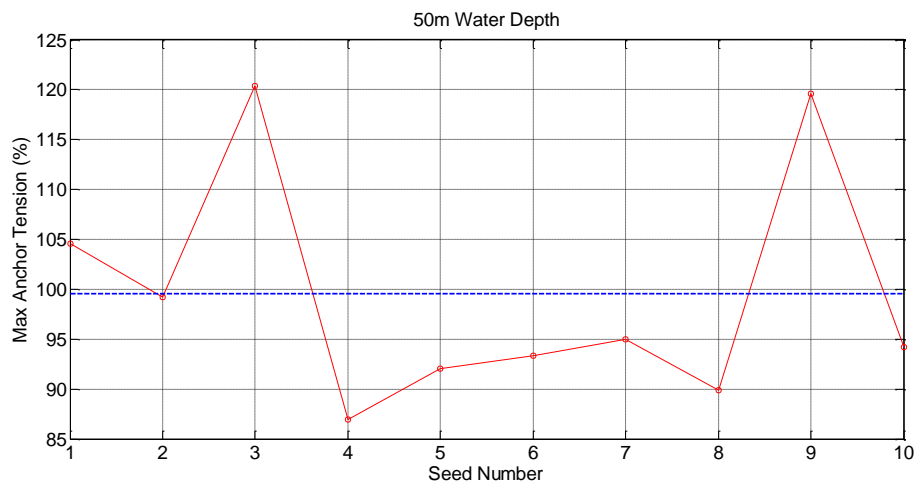

Figure 44 Seed analysis in order to find design wave for the 50 m water depth case.

Appendix C - Pretension Study Case

To have the same pretention for all the cases, a study in the 50 meters water depth is taken as a reference since it is the shallowest and most pretension dependent.

The first step, as it is shown in Figure 32, is to study the heavy chain for different suspended chain length. The resulting maximum anchor tensions are shown in Figure 45. The anchor tension starts to decrease when the mass on the heavy chain increase. The restoring force of the catenary mooring comes from the weight of the line. When the heavy chain mass increases the restoring force of the line increases, resulting in lower anchor tensions. However, this process is not linear, there is a minimum where the anchor tension starts to increase again, typically above 100t. This phenomena is originated by the inertial force created when the heavy chain is lifted and moved due to the translational momentum. In this study, the minimum is at 120t heavy chain.
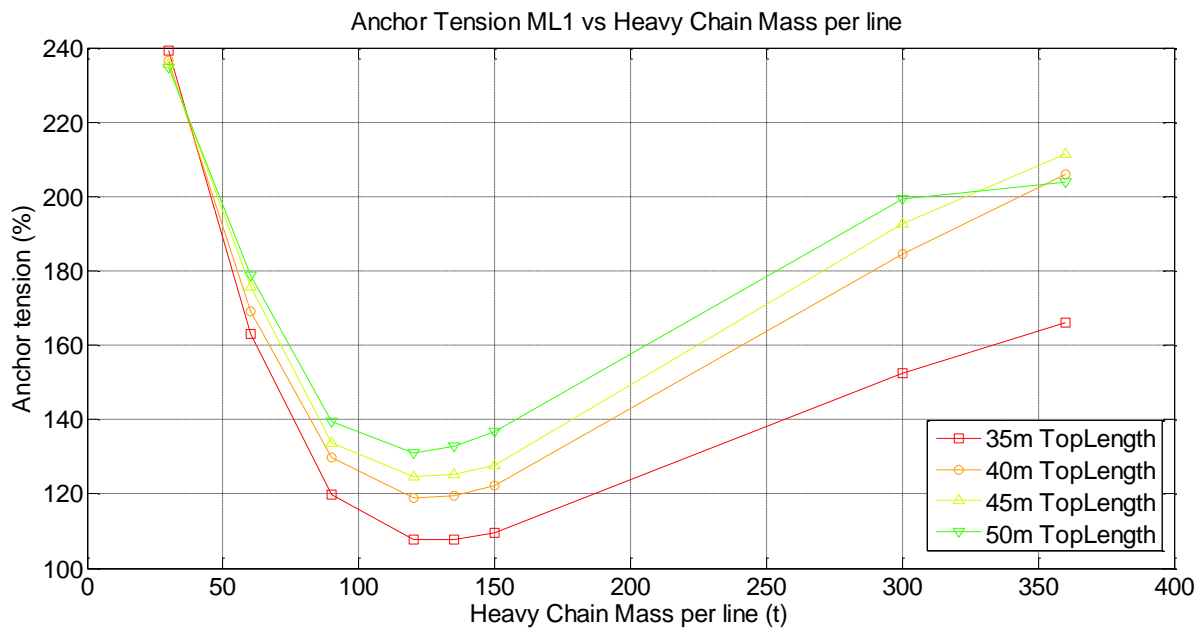

Figure 45 Heavy Chain analysis of 50m Water Depth case

In Figure 45 different suspended chain lengths are plotted in order to compare the results and to analyse how the minimum value changes. As it can be observed, the minimum is at the same point, at 120t. However, the values of the anchor tensions are reduced when the suspended chain length is also reduced.

To know the optimum pretension for the 50 meters water depth case, another study of pretension for different suspended chain lengths is performed setting the heavy chain at 120t. The resulting anchor tension and the offsets from this study are shown in Figure 46 and Figure 47, respectively.
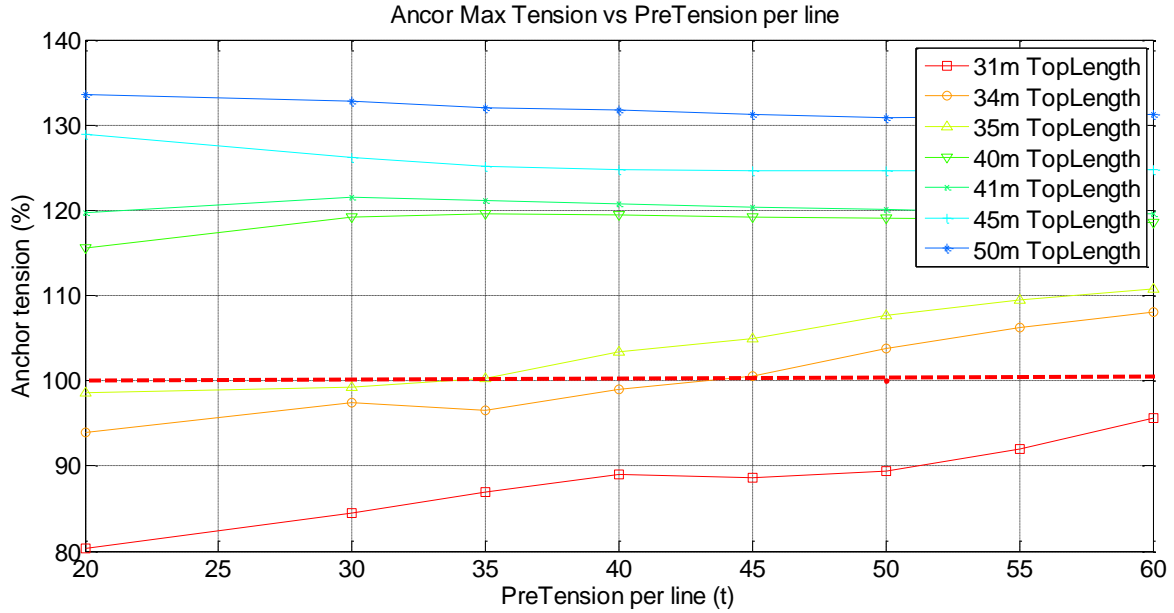
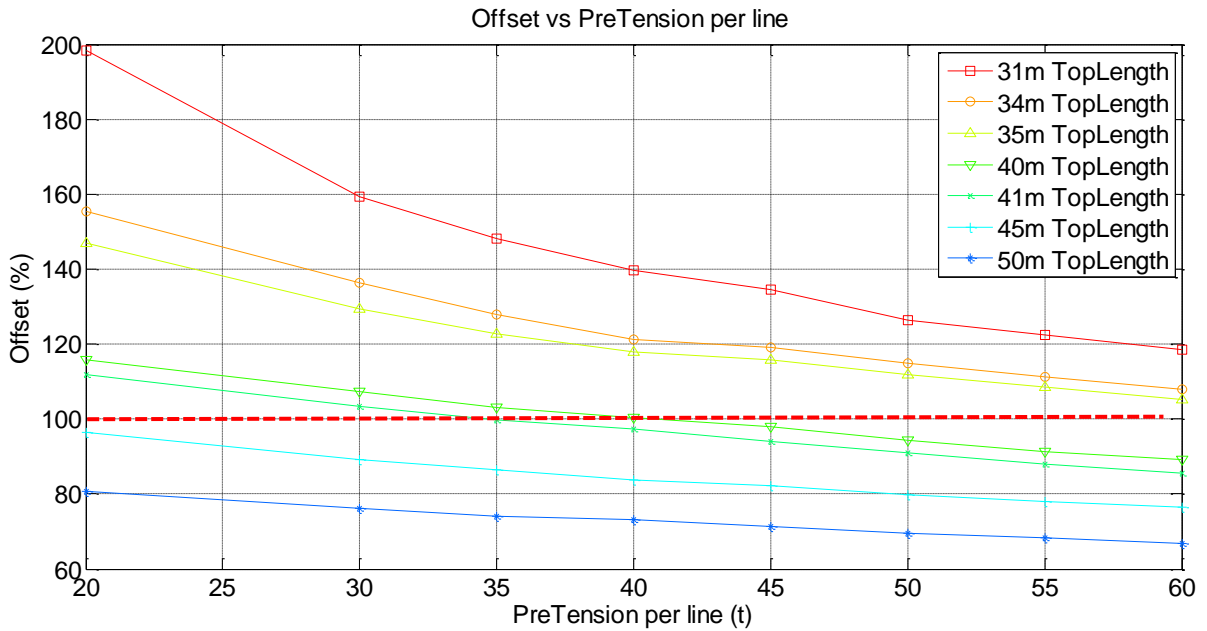*Figure 46 Pretension vs Anchor tension analysis of 50m Water Depth case*

Figure 47 Pretension vs Offset analysis of 50m Water Depth case

As it can be observed in the figures above, there is no optimal combination that satisfy both, anchor tension and offset criteria.

A solution to satisfy both criteria would be to decrease the length of the heavy chain, concentrating the weight and decreasing the anchor tensions and platform motions. Even though, this solution is economically unfeasible.

Another option would be to increase the length of the anchor chain. The anchor tensions would decrease maintaining similar platform motions, see Table 13. This solution is also economically unfeasible. The anchor chain would lengthen into a point where the manufacture and installation of the chain would be too expensive to be comparable with other water depths.

The most optimal and economical solution would be to be more flexible in the anchor tension criteria. A secondary effect of this decision would be to install a heavier and more expensive anchor, reflecting the decision in the financial analysis, being able to be compared with the other cases.

In consequence, the pretension selected may be the one that causes the anchor tensions and offset closest to their criteria. Analysing the results on Figure 46 and Figure 47, the pretensions taken for the analysis should be between 35t to 45t, therefore the mean pretension of 40t is considered for this study and all water depths.