Optimisation of offshore wind floater from dynamic cable and mooring perspective

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Optimisation Of Offshore Wind Floater From Dynamic Cable And Mooring Prospective

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ABSTRACT

Wind energy is one of the most promising energy sources, but it is currently limited to land and sea locations with a maximum depth of 50m. This leaves large areas of uninterrupted high seas unused, which can provide greater capacity than land-based and fixed offshore wind farms. Floating offshore wind farms (FOWF) can be deployed in deeper water depths away from the coast. Therefore, benefit from a greater volume and more consistent wind, resulting in a higher capacity factor, greater flexibility in the installation location, and no restrictions on the size of the wind turbine.

One of the main challenges faced by FOWF is that dynamic power cables are exposed to severe load conditions during their design life. While traditional submarine cables are installed on the seabed, FOWF's cables remain in free span, having floating components that enable them to move with floating objects. Cables continue to be subjected to extreme dynamic loads during their whole design life; therefore, they may suffer mechanical damage in various parts.

This thesis covers the preliminary study of the dynamic cables and their mechanical behaviour for the floating offshore platforms. The cable configuration has been designed considering extreme environmental conditions and then checked with normal sea state. In addition, the mooring system has been taken into account during the dynamic analysis: a preliminary design of the mooring line was considered and optimized for the project specific environmental condition. It also provides information about the challenges faced in developing and modelling designs, and finally, it defines future research for comprehensive design development.

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DECLARATION OF AUTHORSHIP

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

I have acknowledged all main sources of help.

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

Date: 27th August 2021 Signature: 

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1 INTRODUCTION

In the several decades climate change has been an important economic and political issue, and the depletion of fossil fuels has led the focus on more clean energy sources like renewable energy resources.

Wind Energy is a major renewable resource that is unlimited and non-polluting. Offshore wind energy is obtained by harnessing the wind energy at its maximum with no barriers which maintains it constantly. To harness this mega structure are installed in the seabed with innovative technologies. There are fixed platforms and floating platforms for shallow waters and deep waters respectively.

According to (WindEurope, 2021) statistics data, there are 116 offshore wind farms in European countries, with 5,402 turbines connected to the grid, totalling a capacity of 25,014 MW as of 2020.The United Kingdom with the largest installed offshore wind power capacity in Europe, accounting for 42% of all installed capacity. Germany ranks second with 31%, followed by Denmark (10%), Belgium (9%) and the Netherlands (7%). In this most wind farms are fixed at the bottom, their average distance from the shore is 52 [km], and the water depth is 44 [m].

By the end of 2020, the total capacity of floating wind power in Europe was 62 MW, which now accounts for 83% of the global installed capacity of floating wind power. In three years, 28 floating wind turbines, totalling a capacity of 250 MW, will be commissioned.

These seem to be a promising source and is expected to become a significant player in providing this clean energy. Although floating offshore wind farms (FOWFs) are immature and rapidly developing, it requires a thorough study on the different aspects ranging from the cost, environment, dynamics of the market, integration between the technologies and the substructures.

This thesis work propose a preliminary study about the mechanical behaviour of the dynamic cable and mooring system for the offshore wind-floating platform at 100 [m] water depth for extreme environmental condition. Both the system are modelled in OrcaFlex, which is a FEM based commercial software specific for offshore numerical simulations. The structure of the report is as follows:

- ***Chapter 2:*** This chapter discusses the available floating platform technologies and the platform, which are currently used in industries.
- ***Chapter 3:*** This chapter discusses the generic cable types and dynamic power cables, including the cable configuration for FOWT's.
- ***Chapter 4:*** This chapter describes the commercial software that was used and the theories involved in it.
- ***Chapter 5:*** This chapter discusses the initial model setup for different dynamic cable configurations.
- ***Chapter 6:*** This chapter discusses the sensitive static analyses for dynamic cable and their results.
- ***Chapter 7:*** This chapter discusses the dynamic analysis, including the environmental condition, sensitive analysis of mooring, coupled analysis of dynamic cable and mooring and their result.
- ***Chapter 8:*** This chapter gives a conclusion for the thesis.
- ***Chapter 9:*** This chapter suggests the different areas in which future research has to be done.

2 OFFSHORE WIND TURBINE

In this chapter, the first section describe the fixed foundation in general and the next section discuss the floating offshore wind turbine technology, that includs available floating platform technology and the platform, which are currently used in the industries are also discussed.

2.1 Fixed Foundation

Offshore wind turbines have permanent underwater foundations. The turbines are located at average distance from the shore upto 50 [km], at water depth upto 40 [m].The fixed foundation can be divided into three categories: Monopile foundation, Gravity based foundation, and Jacketed foundations as shown in Figure 2.1.

Figure 2.1 Fixed Foundation

Available from: https://www.iberdrola.com/sustainability/offshore-wind-turbines-foundations [Accessed 23rd August 2021]

The monopile foundation is a simple construction. The foundation consists of a steel pile with a diameter of between 3.5 and 4.5 [m]. The pile is driven some 10 to 20 [m] into the seabed depending on the type of underground. It is mostly installed at the maximum of 15 [m] water depth. For monopile foundation, seabed preparation is not necessary and is not suitable for the location with many large boulders (Iberdrola, n.d.).

The Gravity based foundation is a huge structure, relying on its own weight or dead load to achieve sufficient stability to prevent overturning and sliding. They are usually made of concrete and can be reinforced with steel to avoid tensile loads. It can be installed in hard seabed conditions and medium to deep water 30 [m] - 60 [m]. Piling is unnecessary, so damage to marine life is minimized. At this depth, GBF is an excellent alternative to traditional foundation solutions (Iberdrola, n.d.).

Depths below 30 to 35 meters require more complex supporting and anchoring structures. In most cases, the jacket foundation has a grid frame with three or four seabed anchor points, improving the safety level when anchoring the tower. The top of the jacket has a transition piece connected to the turbine shaft, and the legs (three or four) are fixed on the seabed with piles (Iberdrola, n.d.).

2.2 Floating Offshore Wind Turbine

Most offshore wind turbines are fixed to the seabed at a maximum water depth of 60[m]. Nearly 80% of offshore wind resources are available beyond 60[m] of water depth. The floating wind turbine is developed based on the concepts from the oil and gas industries. The floating turbines offer access to large areas with substantial wind resources. For some countries with a narrow continental shelf, floating foundations offer the only opportunity for large-scale offshore wind deployment.

2.2.1 Types of Floating Platform

The floating platforms can be divided into three categories are shown in the Figure 2.2 from right side tension leg platform (TLP), semi-submersible and spar-buoy.

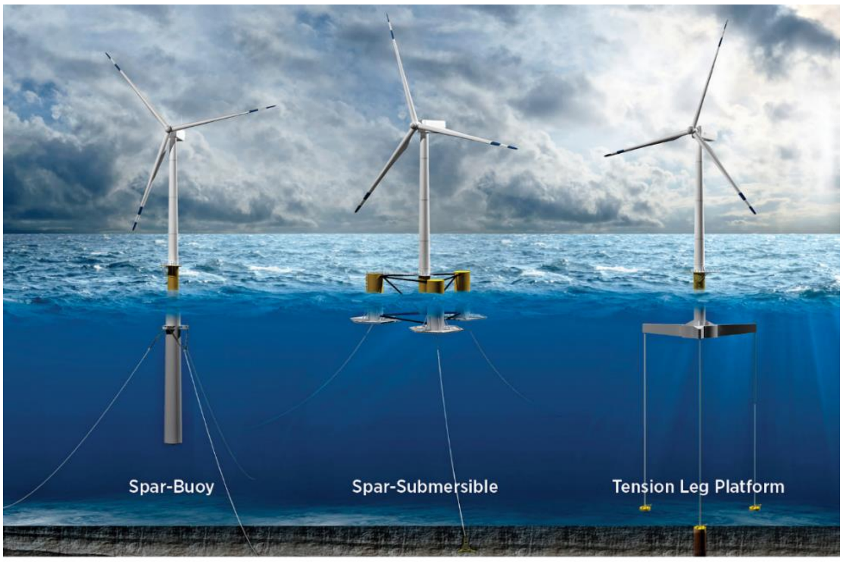

Figure 2.2 Offshore wind floating foundation concept

Available from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Offshore_Wind_Floating_Foundations_2016.pdf [Accessed 23rd August 2021]

2.2.1.1 Spar- Buoy

A spar-buoy is a cylindrical ballast-stabilised structure that stabilises itself by having the centre of gravity lower in the water than the centre of buoyancy. The spar buoy is a large structure that can be used to provide buoyancy in the sea. The lower part of the structure is heavier, while the upper part is lighter, increasing the centre of buoyancy. It is usually easy to manufacture and provides good stability, but the long submersed structure of the spar-buoy makes it challenging for assembly, transportation and installation. It needs to be installed at water depths larger than 75-100 m depending on the size of the wind turbine. The spar-buoy is kept in position by attaching the catenary or taut spread mooring lines and anchored through drag or suction anchors. Both strengths and weakness are shown in Table 2.1(Rhodri, 2015; IRENA, 2016).

Table 2.1 Strengths and weaknesses of Spar-Buoy

Strengths:
• Simple design • Few moving parts (no active ballast required) • Lower mooring installation cost • Tendency for lower critical wave-induced motions • Excellent stability
Weaknesses:
• Constrained to deep water locations larger than 100 [m] • Offshore turbine assembly requires dynamic positioning vessels and heavy-lift cranes • Large draft limits ability to tow the structure back to port for major repairs

2.2.1.2 Semi-submersible

Buoyancy stabilised platform that floats semi-submerged on the ocean's surface whilst anchored to the seabed with catenary mooring lines. The platform consists mostly of 3 to 5 cylindrical platforms interconnected by tubes. The mooring line of the semi-submersible platform is anchored through drag anchors to the seabed to ensure the platform stays in the targeted position. It requires a large and heavy structure to maintains the platform stability. However, due to low draft, it provides a more flexible application and easy installation. The semi-submersible can be deployed in water depth from 40 [m]. Both strengths and weakness are shown in Table 2.2 (Rhodri, 2015; IRENA, 2016).

Table 2.2 Strengths and weaknesses of Semi-submersible

Strengths:
• Flexible application due to the ability to operate in shallow water depths up to 40*m* • Low vessel requirement (only basic tug boats required) • Onshore turbine assembly • Amenable to port-side major repairs • Lower installed mooring cost
Weaknesses:
• High structural mass to provide sufficient buoyancy and stability • Complex steel structures with many welded joints can be difficult to fabricate • Potentially costly active ballast systems • Tendency for higher critical wave-induced motions

2.2.1.3 Tension Leg Platform

The Tension Leg Platform (TLP) is a semi-submersible buoyancy structure with a tensioned mooring line and by using suction or pile anchors the tensioned mooring line are anchored to the seabed. The shallow draft and tensile stability allow smaller and lighter structures to design but will result in increased stress on the mooring line and anchors. TLP can operate at depths of 50 to 250 [m], which is advantageous because TLP can be deployed in shallow water. Both strengths and weakness are shown in Table 2.3 (Rhodri, 2015; IRENA, 2016).

Table 2.3 Strengths and weaknesses of tension leg platform

Strengths:
• Low structural mass • Onshore turbine assembly • Few moving parts • Can be used in depths from 50m • Excellent stability due to tendency for lower critical wave-induced motions
Weaknesses:
• High loads on the mooring and anchoring system • Higher cost for installation of mooring lines • Uncertainty about impact of possible high-frequency dynamic effects on turbine • Challenging installation process • Special purpose installation barge may be required

2.2.2 Leading Technology Types For Floating Offshore Wind Power

In this section, the operational and planned floating wind projects will be discussed.

2.2.2.1 Hywind

Hywind is based on the spar buoy design, and gravity provides great stability. The first full-scale turbine was installed in 2009, named Hywind Demo. The demonstration unit has a 2.3 MW turbine with a blade diameter of 85 meters, which has generated more than 40 GWh of electricity since its start-up. It has experienced a maximum wind speed of 40 [m/s] and 19 [m] wave height. In 2019, it was sold to Unitech to test high-voltage cables that power offshore installations. In 2017, the Hywind Scotland pilot project was installed, which is the successor to the Hywind demo and shown in Figure 2.3. The farm consists of 5 floating turbines; each produces 6 MW and 33 kV transmission voltage (Equinor, n.d.).

Currently, Hywind Tampen is under development. It is scheduled to start in the third quarter of 2022. The wind farm is planned to consist of 11 units with a total capacity of 88 MW, and it will be located about 140 kilometres from the coast of Norway. The water depth of the wind farm site is between 260 m and 300 m (Equinor, n.d.).

Figure 2.3 Hywind Scotland Pilot Project (2017)

Available from https://techxplore.com/news/2017-10-turbines-coast-scotland-renewable-energy.html [Accessed on 22nd August 2021]

2.2.2.2 Gicon -SOF

GICON®-SOF has significant advantages over other floating sub-structure types (such as semi-submersible buoys or spar buoys). In order to support turbines of 6 to 10 MW, the semi-submarine will have huge external dimensions. This greatly reduces the number of possible manufacturing locations. The spar float is very slender, but it requires a very large draft (~100m) to stabilize the 6 MW turbine. This makes manufacturing and transportation, and installation (T&I) particularly difficult. Unlike semi-submarine or spar, TLP is connected to the seabed with a tensioned mooring rope. The buoyancy of the structure is much greater than its weight, resulting in a strong upward force. The entire structure becomes firmly supported by tightening the mooring equipment, thus forming a very strong system that can withstand even the harshest weather conditions. The operation depth of the GICON-SOF's is expected to be between 40 [m] and 250 [m] . The GICON SOF is still in research and development phase and the Figure 2.4 show's evolution of the technology since 2009 (left-hand side) until today (right-hand side). (Gicon-sof, n.d.).

Figure 2.4 GICON – SOF technology

Available from http://www.gicon-sof.de/en/development-history.html

[Accessed on 22nd August 2021]

2.2.2.3 BW Ideol (Floatgen: Damping Pool Floating Foundation)

Floatgen is France's first offshore wind turbine led by BW Ideol, shown in the Figure 2.5. Floatgen has a damping pool floating foundation (36 square meters, draught of 7.5 meters), and it's the world's first floating barge designed for offshore wind. It is equipped with a 2 megawatt wind turbine and installed off the coast of Le Croisic at water depth 33 [m]. It was commissioned in mid of 2018, and it has sets a new record in 2020 by producing 6.8 GWh, for a total of 12.8 Gigawatt hour (GWh) in two years (BW Ideol, n.d.). BW IDEOL's second project is HIBIKI. It is a Japanese demonstration project with a capacity of 3 MW. It was installed in 2018 at a water depth of 55 m in Kitakyushu, Japan (BW Ideol, n.d.). The third project led by BW IDEOL is the Eolmed project, which is expected to commission in 2023. The project has planned to generate 30 MW of power at 55 m water depth in Occitanie, France (BW Ideol, n.d.).

Figure 2.5 BW Ideol – Floatgen

Available from https://www.bw-ideol.com/en/floatgen-demonstrator

[Accessed on 22nd August 2021]

2.2.2.4 WindFloat

Principle Power Inc. implemented the WindFloat project. In October 2011, the first full-scale 2 MW WindFloat prototype was deployed 5 kilometers off the coast of Agusadura, Portugal, with a water depth of 40-50 meters is shown in Figure 2.6. The structure is fully assembled and commissioned on shore, and then towed along the Portuguese coast for about 400 kilometers (from the assembly plant near Setúbal, Portugal). So far, the system has generated more than 16 GWh of electricity, which is transmitted to the local grid via submarine cables. In July 2016, FOWT was decommissioned and towed back to shore, becoming the first decommissioned floating offshore wind turbine (Principle Power , n.d.). Due to the success of the WindFloat prototype, it is planned to expand the project in the United States (Oregon, 30 MW; Hawaii, 2 x 408 MW), Scotland (Kincardine, 48-50 MW) and Portugal (Agu in the next 5-10 years. Sadura, 25 MW) (Rhodri, 2015).

Figure 2.6 WindFloat

Available from https://www.offshore-mag.com/renewable-energy/article/14188688/windfloat-atlantic-represents-major-offshore-wind-milestone [Accessed on 26th August 2021]

2.2.2.5 Fukushima Forward

Fukushima FORWARD project is a floating offshore wind farm demonstration project funded by the Ministry of Economy, Trade and Industry. In this project, three floating wind turbines and one floating power sub-station have been installed off the coast of Fukushima. The first phase of the project completed, consisting of the 2MW floating wind turbine (Fukushima Mairai) as shown in Figure 2.7, the world first 25MVA floating substation(Fukushima Kizuna), and submarine cable was completed in 2013. In the second phase, installing the 7MW floating wind turbine, (Fukushima Shimpuu), was completed in June of 2015. The 5MW floating wind turbine (Fukushima Hamakaze) has been installed in the summer of 2016 (Fukushima FORWARD, 2014).

Figure 2.7 Fukushima Mirai 2MW FOWT

Available from https://www.mhi.com/news/131111_2en.html [Accessed on 22nd August 2021]

3 SUBMARINE POWER CABLE

In recent years, the amount and size of installed offshore wind farms have increased rapidly, and bigger farms are planned. Submarine cables are essential part of this development where they are used as array cables between the generators, as export cables to attach the offshore generation farms with the onshore transmission grid and whilst a part of interconnections between different synchronous systems, countries. In this chapter the first section covers the generic static cable types, which are widely used for offshore wind power generation in fixed foundation, and the next section covers the design of dynamic power cable and it current configuration with related components.

3.1 Generic Static Cable Type

In this section, the generic cable types, which are widely used for offshore wind power generation in fixed foundation are discussed based on the Technical Broacher: CIGRE TB 610 - Offshore generation cable connections (JENSEN, 2015).

3.1.1 Array Cables

Individual turbines are connected using these cables. The array cable from the turbine is connected to the offshore substation (if present). Inter-array cables, field cables, and collector cables are all terms used to describe array cables. The array cable is a three-core AC cable as shown in Figure 3.1 and it has a rated voltage up to 36 kV under all known conditions. It is generally considered that medium-voltage submarine cables with a rated voltage less than or equal to 36 kV do not require a metallic waterproof layer. Steel wire armour is used to array cables to increase tension and provide mechanical protection. It is important to consider the array layout for conductor and cable size, as it depends on the number of turbines in the offshore wind farm. The array cable are usually pulled into the turbine towers within the elbow steel J-tubes.

Figure 3.1 Three core Array Cable

Available from https://www.researchgate.net/publication/338388640_CIGRE_TB_610_-_Offshore_generation_cable_connections (Page: 69) [Accessed on 26th August 2021]

3.1.2 High Voltage AC And DC Export Cables

The medium voltage array cable function as an export cable if there is no offshore sub-station. In that case, the carry cables collect the power from a group of turbines and transport it to the onshore substation. If there is an offshore substation, the high voltage AC export cable transports the collected power from the offshore substation to the onshore substation or to an offshore HVDC converter station. Export cables are usually three-core AC cables, as shown in Figure 3.2. The export cables operate at around 145 kV AC, with some systems having up to 245 kV system voltage.

Figure 3.2 High voltage AC three core export cable

Available from https://www.researchgate.net/publication/338388640_CIGRE_TB_610_-_Offshore_generation_cable_connections (Page: 69) [Accessed on 26th August 2021]

Because they transport electricity to shore, high-voltage DC cables are also called output cables. However, they form their group because they are fundamentally different from high-voltage AC output cables. The offshore AC/DC converter station is connected to the onshore

AC/DC converter station through a high-voltage DC output cable. As shown in Figure 3.3, they are usually single-core cables with an extruded insulation layer and a metal radial waterproof layer. The circuit consists of two cables, usually installed in bundles. HVDC cables with a large amount of impregnated paper or PPL insulation are also suitable for HVDC output.

Figure 3.3 High voltage DC single core export cable

Available from https://www.researchgate.net/publication/338388640_CIGRE_TB_610_-_Offshore_generation_cable_connections (Page: 69) [Accessed on 26th August 2021]

3.1.3 Difference Between AC Cable And DC Cable

The key difference between cable types is whether they carry alternating current (AC) or direct current (DC). DC cables are sometimes laid as a pair of separate cables with just one conductor each. Although AC cables have three conductors, each of which transports current at a different phase. Since power generated in AC, AC cables are the most common cable used in offshore wind energy production. DC cables transmit electricity with fewer delays, but they are only used where vast quantities of energy must be transmitted over long distances to justify the cost of power transfer devices. The number of DC power solutions is projected to increase as potential windfarms expand in capability and move further offshore.

3.2 Dynamic power cable

In this section, the design of dynamic power cable and it current configuration and related components discussed.

3.2.1 Design Elements of Dynamic Power Cables

The design elements of the medium-voltage and high-voltage dynamic power cables are not significantly different from those of the submarine power cables. Currently, all dynamic power cord designs are three-core cable.

The medium voltage dynamic power cable has a wet design and are smaller in size, and it must face more and more minor design challenges than the high voltage dynamic cable. The first significant difference between the design elements of medium-voltage submarine cables and power cables is that the medium voltage power cables have double armour. Due to dynamic applications, an additional layer of armour wire is added to increase torsional stiffness. The second difference is the cross-sectional area of the conductor, which is more significant than submarine power cables due to thermal limitations at the bend stiffener. By increasing the cross-sectional area of the conductors, the induced heat is reduced, solving the thermal problem of the cable.

3.2.2 Typical Cable Cross Section

The typical cross section is shown in Figure 3.4 and the cable elements are discussed majorly based on the Technical Broacher: CIGRE TB 610 - Offshore generation cable connections (JENSEN, 2015).

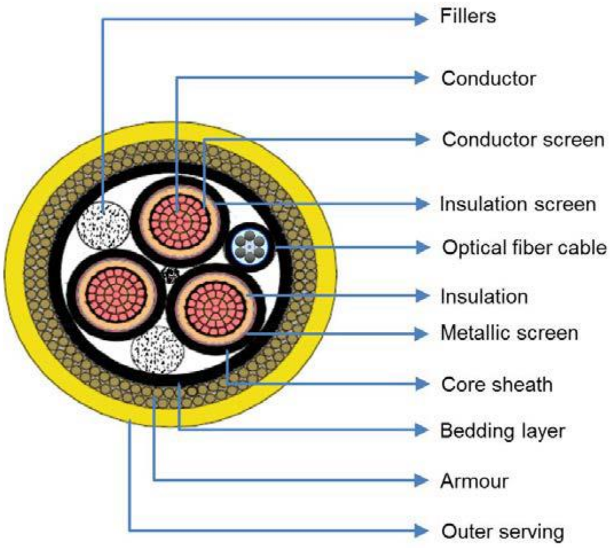

Figure 3.4 Typical Dynamic cable cross-section

Available from https://www.researchgate.net/figure/3-TYPICAL-CROSS-SECTION-FOR-A-DYNAMIC-CABLE_fig22_338388640 [Accessed on 27th August 2021]

3.2.2.1 Metallic Screen And Metallic Sheath

This metallic layer is applied over the insulation screen (over proper semi-conductive bedding) as shown in the Figure 3.4. It acts in normal operating conditions as a return path for both capacitive charging currents and induced currents. In the event of an electrical failure, this metallic screen can also carry zero-sequence short circuit currents. A lead sheath is not recommended for dynamic cables since it is highly prone to fatigue issues.

3.2.2.2 Core Sheath

Depending on the insulation material, a layer of thermoplastic material can be extruded over the metallic screen for extra protection as shown in Figure 3.4. This sheath can be made of medium density polyethylene (MDPE) coloured black. The electric phases should be identified by marking each core's specific ID (colour or number).

3.2.2.3 Bedding Layer

To achieve a circular cable cross-section, the three cores and any extra parts (e.g. fiber optic cables) are built up together, and the interstices are filled with suitable fillers. Over this core, a constantly extruded thermoplastic material might be used. If the free span between the hang-off connector and the entrance into the wind turbine is not shielded from direct sun radiation, the thermoplastic material should have UV protection. The material should also be able to withstand exposure to seawater. The thickness of this sheath should be adequate to allow proper radial compression distribution by the armour wire layers placed over it. The coefficient of friction between the sheath and the sheaths of the electric cores and other components (optical fibre cable, fillers, etc.) should be reduced to release axial tensions during bending.

3.2.2.4 Armour

Typically, the installation water depth and other installation issues drive the armour design for static submarine cables specific for each project. For dynamic submarine cables, this concept changes radically. The armour design must address the same installation issues as for the static cables, and at the same time, satisfy all of the post-installation dynamic loads experienced by the free span between the floating generator/platform and the touch-down point (TDP).

Static submarine cables designed for shallow waters usually require single layer armour. The twisting action induced by the single layer of stranded wires prompts a significant load transfer to the inner core for higher axial loads. Two or more contra-helically wound layers of stranded armour wires need to be applied to counteract the

Dynamic cables hanging off a floating generator/platform should have at least a double layer armour. The cable design should be torque balanced, and such behaviour verified during the type test. For a less demanding tensile performance, thermoplastic filler rods can replace a few metallic wires.

3.2.2.5 Outer Serving

A layer of thermoplastic material may be continuously extruded over the armour. This layer may provide additional corrosion protection, especially in the splash zone. The outer serving should have a high-visibility colour to assist the underwater operations during the cable installation.

3.2.3 Catenary Cable Configuration

In this section, the four catenary cable configuration for dynamic power cable is discussed and are shown in Figure 3.5. The final configuration for the cable section between the seabed and the floating platform is defined by the magnitude of the movements of the later and restrictions settled by the position of the mooring lines.

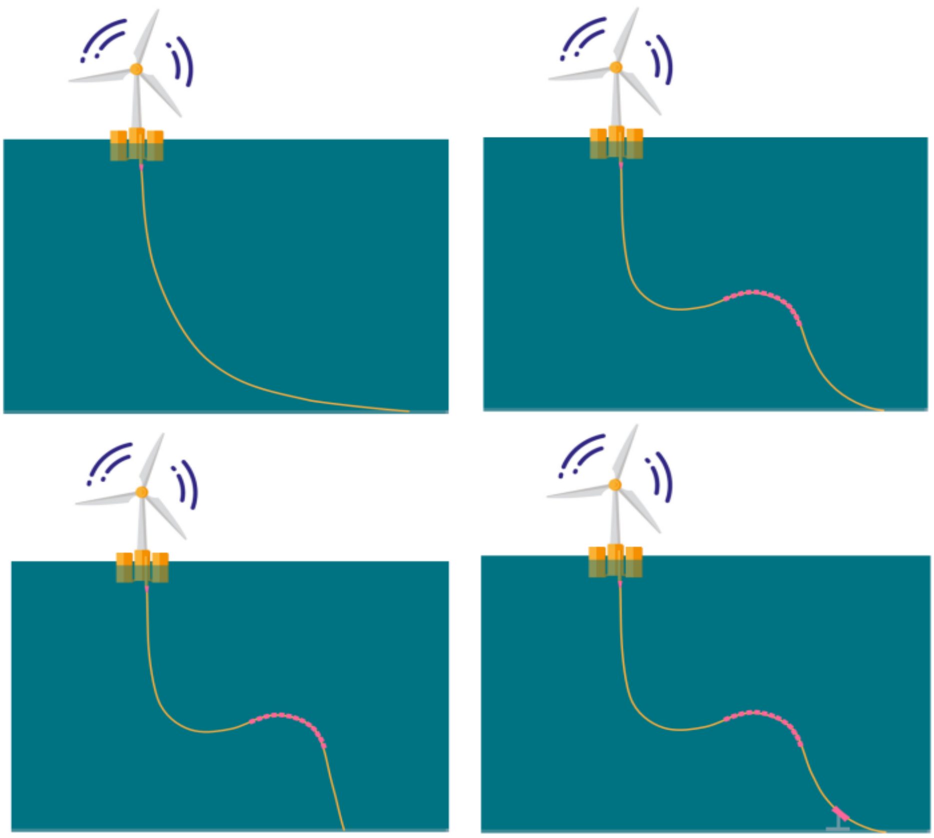

Figure 3.5 Catenary cable configuration: From top left a) Free-hanging; a) Lazy wave; c) Steep wave; d) Tethered wave

Available from https://corewind.eu/wp-content/uploads/files/publications/COREWIND-D3.1-Review-of-the-state-of-the-art-of-dynamic-cable-system-design.pdf [Accessed on 27th August 2021]

3.2.3.1 Free-hanging

The free-hanging configuration is the trouble-free configuration, and this configuration needs minimal subsea infrastructure and is the easiest one to be installed. The line is spread in a catenary shape from the floating structure to the seabed as shown in Figure 3.5 (a). This configuration is the lowest cost cable solution and suitable for minimal dynamic motion. There some disadvantages in this system, they require some bend controller at the entrance of the floating structure, floater motion can not be decoupled and there will be no lateral motion restriction. Both advantages and disadvantages can be in Table 3.1.

Table 3.1 Advantages and Disadvantages of free hanging

Strengths	Weaknesses
– Simplest configuration	– Vessel motion are not decoupled – No restriction of lateral motion – Likely to require a bend control at the floating structure entrance

3.2.3.2 Lazy Wave

The lazy Wave configuration is used commonly in moderately harsh environmental conditions. In this configuration, to provide a lift to the cable at a midwater section a distributed buoyancy modules are attached as shown in Figure 3.5 (b). It is a low-cost cable solution suitable for applications that require reasonable dynamic motion. If the distance between the floating structure and the touchdown point is very limited, and strong currents cause touchdown migration, it may not be appropriate. Both advantages and disadvantages can be in Table 3.2.

Table 3.2 Advantages and Disadvantages of lazy wave

Advantages:
– Simple configuration – Buoyant section which decouples reasonable dynamic FOWT motions from fixed subsea end – Accommodates reasonable levels of marine growth relative to depth. For shallow waters it may be possible to accommodation higher levels of marine growth by adding buoyancy modules during the lifetime of the system. – Proven use for deep water application.
Disadvantages:
– No restraint on lateral motion – Change in configuration shape with marine growth – Requirement for a bend control at the floating structure entrance – Requirement for Buoyancy modules

3.2.3.3 Steep Wave

A steep wave is like a lazy wave configuration, but a subsea base and bend stiffener are added to connect the cable vertically to the top face of a seabed junction as shown in Figure 3.5 (c). Near the seabed end of the cable, it also has buoyancy modules attached. . Both advantages and disadvantages can be in Table 3.3.

Table 3.3 Advantages and Disadvantages of steep wave

Advantages:
– Buoyant section which decouples FOWT motions from fixed subsea end but subsea base and bend stiffener limiting vessel motions – Limited changes in configuration shape with reasonable levels of marine growth – Subsea base reducing excursions under cross current – Reduced distance between floating structure and seabed termination point required.
Disadvantages:
– Requirement for a bend control at the floating structure entrance and subsea base connection point. – Requirement for Buoyancy modules

3.2.3.4 Pliant Wave (Tethered Wave)

The tethered wave configuration is similar to a lazy wave. A buoyancy module section is attached to the cable at midwater and has a tether restraining at the touchdown point Figure 3.5 (d). Both advantages and disadvantages can be in Table 3.4.

Table 3.4 Advantages and Disadvantages of tethered wave

Advantages:
– Buoyant section which decouples FOWT motions from fixed subsea end – Tether reducing touchdown point migration under cross current – Accommodates reasonable levels of marine growth relative to depth. – For shallow waters you can accommodate higher levels of marine growth without the need for adding extra buoyancy modules during the lifetime of the system.
Disadvantages:
– Requirement for hold-down tether and clamp which will increase complexity and time of installation. – Requirement for a bend control at the floating structure entrance – Requirement for Buoyancy modules

3.2.4 Related Components

The components that are involved in the dynamic power cable configuration can be found in Figure 3.6. Below the most important components along with their characteristics are discussed.

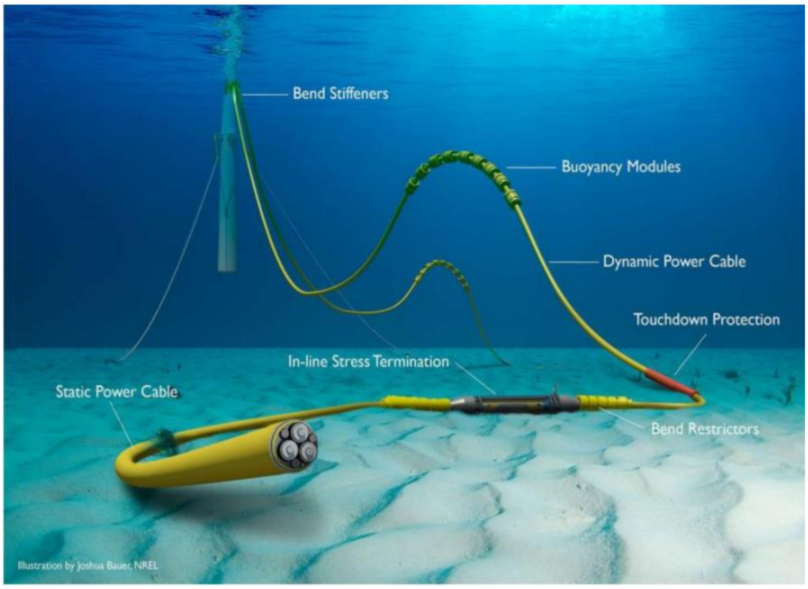

Figure 3.6 Dynamic cable related components

Available from https://www.nrel.gov/wind/newsletter-202102.html [Accessed on 22th August 2021]

3.2.4.1 Transition Joint

The transition joint is attached to the seabed and provides a smooth connection between the static submarine power cable and dynamic power cable. The joint is made flexible to deal with the dynamic motions of the dynamic cable. The transition joints it consists of (Erik Eriksson, 2011):

- Three flexible molded core joints to provide the connection for each phase. These core joints are covered by a lead sheath and soldered to the metallic sheath of both the static and dynamic power cable
- One fiber-optical cable joint
- Armoring

3.2.4.2 Bend Restrictors

The bend restrictors are attached at bottom part near to the transition joint on the seabed. Two bend restrictors are attached one on the dynamic cable and other one the static cable as shown in Figure *3.6*. The main function of the bend restrictors is to protect the cable from over bending, whereas fatigue is less of a concern compared to dynamic stiffeners.

3.2.4.3 Bend Stiffener

At the top part, a dynamic bending stiffener is mounted to cope with heavy axial loads and curvatures to avoid over bending and fatigue failure. In Figure 3.7, a drawing of a dynamic bend stiffener is shown. A bend stiffener has a conical body with an axial opening for the cable inlet. An internal steel work is mounted to the stiffener to transfer the induced loads to the floating structure.

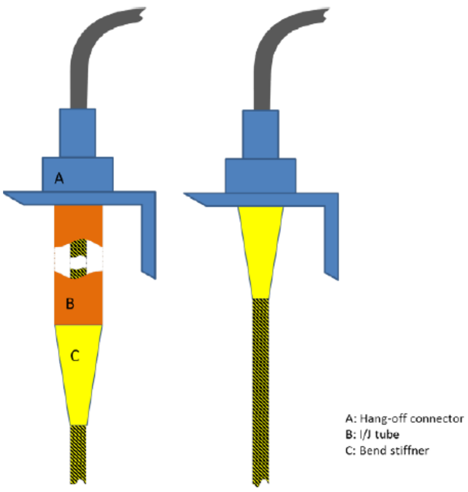

Figure 3.7 Bend Stiffener

Available from https://www.researchgate.net/publication/338388640_CIGRE_TB_610_-_Offshore_generation_cable_connections (Page: 69) [Accessed on 26th August 2021]

On top of the stiffener a flange is added in order to connect the stiffener to the floating structure. The stiffener provides a smooth transition between the floating installation and the dynamic cable with low stiffness. The bend stiffener is made to increase the local stiffness gradually and to keep the stresses and curvatures of the cable between acceptable bounds. Instead of a bent stiffener, a bell-mouth (trumpet termination of I-tube) could be used. It can be a safer and less expensive option for narrower array cables.

3.2.4.4 Buoyancy Modules

Buoyancy modules are essential for the dynamic power cable, since they enable motion decoupling between the floating installation and the touchdown point on the seabed. Buoyancy module attachments will likely be required to achieve the required shape for the extra-length of cable several equally spaced buoyancy modules need to be installed on the cable. Buoyancy modules are made of syntactic foam and consists of two main components which are the internal clamp and the external buoyancy modules which are two identical halves attached to the internal clamp as shown in the Figure 3.8. Internal clamps must be carefully constructed to prevent slippage, high generated stresses in the armour, and damage to the sheath, which might result in water intrusion inside the cable. External buoyancy modules' diameter, submerged weight, and spacing must all be carefully considered. These variables affect the dynamic cable's buoyancy, which might result in an undesirable configuration at the hang-off, arch bend, and touchdown point.

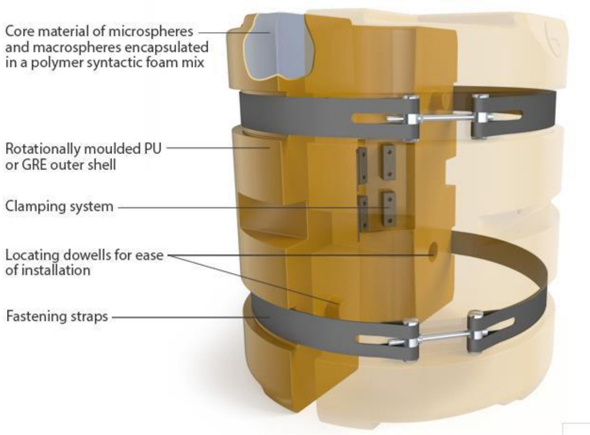

Figure 3.8 Buoyancy modules

Available from https://www.balmoraloffshore.com/solutions/buoyancy/distributed-riser-buoyancy [Accessed on 27th August 2021]

4 ORCAFLEX

The description of the OrcaFlex software and the related theory implemented in this study is provided in this section. Main reference used for this Section is Orcaflex manual (OrcaFlex, 2021).

4.1 Description

OrcaFlex is an marine dynamics software package developed by Orcina Ltd. The software can perform static and dynamic analysis in the time domain and frequency domain for various offshore systems including mooring. It has an extensive 3D graphical interface and uses graph to better understand the problem.

It can simulate the movement of a slender element and use the Morison method to calculate the wave load acting on it. For larger structural motions, hydrodynamic data must be provided as input based on RAO, QTF, additional mass, damping, stiffness, mass, and inertia of the software based on radiation diffraction analysis. Compatible with OrcaWave, Ansys Aqwa, WAMIT, MOSES, Hydrostar, WADAM and other software to import data. According to the input, the first-order and second-order wave forces can be calculated separately. Although it adopts the analysis-based methods proposed in the design standards including current and wind loads.

OrcaFlex provides options to implement user-defined environmental conditions (such as wave, wind, and ocean current data). Different wave types such as regular waves and irregular waves can be simulated. Regular waves defined by the following options: Airy, Dean, Stokes' 5th or cnoidal. These are various wave theories for regular linear (Airy) waves and nonlinear waves. Irregular waves are defined by the following options: JONSWAP, ISSC (also known as Bretschneider or modified Pierson-Moskowitz), Ochi-Hubble, Torsethaugen, Gaussian dilation, or user-defined spectrum, which are various different spectrums of random waves (OrcaFlex, 2021)

4.2 Line Theory

OrcaFlex uses a finite element model for a line, as shown in the Figure 4.1. This line is divided into a series of line segments, which are then modelled by straight-line massless model segments, with a node at each end.

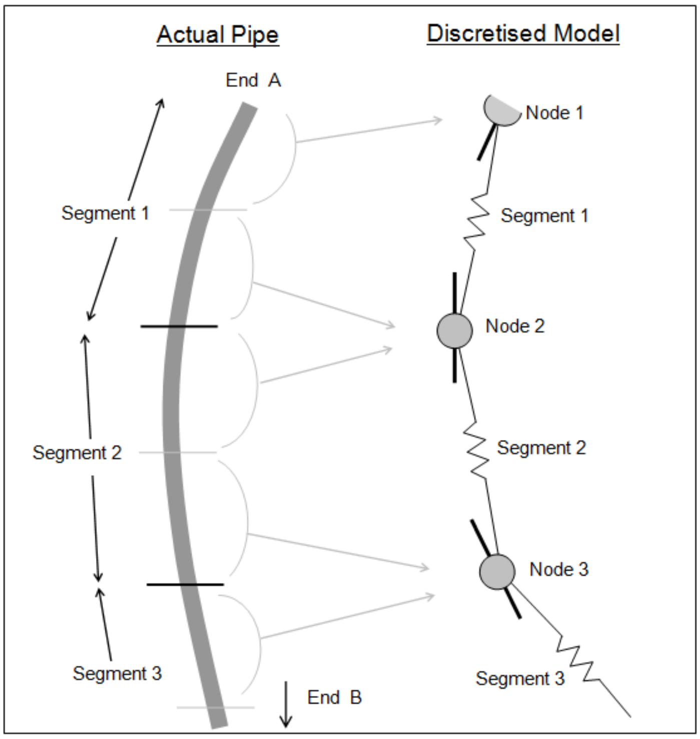

Figure 4.1 OrcaFlex line model

Available from https://www.orcina.com/webhelp/OrcaFlex/Default.htm [Accessed on 26th August 2021]

The node represents the two half-line segments on both sides of the node and defines the mass, weight, buoyancy and resistance properties of the line segment. Forces and moments are applied to the nodes, and the line segment is a massless element, only the axial and torsional characteristics of the line are modelled. It is conceivable that these are composed of two coaxial telescopic rods, connected by axial and torsion spring dampers. The rotational spring dampers at each end of the segment represent the bending properties, shown in Figure 4.2

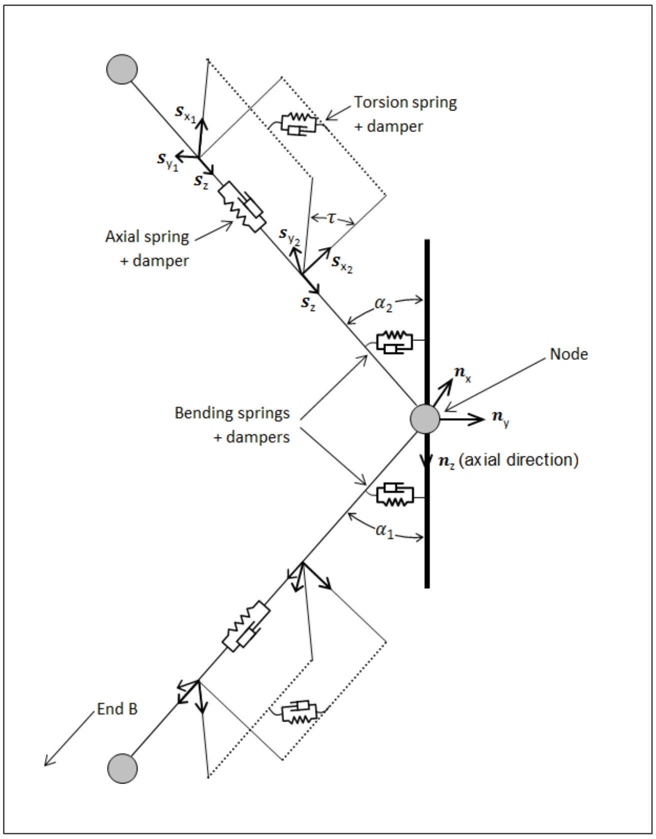

Figure 4.2 Detailed representation of OrcaFlex line model

Available from https://www.orcina.com/webhelp/OrcaFlex/Default.htm [Accessed on 26th August 2021]

4.3 Static Analysis

The main aim of the static analysis is to find the equilibrium configuration of the system under loads applied on it, which will also be the starting point of the dynamic analysis. If the system is linear, then the equilibrium configuration can be calculated directly with a single matrix solution; however, in practice, the OrcaFlex model is always nonlinear, so the calculation of statics requires a multi-dimensional iterative of Newton's method. .The iterative stages in which OrcaFlex determines the static equilibrium are given below:

1. Fixes the degrees of freedom (DOF) of all objects except lines (such as buoys, vessel, constraints, etc.)
2. Calculate line statics to determine the equilibrium configuration of all lines (itself is a two-step iterative process)
3. Release all degrees of freedom and use Newton's method to perform a full system static analysis of the entire system. The initial guess of the iteration comes from the first two stages.

4.4 Dynamic Analysis

The main purpose of dynamic analysis is to obtain the behaviour and response of the system under time-varying loads. It starts from a static analysis that is constant over time. OrcaFlex provides two options for solving dynamic analysis: time domain and frequency domain.

4.4.1 Time Domain

Time domain analysis is completely non-linear. Evaluates mass, damping, stiffness, load, etc. at each time step, while considering instantaneous and time-varying geometry. The equation of motion that OrcaFlex solves in the time domain is shown in Eq. 1.

$$M(p,a) + C(p,v) + K(p) = F(p,v,t) \tag{1}$$

Where,

$M(p,a)$ *:the system inertia load*

$C(p,v)$ *: the system damping load*

$K(p)$ *: the system stiffness load*

$F(p,v,t)$ *: the external load*

p, v *and* a *are the position, velocity and acceleration vectors respectively*

t *: the simulation time.*

It implements two integrated schemes for solving time domain analysis: explicit and implicit. Both schemes recalculate the system geometry at each time step, so the simulation fully considers all nonlinearities. The semi-implicit Euler with a constant time step is used for the explicit scheme, and the implicit integration uses the generalized α-integration scheme. For these two schemes, the initial positions and directions of all nodes are derived from static analysis, and forces and moments are calculated. In the explicit scheme, the local motion equation solves for the acceleration vector at the beginning of each time step. Then use semi-implicit Euler integration to integrate the equation. In the implicit scheme, it is solved at the end of each time step of the system equation.

4.4.2 Frequency Domain

Frequency domain analysis is linear. The frequency domain solver approximates any existing nonlinearity to linearity in a process called linearization. The frequency domain solver is designed to solve the dynamic response of the system at wave frequency or low frequency, which is determined by the solution frequency specified by the user.

The response at wave frequency is defined as the response of the system subjected to the first-order dynamic load associated with the random process of wave elevation. The low-frequency response is defined as the system's response to the second-order wave drift dynamic load related to the wave height random process and the wind dynamic load related to the wind speed random process at the same time.

5 MODEL SETUP

In this section, four catenary cable configurations are modelled and the initial stage of static analysis is performed on specific cable properties. According to this analysis, one of the four configurations is used for further optimization.

5.1 Floating Platform And Dynamic Cable Properties

A semi-submersible platform with a total length and width of 40 [m], a depth of 45 [m], and a draft of 30 [m] has been considered. The OrcaFlex model is shown in Figure 5.1. The main parameters for the dynamic cables are the minimum breaking load and maximum bending moment, this and other mechanical properties of the dynamic cable used in this work are shown Table 5.1.

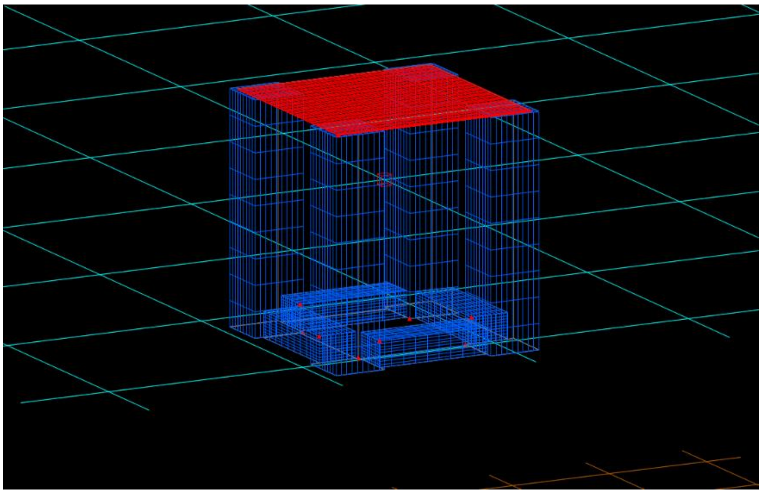

Figure 5.1 Semi-Submersible platform: OrcaFlex model

Table 5.1 Dynamic power cable properties

Outer Diameter of cable	0.281	[m]
Weight of cable in air	148	[kg/m]
Weight of cable in water	85	[kg/m]
Minimum breaking load	2720	[kN]
Maximum handling tension	1150	[kN]
Minimum allowable bending radius (MBR)	6	[m]
Axial stiffness	$4*10^5$	[kN]
Torsional stiffness	60	[kN.m^2/rad]
Bending stiffness	80	[kN.m^2]
Maximum bending moment	13.33	[kN.m]

5.2 Initial Catenary Cable Modelling

The static analysis considers the following scenarios: The dynamic cable is suspended at a fixed point 30 [m] below sea level. This value corresponds to the draft of the semi-submersible platform considered in this work.

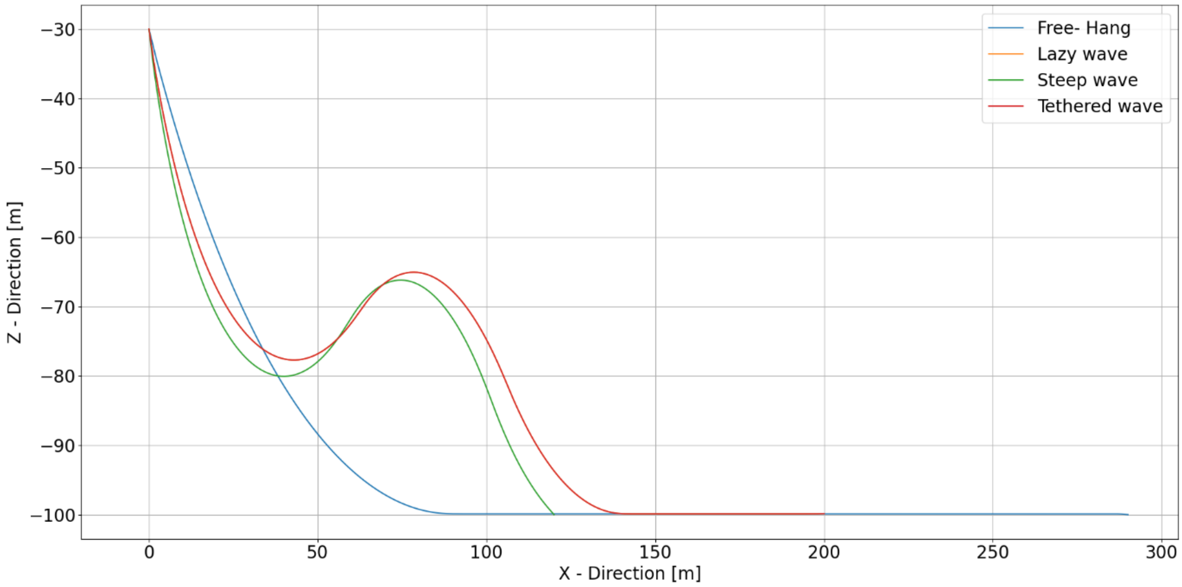

Figure 5.2 Catenary configuration OrcaFlex model

Four different catenary configurations are setup in OrcaFlex, as shown in Figure 5.2. In addition to free suspension, the buoyancy module is connected to a dynamic cable configuration. In the tether wave, a tether is attached before the landing point, with an unstretched length of 10 [m] and stiffness of 1000.00 [kN]. Since OrcaFlex uses the finite element method to model dynamic cables, the discretization of the cables is called the target segment length (TSL), which is used to consider the 1 [m] complete analysis of the TSL. Each configuration has a different section length, as shown in the buoyancy module properties in Table 5.2 and Table 5.3.

Table 5.2 Dynamic cable section length

Catenary Configuration	Section Length [m]			
	DC 1	DC with Floater	DC2	Total Length
Free Hang	320	0	0	320
Lazy wave	90	50	100	240
Steep wave	90	50	25	165
Tethered wave	90	50	100	240

Table 5.3 Buoyancy module properties

Buoyancy module	
Diameter [m]	2
Pitch [m]	10
Mass [te]	1.25
Displacement [kN]	30.95
Weight in water [kN]	-18.63

5.3 Result: Initial Modelling

The two main parameters of a dynamic cable are the bending moment and the effective tension. For the four catenary configurations, the values obtained for these parameters from the initial analysis of the entire section length are shown in Figure 5.3 and Figure 5.4.

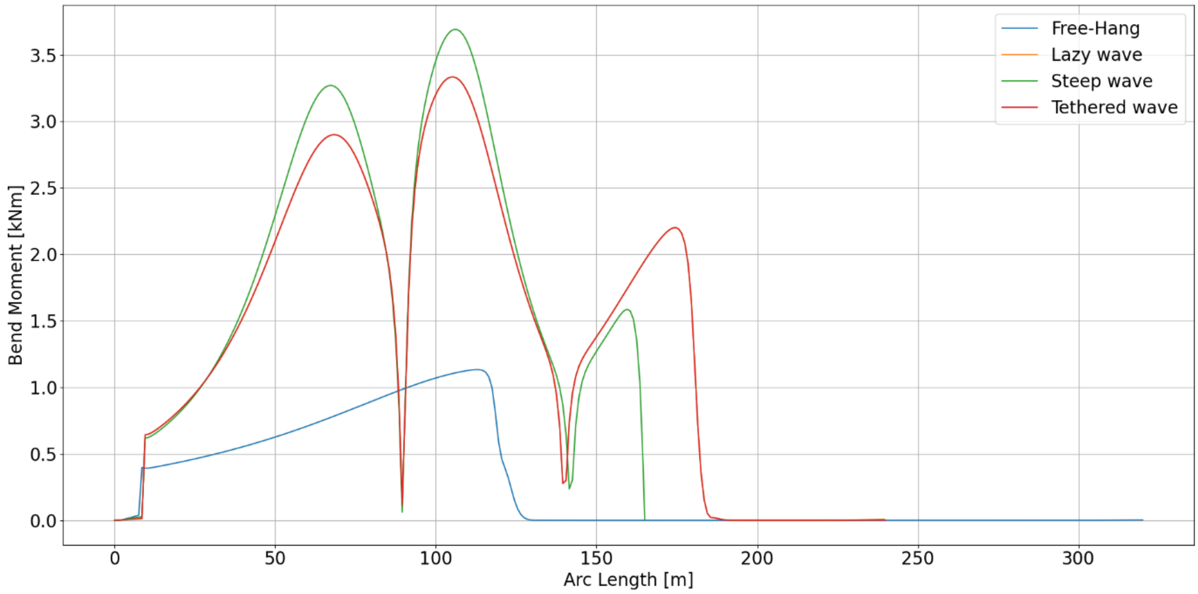

Figure 5.3 Bending Moment for four Catenary cable configuration

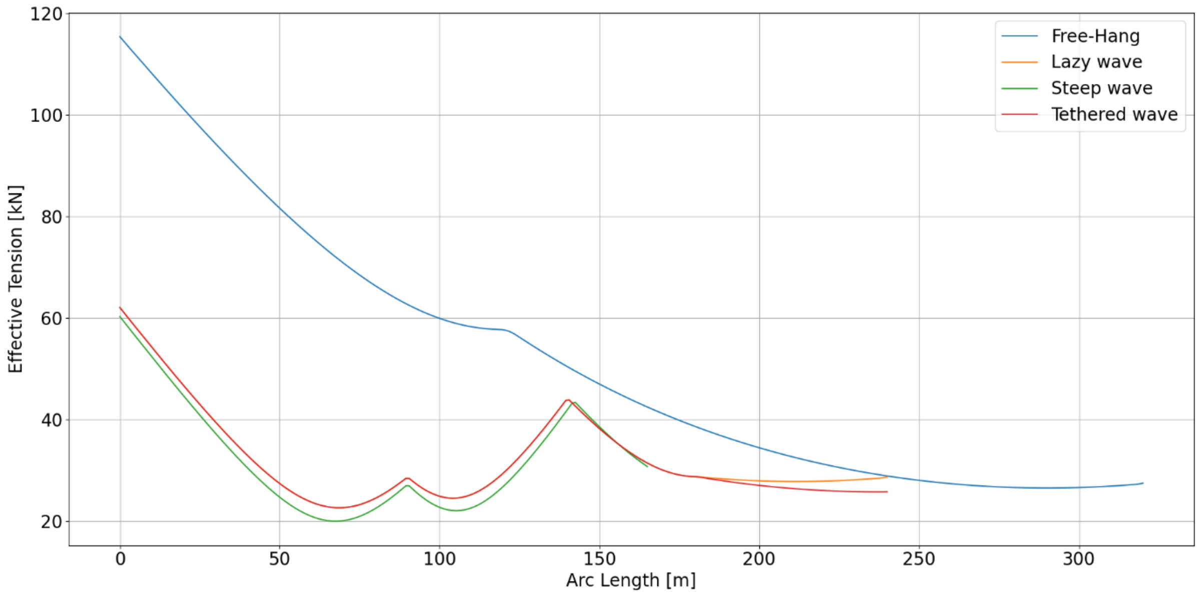

Figure 5.4 Effective Tension at End A for four Catenary cable configuration

Table 5.4 shows the maximum bending moment and effective tension of the entire cross-sectional length of the cables for the four configurations.

Table 5.4 Maximum Bending moment and Tension for four catenary configurations

Configuration/Parameters	Max. Bending Moment [kNm]	Max. Tension [kN]
Free Hang	1.1	115.43
Lazy wave	3.3	62.07
Steep wave	3.6	60.29
Tethered wave	3.3	62.07

It can be clearly seen from the Table 5.4 that the free suspension structure has the minimum bending moment and maximum effective tension at End A (fairlead point). The maximum bending moment and minimum tension are in the steep wave configuration. In the lazy and tethered wave configurations, there are the same amount of bending moment and effective tension. This is because they replicate the same layout configuration, and the additional tether is connected to the tether wave configuration, which does not affect any of these parameters.

From this preliminary analysis, it is found that the free suspension configuration is not suitable for long-term service of 25 to 30 years because the maximum tension is observed in the initial stage of the study. At this time, for the analysis environmental load is not considered but in real-time due to the dynamics of the float exercise it may cause fatigue failure.

Therefore, comparing the other three configurations, the lazy wave configuration is selected, because this is mainly used in harsh environments and has minimal accessories, namely, bending stiffeners and buoyancy modules. Additionally, in steep waves, it needs a bend controller at the connection point of the subsea base, and in tethered waves, it needs fixed tethers and clamps, which will increase the complexity and time of installation.

6 OPTIMIZATION OF THE CATENARY CABLE CONFIGURATION

In this section, the lazy wave configuration is subjected to sensitivity analysis to obtain the best cable configuration, which will be used as the primary model for dynamic analysis. This sensitive static analysis is performed by optimizing the section length of the dynamic cable and optimizing the buoyancy module. The Excursion analysis is performed to study the behaviour of the cable when the float drifts and the influence of the length of the bending stiffener.

6.1 Buoyancy Module

The buoyancy module is modeled in OrcaFlex. A new cable type is setup, its properties are equivalent to the combination of a dynamic cable and a float. This is achieved by evenly distributing the buoyancy and drag of each buoy on the length of the line from sf/2 before the center of the buoy to sf/2 after the center of the buoy, where sf is the float pitch i.e., the spacing between float centers shown in Figure 6.1. The outer diameter and mass per unit length of the new cable are obtained by evaluating Eq.2 and Eq. 3 (OrcaFlex, 2021)

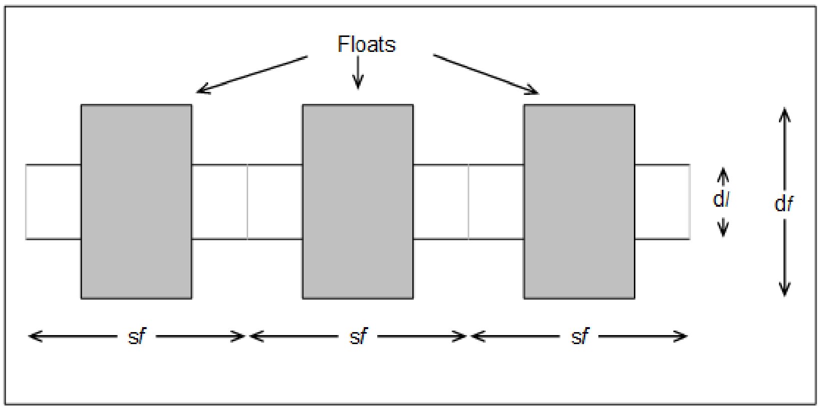

Figure 6.1 Float pitch

$$OD = \left(OD_l^2 + \frac{4}{\pi}\frac{v_f}{s_f}\right)^{\frac{1}{2}} \tag{2}$$

$$m = m_l + \frac{m_f}{s_f} \tag{3}$$

Where,

OD: Outer diameter of cable with floater

OD_l: Outer diameter of the original cable

v_f: volume of the floater

s_f: float pitch

m: weight of cable with floater

m_l: weight of cable in air/water

m_f: weight of floater in air/water

In this analysis, the outer diameter (df) of the buoyancy module is 1 [m] and 1.2 [m], and the float pitch (sf) distance is 3 [m] and 4 [m]. The characteristics of the floater are shown in Table 6.1.

Table 6.1 Floater properties

Floater Diameter [m]	1	1.2
Floater Length [m]	1	
Volume (vf) [m^3]	0.72	1.06
Mass (mf) [te]	0.31	0.45
Displacement [kN]	7.27	10.74
Weight in water [kN]	-4.18	-6.30

A dynamic cable with floating characteristics are obtained by evaluating Eq.2 and Eq.3, as shown in Table 6.2.

Table 6.2 Dynamic cable with floater properties

Float Diameter [m]	Float Pitch [m]	Outer Diameter [m]	Weight in Air [kg/m]	Weight in water [kg/mm]
1	3	0.56	226.59	-22.34
	4	0.62	252.78	-57.93
1.2	3	0.73	298.86	-129.93
	4	0.65	261.15	-76.34

6.1.1 Result: Buoyancy Module

For the floater dimeter of 1 [m], several sets of static analyses were performed and it is found that the floater pitch of 3[m] provides the required buoyant force which helps to form the arc in mid-water level than the floater pitch 4 [m]. It is observed that the bending moment is less in the float pitch of 3[m]. The layout comparison between pitch of 3 [m] and 4 [m] for floater diameter 1[m] is shown in the Figure 6.2.

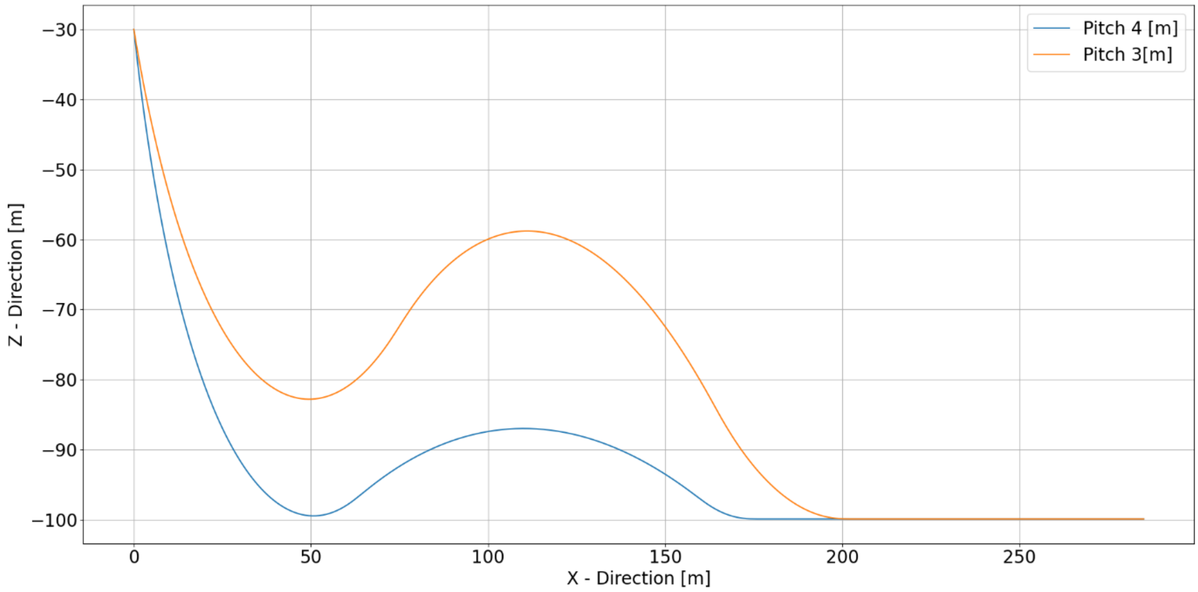

Figure 6.2 Floater diameter 1 [m] with float pitch of 3[m] and 4[m] layout

From the above Figure 6.2 the blue line represents a dynamic cable with a floating pitch of 4 [m]. In this case, the sagging part is only a few meters above the seabed. When the platform drifts along the positive X direction, the sagging part of the cable will totally come in contact with the seabed, which may cause the cable to twist and increase the bending moment due to the compression of the dynamic cable.

Similarly, for a floater diameter of 1.2 [m], several sets of static analysis have been carried out, and it is found that a float pitch of 4 [m] provides the required buoyancy and helps to form an arc in the middle of the water level, similarly lift is observed in float pitch of 3 [m]. Nevertheless, the arc height is still close to the draft level in pitch 3[m]. The layout comparison of the floater diameter of 1[m] with a float pitch of 3[m] and 4[m] is shown in Figure 6.3

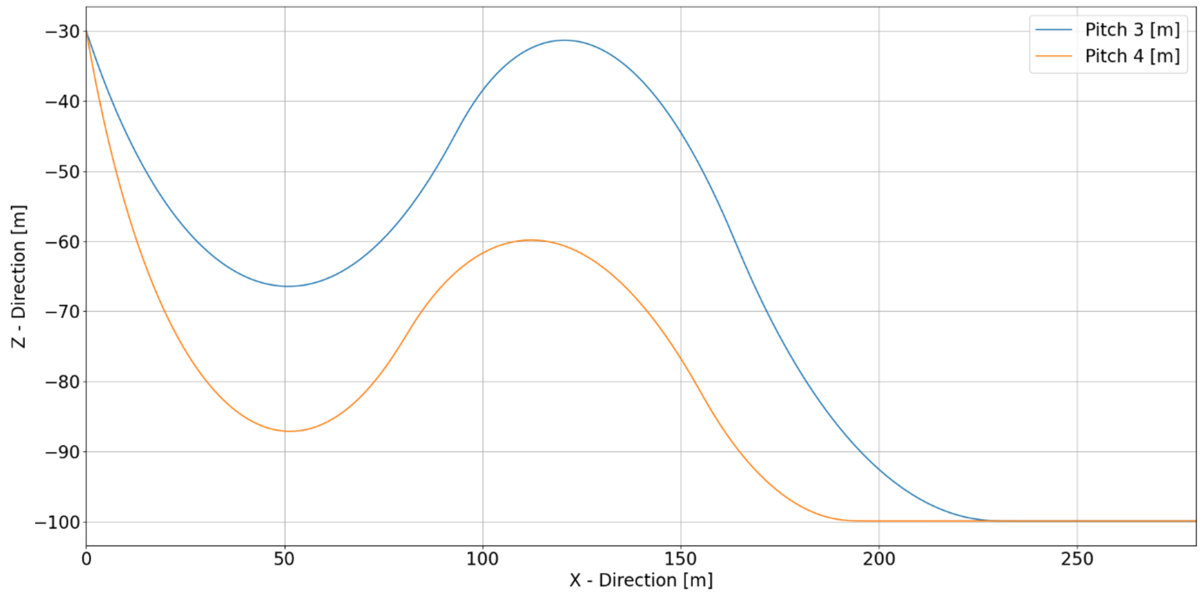

Figure 6.3 Floater diameter 1.2 [m] with float pitch of 3[m] and 4[m] layout

From the above Figure 6.3the blue line represents a dynamic cable with a floating pitch of 3 [m]. The suspension part is the place where the buoyancy module is connected. It almost reaches the draft level of the floating object, which is 30 [m] below sea level. In this case, it observes the maximum bending moment of the middle arch section (buoyancy module). From the analysis, it can be concluded that for a float diameter of 1 [m], a float pitch of 3 [m] is appropriate, and for a float diameter of 1.2 [m], a float pitch of 4 [m] is appropriate. Further analysis are carried out on this basis.

6.2 Dynamic Cable Length

This analysis aim at determining the optimal dynamic cable length with the least bending moment in the system. Therefore, using the results obtained from the analysis of the buoyancy module, different cable length combinations are considered for each float diameter and analyzed individually.

Table 6.3 Dynamic cable section for floater diameter 1[m] with pitch 3 [m]

Floater Diameter 1 [m] with float pitch 3 [m]					
Section	Case 1	Case 2	Case 3	Case 4	Case 5
DC [m]	70	80	100	105	110
DC + Floater [m]	80	80	100	100	100
DC [m]	190	190	150	140	130
Total length [m]	340	350	350	345	340

Table 6.3, the power cable combinations with buoyancy modules of different lengths have a float diameter of 1 [m] and a float pitch of 3 [m]. The layout is shown in the Figure 6.4.

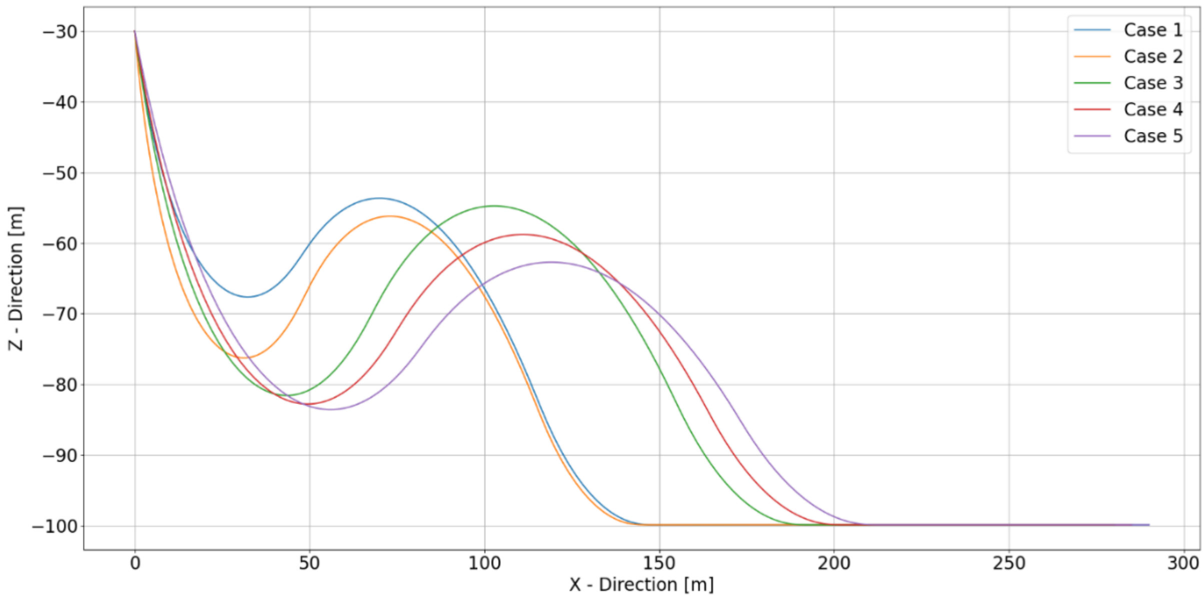

Figure 6.4 Layout of Dynamic cable with floater diameter 1 [m]

Table 6.4 Dynamic cable section for floater diameter 1.2[m] with pitch 4 [m]

Floater Diameter 1.2 [m] with float pitch 4 [m]					
Section	Case 1	Case 2	Case 3	Case 4	Case 5
DC [m]	100	100	100	115	115
DC + Floater [m]	50	60	70	85	85
DC [m]	200	190	170	150	140
Total length [m]	350	350	340	350	340

In Table 6.4, the combination and arrangement of different lengths of power cables with buoyancy modules with a float diameter of 1.2 [m] and a float pitch of 4 [m] are shown in Figure 6.5.

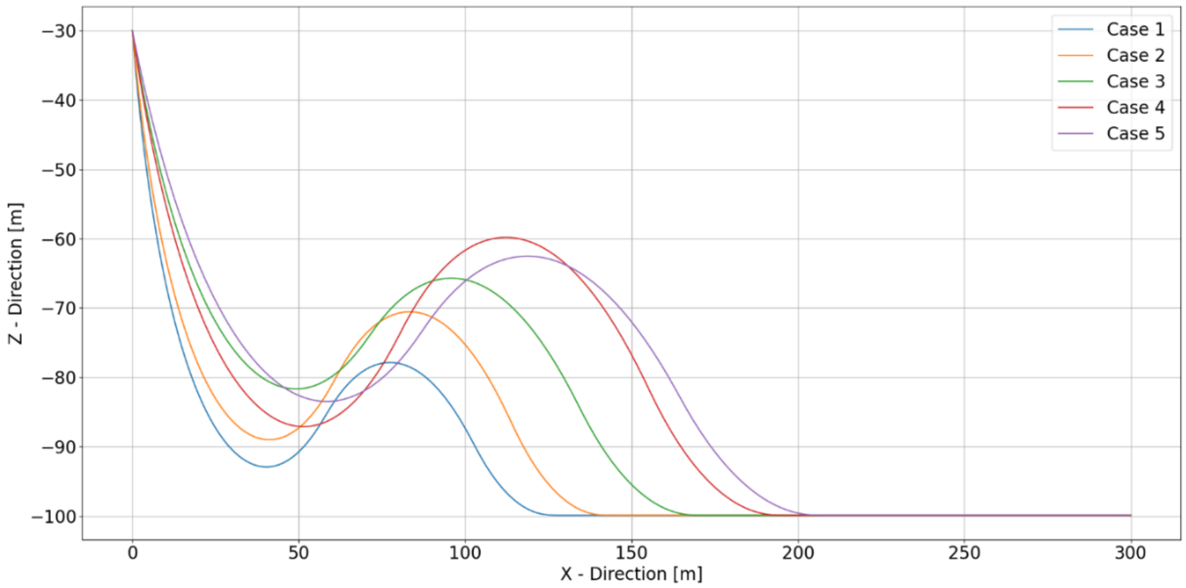

Figure 6.5 Layout of Dynamic cable with floater diameter 1.2 [m]

Table 6.5 Maximum bending moment

Floater Diameter [m]	Float Pitch [m]	Maximum Bending Moment [kNm]				
		Case 1	Case 2	Case 3	Case 4	Case 5
1	3	3.91	4.47	2.98	2.48	2.06
1.2	4	3.64	3.44	2.48	2.45	1.93

It is seen from Table 6.5 that the minimum bending moment for a float diameter of 1.2 [m] and a float pitch of 4 [m] is 1.93 [kNm], which is obtained as the maximum value of the entire cable length of 340 [m] in case 5. When comparing the cross-sectional length of power cables with floats, a float diameter of 1 [m] requires more sectional length than a float diameter of 1.2 [m], which is seen from Table 6.3 and Table 6.4. The bending moments obtained by dynamic cables with a float diameter of 1.2 [m] with a float pitch of 4 [m] in all the five cases mentioned in Table 6.4 are shown in Figure 6.6. The purple line represents Case 5, which is determined as the optimal length of the dynamic cable system, therefore it will be used for further dynamic analysis.

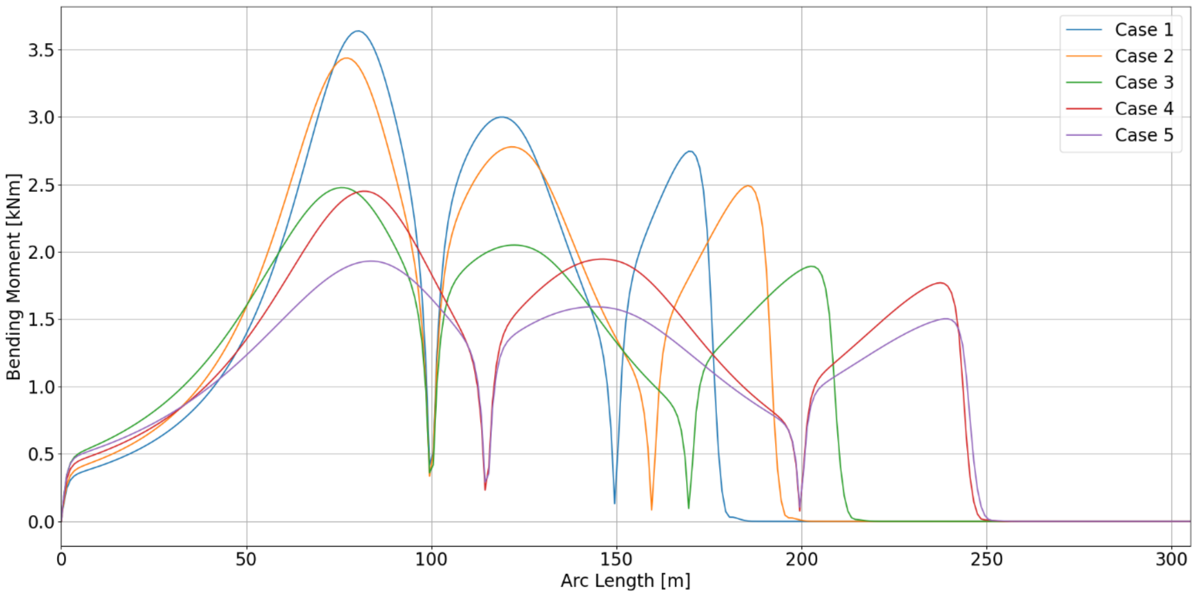

Figure 6.6 Bending Moment of dynamic cable with floater diameter 1.2 [m]

6.3 Excursion Analysis

The excursion analysis is performed to study the behavior of the dynamic cable when the floating platform deviates from the target position due to environmental loads to achieve the best inert wave configuration. In this case, the target position is 0 [m] i.e., the center of the float, which moves +/- 25 [m] in the X direction with an interval of +/- 5 [m], as shown in Figure 6.7.

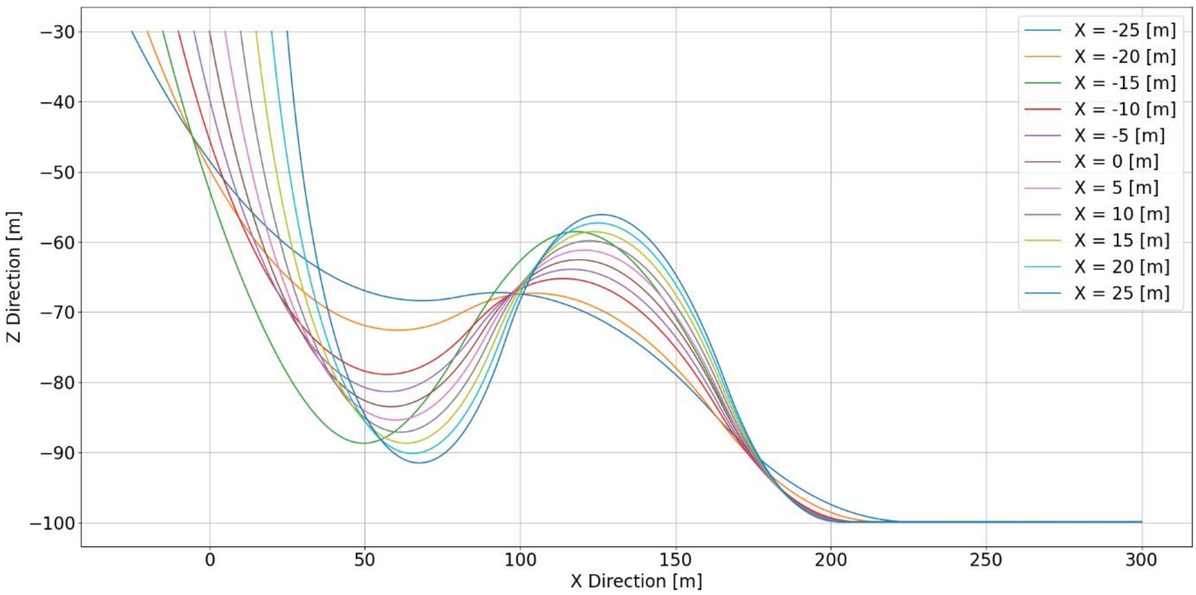

Figure 6.7 Excursion analysis +/- 25 [m]

The maximum bending moment and effective tension of the moving cable when the float position is +/-25[m] and the interval is +/-5[m] are shown in Table 6.6.

Table 6.6 Excursion analysis: Maximum Bending Moment and Effective Tension

Cable Parameter/X Axis[m]	-25	-20	-15	-10	-5	0	5	10	15	20	25
Max. Bend Moment [kN.m]	0.65	0.94	1.19	1.44	1.68	1.93	2.18	2.44	2.72	3.02	3.35
Max. Tension at End A [kN]	132.69	105.41	93.2	86.19	81.63	78.4	75.99	74.12	72.63	71.42	70.41

It can be seen from the above Table 6.6, that when the float drifts near the touch down point i.e., along the positive X direction, the bending moment of the sagging part of the cable increases, because in this area, the cable is subjected to lower tension, But as the catenary angle is minimized, the effective tension at the end A is decreasing. Conversely, when the float drifts away from the touch down point i.e., in the negative X direction, the bending moment decreases with the elongation of the cable, due to the elongation and increase of the catenary angle, the effective tension increases. Figure 6.8 and Figure 6.9 show's the comparison between the bending moment and the effective tension of the entire section length of the float position at -5 [m] and +5[m].

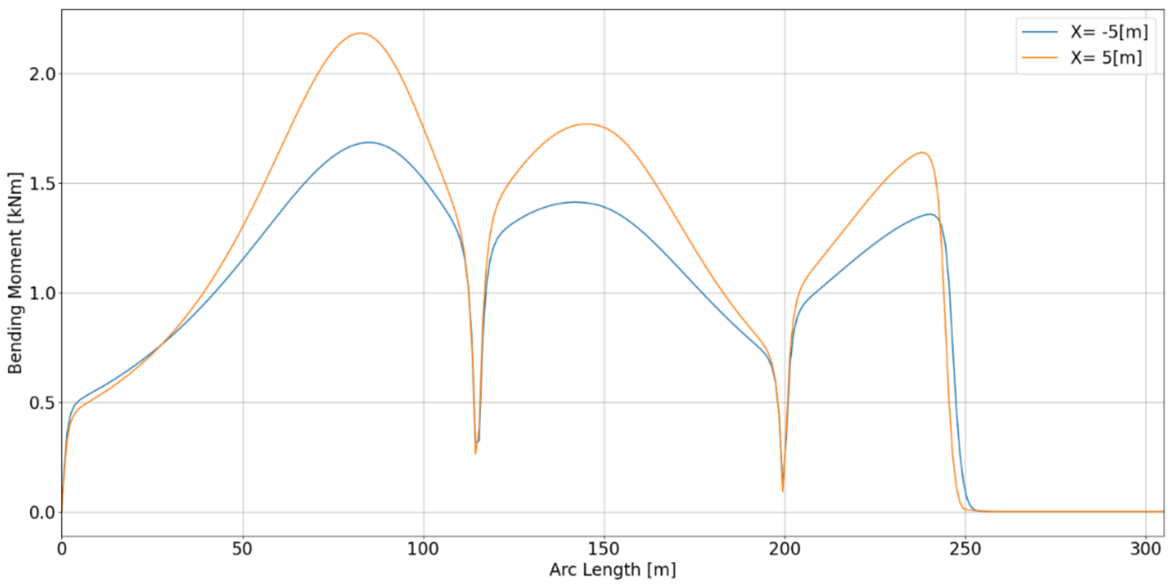

Figure 6.8 Excursion analysis +/- 5 [m]: Bending Moment

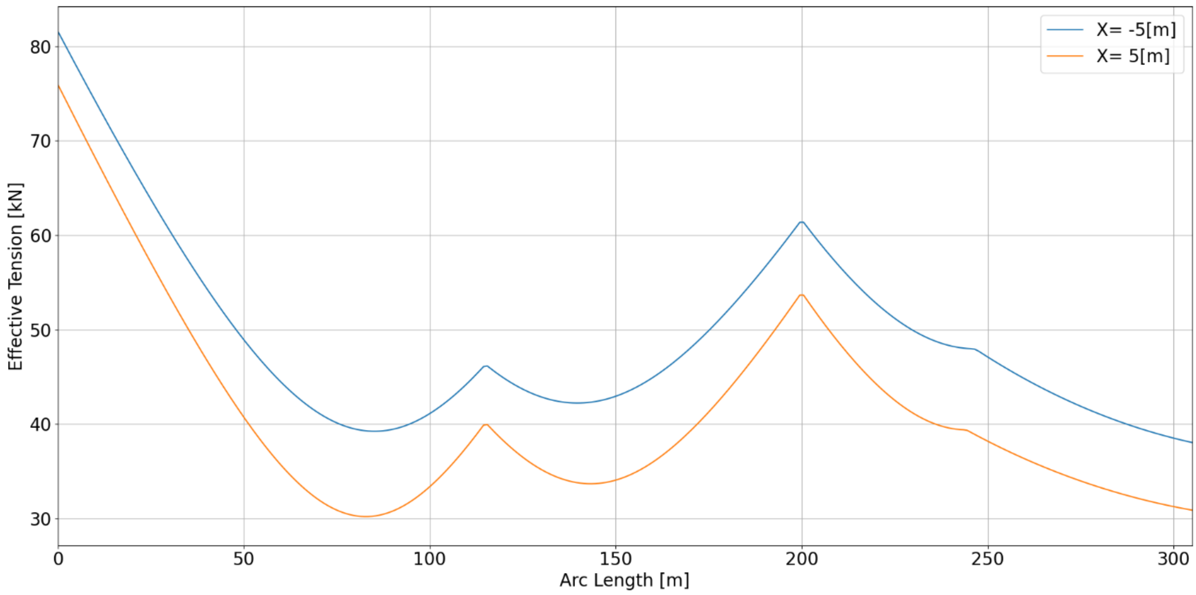

Figure 6.9 Excursion analysis +/- 5 [m]: Effective Tension

6.4 Bend Stiffener

The optimal lazy wave configuration is analyzed to study the influence of different bending stiffener lengths. For this analysis, the modeling lengths of the curved stiffeners are 3 [m], 5 [m], and 7 [m], the outer diameter is reduced from 0.7 [m] (at end A) to 0.38 [m], a 1200 [kg /m^3] material density and 45 [Mpa] Young's modulus. (Reference: Study on the parameters of the cable system between dynamic arrays of floating offshore wind turbines).

From the analysis, it is found that the maximum effective tension at end A is 78.4 [kN] for all three bending stiffener lengths, and the maximum bending moment is 1.93 [kNm] for all three bending stiffener lengths. These maximum values are obtained for the entire cable length, and the bending of the stiffener will not affect the tension of the dynamic cable.

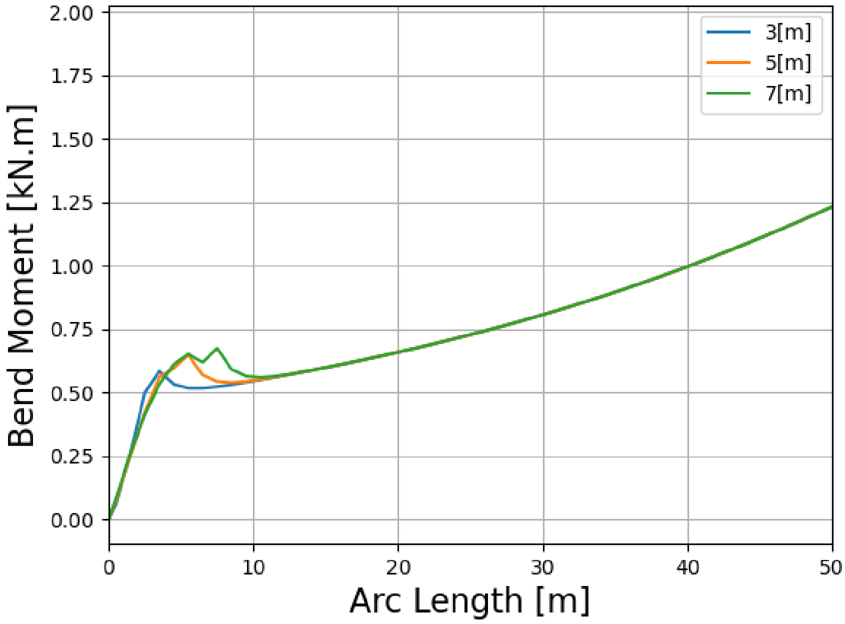

Figure 6.10 Bend Stiffener analysis: Bend moment

It can be seen from above Figure 6.10, when the length of the bending stiffener increases, the bending moment gradually increases. The bending moment for the length of 3 [m] is 0.58 [kNm], the length of 5 [m] is 0.65 [kNm], and the length of 7 [m] is 0.68 [kNm]. Bending stiffeners will not affect the dynamic cable in the static analysis because the float is the target location. Nevertheless, it may be different when the floating object undergoes dynamic movement, so an intermediate length of 5 [m] is connected to the dynamic cable for further analysis.

6.5 Conclusion

Static analyses has been performed to find the optimal configuration. From this analysis, the optimal configuration of dynamic cable is to found be: total section length of 340 [m] dynamic cable including 80 [m] of buoyancy module whose floater diameter is 1.2 [m] with a float pitch of 4 [m]. In addition, the bending stiffener length of 5 [m] was selected.

7 DYNAMIC ANALYSIS

In this chapter, a dynamic analysis is conducted for the optimal lazy wave configuration under specific environmental conditions, and the mooring chain is connected to the buoy. Before performing a complete dynamic analysis, a preliminary mooring analysis is performed.

7.1 Environment Load

The environmental load conditions of the dynamic analysis are carried out for different wave directions to obtain the extreme response of the power cable and the mooring system under the environmental load conditions shown in Table 7.1.

Table 7.1 Environmental Load condition

Load condition	Load Case	Wave Height Hs [m]	Wave Period Tz [sec]	Wave Type	Current [m/s]
Normal Sea State	1	3.5	3	Jonswap Spectrum	1
	2		5.5		
	3		7		
Extreme Sea state	1	12.1	10.92		

Initially, extreme load conditions analysis was performed for 1000 seconds to determine the optimum mooring system configuration, and then all load conditions were analyzed for 3 hours to capture all possible extreme sea conditions. Statistically three hours is sufficient to achieve this goal; in terms of cable mechanical properties, using more will not add any important insight.

7.2 Mooring Analysis

FOWT's mooring system is one of the main systems that need to be studied in depth, because it constitutes the main part of the float's drifting motion. The choice of mooring system layout depends on many criteria, such as the type of floating objects, redundancy, cost and installation of the mooring system, standards mentioned in the mooring requirements.

In this study, catenary mooring system with 8 mooring line are considered to be the first attempt at analysis. The scope of this study is to conduct multiple sensitivity analyses to find the best mooring configuration, using a trial-and-error method. Since it is calculated based on many assumptions and concepts, it is best to start with the method of determining the optimal mooring chain size and mooring length. The 8 mooring lines are connected to the float at 30 [m], the value of which corresponds to the draft of the float. The fixed connection points and anchor points of each mooring line are shown in Table 7.2, and the mooring arrangement is shown in Figure 7.1.

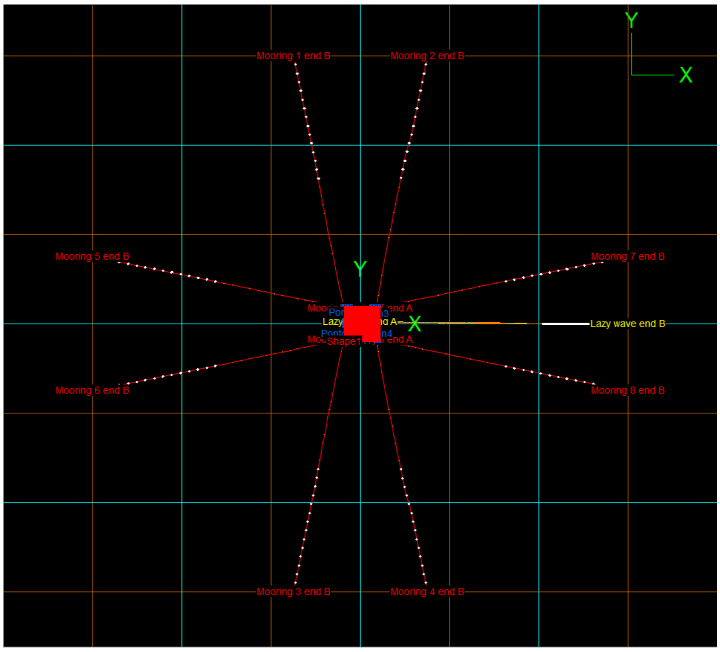

Figure 7.1 Mooring system layout

Table 7.2 Mooring line position

Mooring Line No:	Platform (Fairlead Point) [m]			Anchored [m]		
	X	Y	Z	X	Y	Z
1	-18	17.5	-30	-75	300	0.16
2	18	17.5	-30	75	300	0.16
3	-18	-17.5	-30	-75	-300	0.16
4	18	-17.5	-30	75	-300	0.16
5	-18	17.5	-30	-300	75	0.16
6	-18	-17.5	-30	-300	-75	0.16
7	18	17.5	-30	300	75	0.16
8	18	-17.5	-30	300	-75	0.16

7.2.1 Optimal Mooring Chain Size

The preliminary analysis considers the use of steel grade R4 mooring lines without stud chains. In order to determine the optimal chain diameter, two diameters need to be considered, namely 100 [mm] and 120 [mm] diameter and their mechanical properties are shown in Table 7.3. This analysis takes into account a mooring chain length of 320 [m].

Table 7.3 Mooring chain mechanical properties

Chain Diameter	100 [mm]		120 [mm]	
Material	Grade R4 Stud-less			
Breaking Point	9864.00	[kN]	13570.00	[KN]
Weight in air	1.95	[kN/m]	2.81	[kN/m]
Displacement	0.26	[kN/m]	0.37	[kN/m]
Weight in water	1.70	[kN/m]	2.44	[kN/m]
Diam/Wt ratio	0.11	[m/kN/m)]	0.09	[m/(kN/m)]

The initial analysis was conducted on the extreme sea conditions mentioned in Table 7.1. For the wave direction from 0° to 180°, the interval is 15°. The dynamic analysis of the mooring line is carried out for two diameters, and the maximum tension of the mooring line always appears at the End A (fairlead point) connected to the platform. Therefore, for each considered chain diameter under extreme sea conditions, the mooring line with the highest tension among all the other mooring lines is shown in Figure 7.2 for each environmental load directions (i.e. 0° to 180°, interval 15°) considered in the analysis.

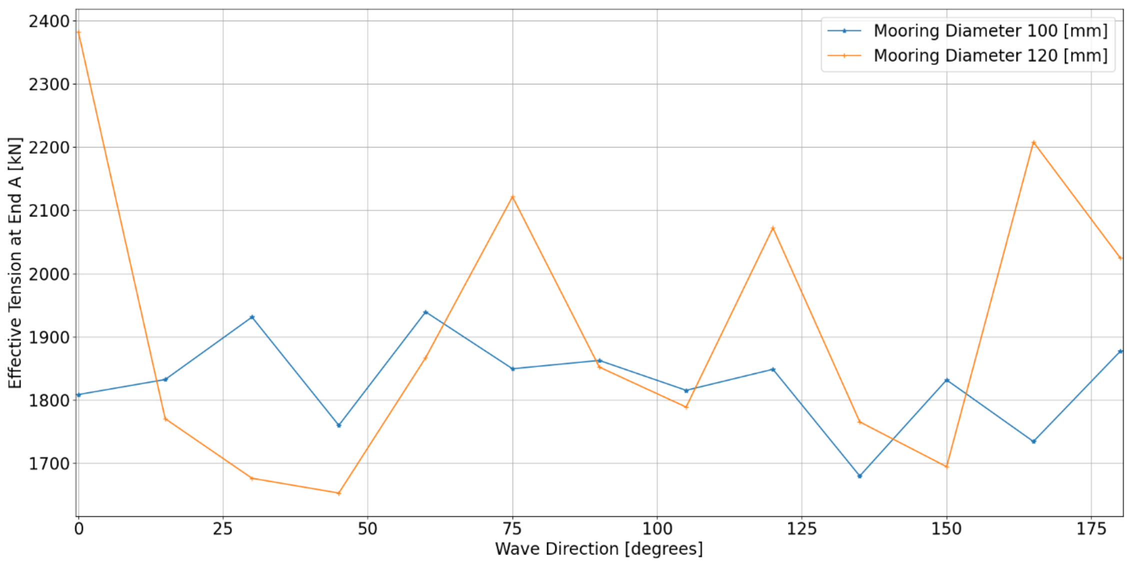

Figure 7.2 Mooring chain diameter analysis: Maximum effective tension in mooring line

As seen from the above figure, the tension of the 120 [mm] diameter chain is slightly higher than that of the 100 [mm] diameter chain, which is mainly due to the weight of the chain, the surge, sway and heave movement of the platform. Table 7.4 and Table 7.5 show the effective tensions of two diameter-mooring lines in all wave directions.

Table 7.4 Mooring diameter 100 [mm]: Maximum tension at End A

Wave Direction [deg]	Effective tension at End A							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	990.53	781.00	1150.75	1021.26	1808.05	1808.37	1103.22	843.60
15	1050.44	910.94	1108.94	1017.13	1478.85	1832.15	831.52	752.40
30	810.58	1182.88	1238.36	1782.92	1351.28	1930.97	674.18	787.99
45	728.29	902.20	1658.39	1167.20	1249.52	1759.67	744.34	1093.06
60	1267.17	891.20	1939.21	1385.78	991.03	1334.36	800.90	1381.36
75	1163.19	947.53	1849.21	1658.43	782.83	1302.38	871.22	995.68
90	919.88	798.93	1862.39	1788.16	1143.95	1049.49	792.58	875.85
105	946.03	926.58	1566.36	1815.11	963.28	805.08	989.87	1574.95
120	907.48	801.28	1436.61	1848.38	1250.44	959.95	879.24	1337.17
135	845.51	843.03	1362.50	1679.46	981.78	860.12	1132.08	1557.41
150	948.85	862.62	928.43	1297.92	799.61	1675.70	1227.13	1831.52
165	929.91	1300.45	798.16	1189.98	781.18	1381.18	1444.96	1734.04
180	979.48	1133.20	923.93	1223.30	733.51	820.84	1864.99	1876.80

Table 7.5 Mooring diameter 120 [mm]: Maximum tension at End A

Wave Direction [deg]	Effective tension at End A							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	1193.05	1034.02	950.64	958.67	1824.86	1817.56	953.70	2382.40
15	972.19	921.92	1144.50	1041.61	1418.38	1770.22	1181.67	1445.10
30	1469.38	1006.06	1446.59	1072.23	1259.59	1675.89	1200.26	933.82
45	1015.26	1314.98	1599.18	1233.41	1652.49	1444.19	961.97	1040.72
60	743.94	1646.66	1866.74	1463.50	1107.60	1574.91	870.05	1001.92
75	796.66	916.88	1807.13	1861.23	923.21	2121.48	1009.75	1005.06
90	1079.25	1076.32	1851.87	1802.49	968.58	966.30	1127.41	1221.68
105	775.57	1152.87	1432.94	1760.82	799.90	1394.81	957.52	1788.61
120	847.54	1056.73	1189.45	2072.22	729.55	1139.93	1469.90	1234.27
135	905.56	827.97	1316.29	1765.12	1001.78	1257.60	1349.99	1393.85
150	996.36	1325.49	903.30	1364.08	1534.20	1212.82	1209.92	1694.20
165	1370.46	1182.39	2208.04	1378.75	1063.97	976.88	1716.92	1816.69
180	818.94	1161.93	1096.22	940.83	1158.37	1002.66	2024.63	1719.70

It can be seen from the above tables that the maximum tension generated by the two mooring chain diameters under extreme sea conditions is always lower than the allowable breaking limit in Table 7.3.

Since the tension of the mooring line of the two diameters is within the allowable range, to determine the optimal chain size, it is necessary to consider the impact of the environmental load on the floater and the power cable and to conduct further analysis. The maximum bending moment and effective tension of the power cable and the movement of the platform, considering the two different mooring diameters are shown in Figure 7.3, Figure 7.4, Figure 7.5, Figure 7.6 and Figure 7.7.

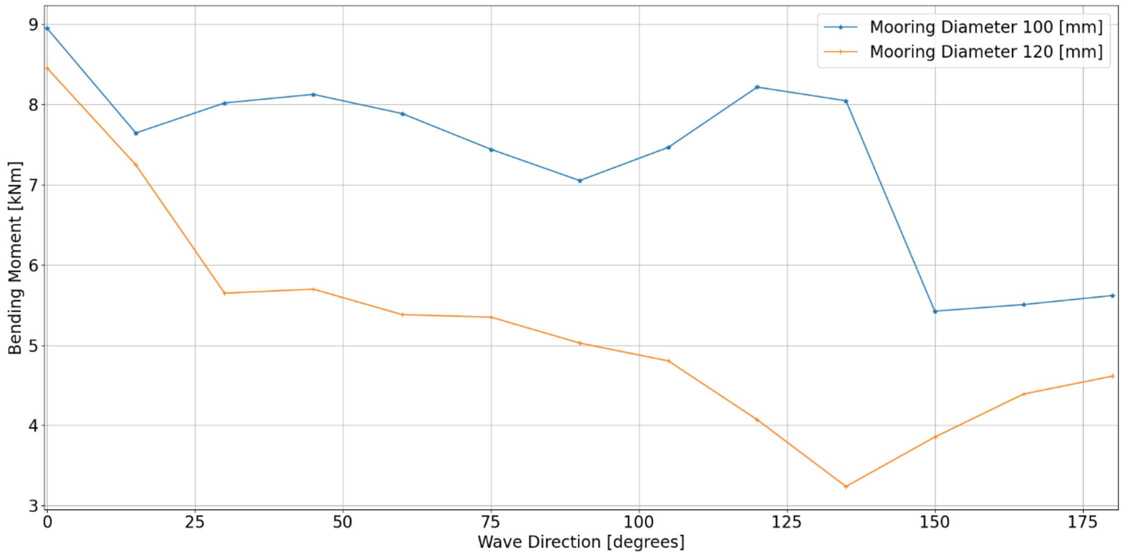

Figure 7.3 Mooring diameter analysis: Maximum bending moment for dynamic cable

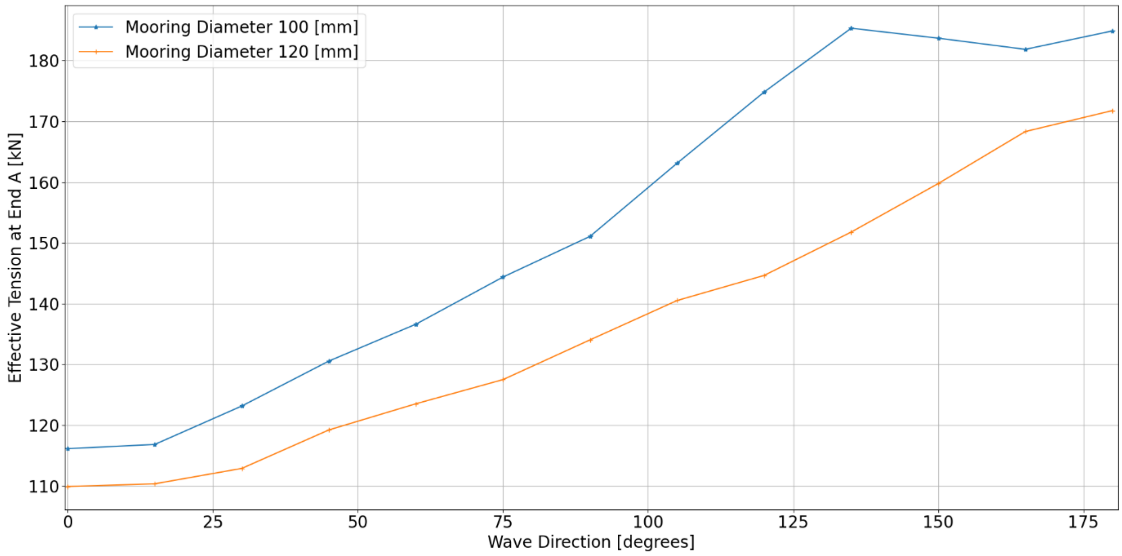

Figure 7.4 Mooring diameter analysis: Maximum effective tension at End A for dynamic cable

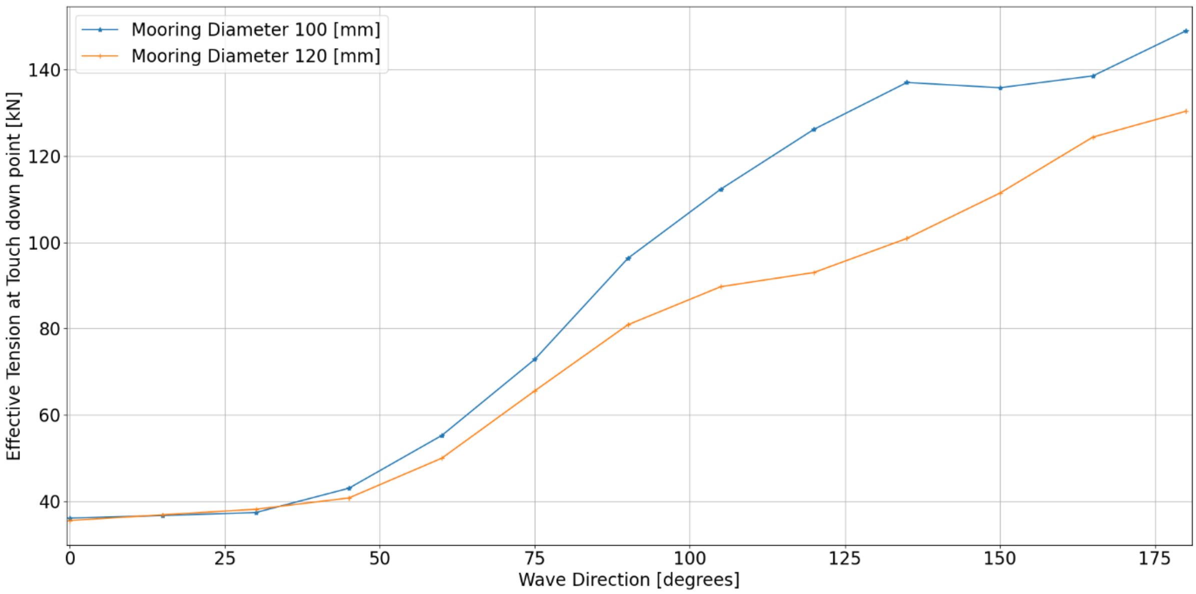

Figure 7.5 Mooring diameter analysis: Maximum effective tension at touch down point (TDP) for dynamic cable

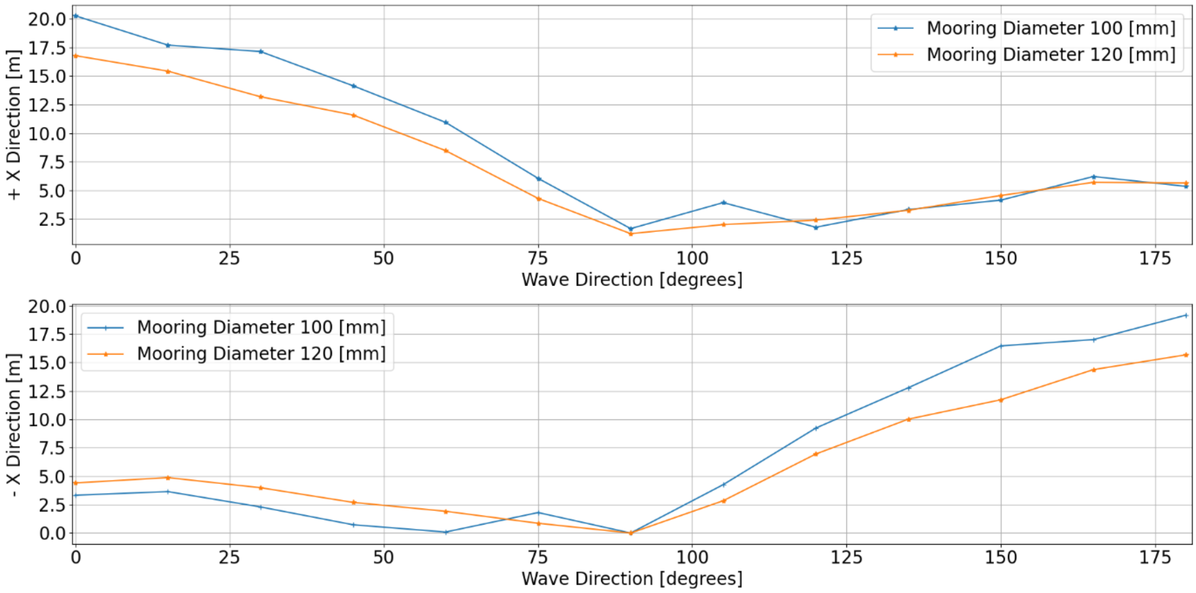

Figure 7.6 Mooring diameter analysis: Maximum surge movement of the floater

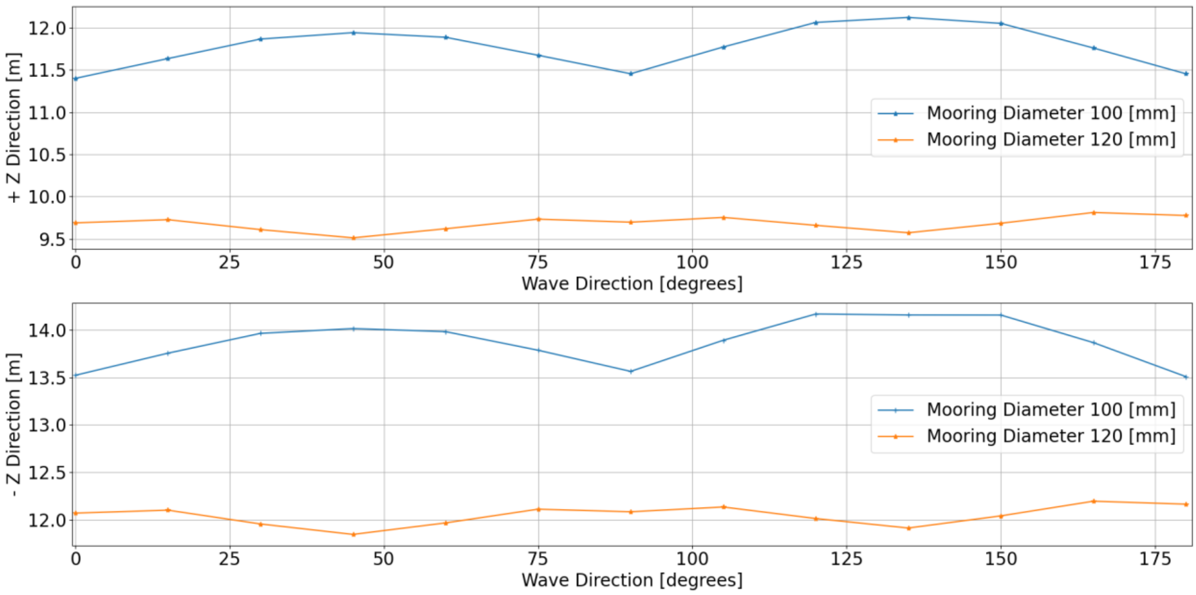

Figure 7.7 Mooring diameter analysis: Maximum heave movement of the floater

The above Figure 7.6 clearly shows that a mooring chain with a diameter of 100 [mm] cannot control the surge movement of the platform. A maximum surge of 20.28 [m] was noticed at a wave direction of 0° (that is, the wave heading in positive X direction) and 19.17 [m] in wave direction 180° (that is, the wave heading in negative X direction). This movement has a significant impact on the dynamic cable system, in terms of the bending moment and effective tension of the cable. It can be seen from Figure 7.3 that when the wave direction is 0°, the maximum bending moment on the power cable is 8.95 [kNm]. From Figure 7.4, the maximum tension at end A at 180° in the wave direction is 184 [kN].

In a mooring chain with a diameter of 120 [mm], the platform surge and heave motion control is better than the mooring chain with a diameter of 100 [mm]. The maximum surge in wave direction of 0° it is 16.78 [m], and in wave direction of 180° it is 15.68 [m], which is 3.5 [m] smaller on average than the mooring chain diameter of 100 [mm]. In mooring diameter 120 [mm] the average bending moment is 2.13 [kNm], which is less than 100 [mm] mooring diameter, and the effective tension is less than 100 [mm], for an average of 20 [kN].

It can be concluded that a mooring chain diameter of 120 [mm] is considered the optimal chain size under this environmental load condition, and the maximum value obtained under this load condition is much lower than the allowable dynamic cable and mooring chain properties as indicated in the Table 5.1 and Table 7.3.

7.2.2 Optimal Mooring Chain Length

In this section, the initial mooring line length is modified to obtain an optimized mooring length, and to more effectively restrain the movement of floating objects without changing the anchor point, which is established at a distance of 300 [m] from the center of the floater. In this case, the optimized mooring line with a chain diameter of 120 [mm] (investigated in the previous section) is considered, and the same environmental load conditions were applied. The analysis was performed considering mooring lines length of 320[m] and 310[m], for the wave direction from 0° to 180°, with an interval of 30°.

Figure 7.8 shows the summary effective tension of two lengths of mooring lines in all environmental load directions.

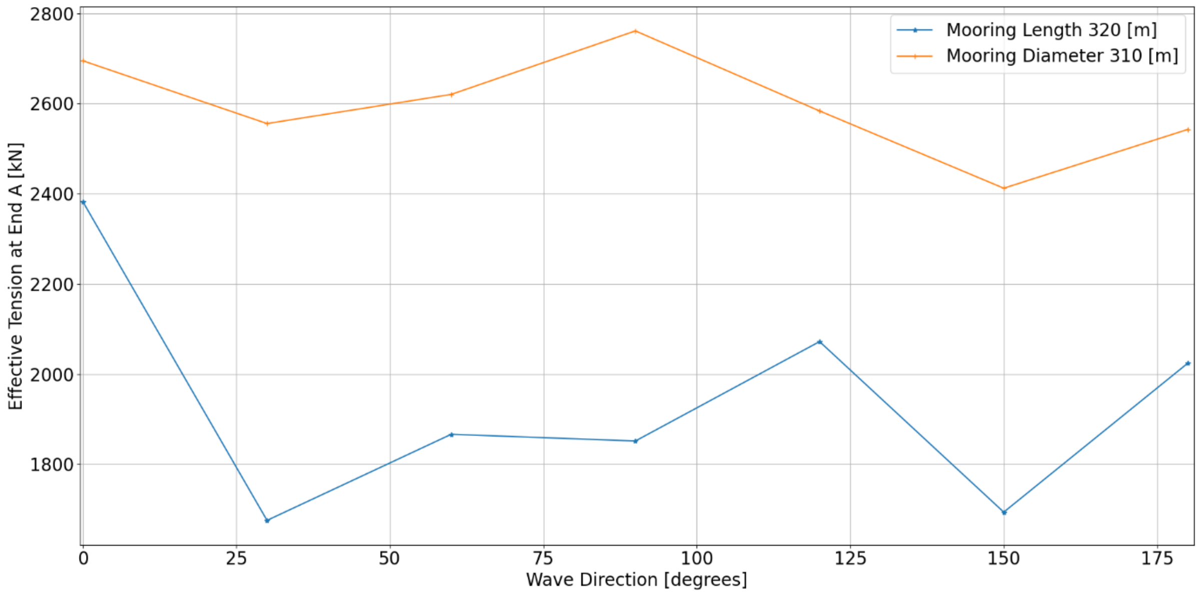

Figure 7.8 Mooring line length analysis: Maximum effective tension in mooring line

Since the tension of the mooring line of the two length is within the allowable range, in order to determine the optimal chain length, it is necessary to consider the impact of the environmental load on the floater and the power cable to conduct further analysis. The maximum bending moment, effective tension of the power cable and the movement of the floater under the two mooring length are shown in Figure 7.9, Figure 7.10, Figure 7.11, Figure 7.12 and, Figure 7.13.

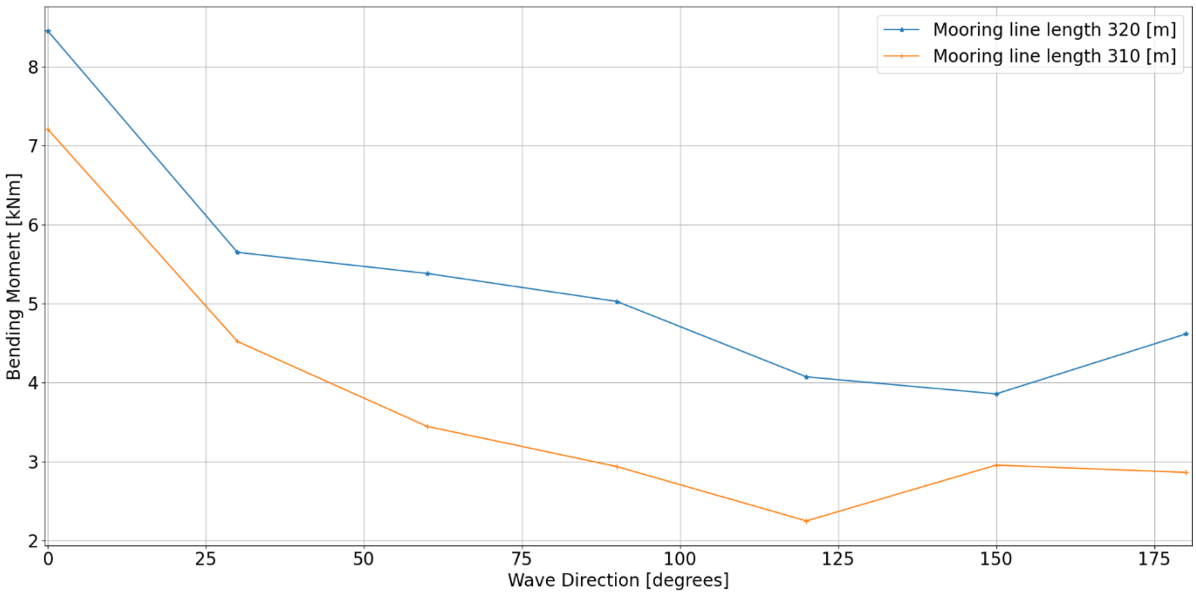

Figure 7.9 Mooring line length analysis: Maximum bending moment for dynamic cable

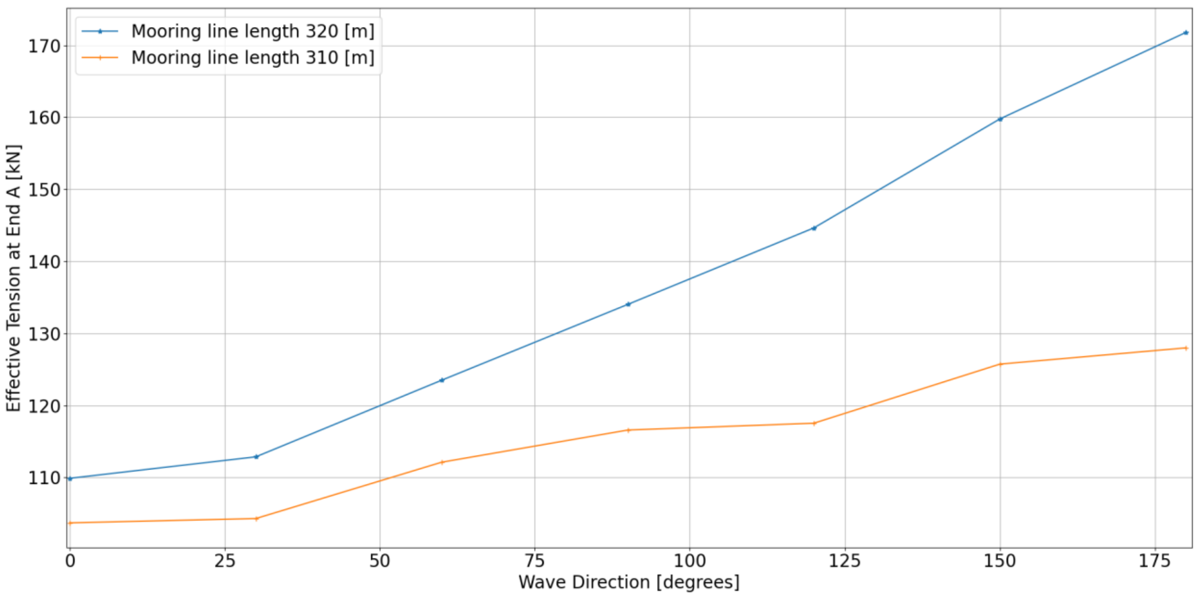

Figure 7.10 Mooring line length analysis: Maximum effective tension at End A for dynamic cable

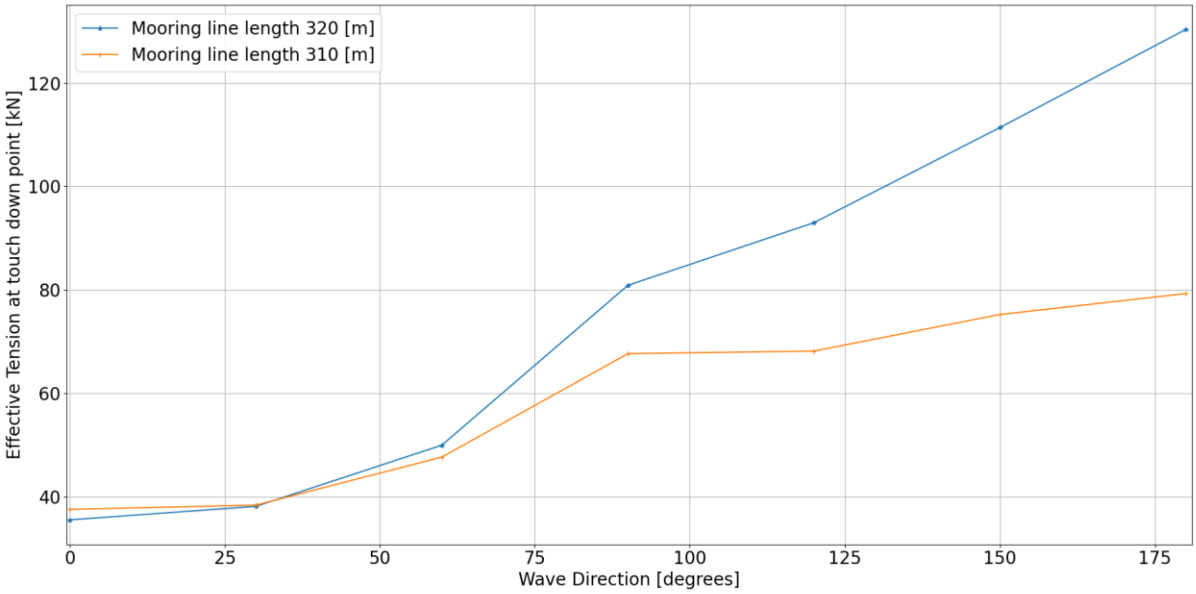

Figure 7.11 Mooring line length analysis: Maximum effective tension at touch down point (TDP) for dynamic cable

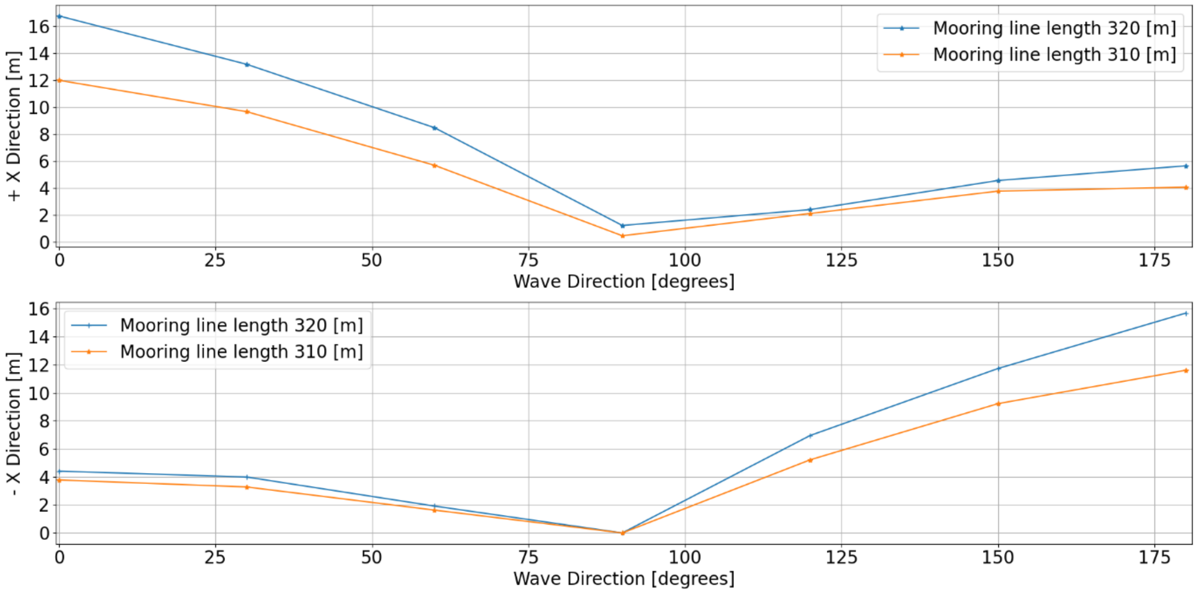

Figure 7.12 Mooring line length analysis: Maximum surge movement of the floater

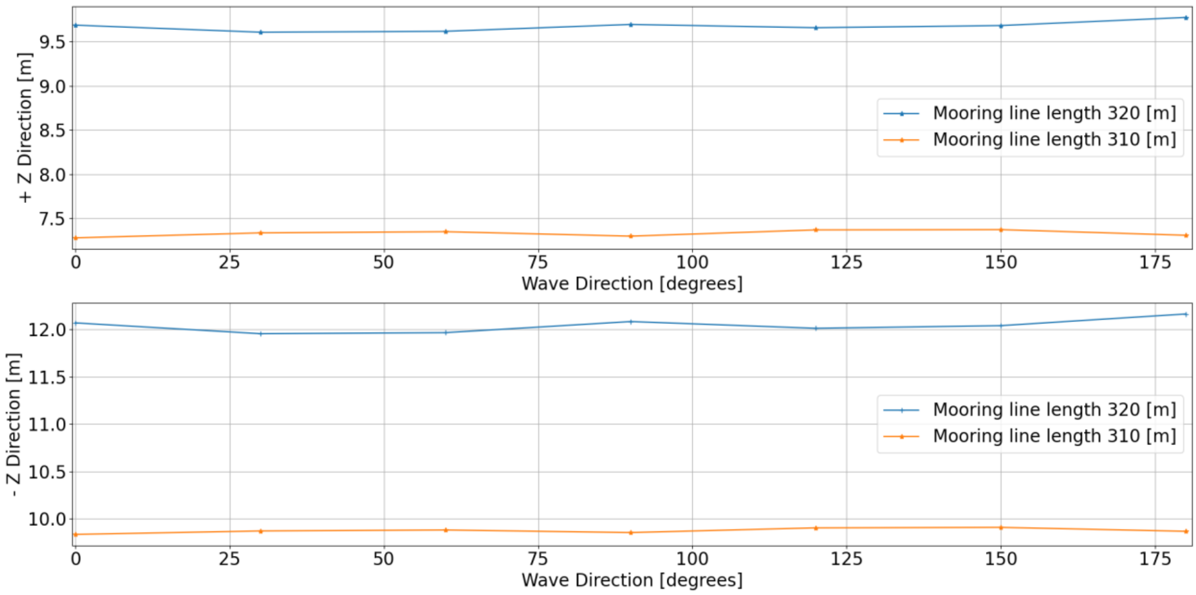

Figure 7.13 Mooring line length analysis: Maximum heave movement of the floater

In the above Figure 7.12, it can be noticed that for the 310 [m] long mooring line, the surge and heave movement of the floater are controlled better than the 320 [m] long mooring line. The maximum surge in the 0° wave direction is 12 [m], and the maximum surge in the 180° wave direction is 11.6 [m], which is 4 [m] smaller on average than the 320 [m] long mooring line. In the mooring length 310 [m] the bending moment of the dynamic cable's average is 3.73 [kNm] and the average effective tension is 25 [kN] which is less than 320 [m] mooring length.

It can be concluded that mooring line with a length of 310 [m] and a diameter of 120 [mm] are considered to be the optimal mooring system under such environmental load conditions. The maximum value obtained under this load is much lower than the allowable limits for the mechanical properties of dynamic cables and mooring chains mentioned in Table 5.1 and Table 7.3.

7.3 Coupled Analysis of Dynamic Cable And Mooring

In this section, the optimized dynamic cable configuration with optimized mooring system will be analyzed under the different load combinations mentioned in section 7.1. The direction of the waves is from 0° to 180° with 30° interval. These load combinations are divided into two sea state conditions: extreme sea state and normal sea state conditions, that is simulated for 3 hours to capture all possible sea state limits.

7.3.1 Extreme Sea State Condition

The analysis is carried out for the extreme sea conditions mentioned in Table 7.1. The wave course ranges from 0° to 180°, with an interval of 30°, and the operation time is a 3-hour storm period. For these wave directions, the maximum bending moment and effective tension absorbed on the dynamic cable are shown in Table 7.6.

Table 7.6 Extreme Analysis: maximum bending moment and tension in dynamic cable

Environment			Dynamic Cable					
Wave Height Hs [m]	Wave Period Tz[s]	Wave Direction [deg]	Bend Moment [kN.m]		Tension at End A [kN]		Tension at TDP [kN]	
			Max	Mean	Max	Min	Max	Min
12.1	10.92	0	9.60	0.99	128.60	24.99	55.98	-0.37
12.1	10.92	30	7.93	1.01	127.93	28.22	46.26	9.75
12.1	10.92	60	7.65	0.96	141.89	37.77	61.60	25.56
12.1	10.92	90	7.18	0.88	148.78	50.57	98.44	25.85
12.1	10.92	120	6.42	0.90	151.62	44.94	103.51	30.91
12.1	10.92	150	4.93	0.90	171.68	30.63	112.09	30.85
12.1	10.92	180	5.90	0.86	198.92	25.77	158.96	29.57

The above Table 7.6 clearly shows that the 0° and 180° wave directions have a greater influence on the bending moment and effective tension of the dynamic cable. This is because of the surge motion of the float; in the 0° wave direction, the float drifts toward the touch down point (TDP) (that is, the positive X direction), which will cause the bending moment to increase as the dynamic cable is compressed. The maximum bending moment absorbed in this direction is 9.60 [kNm], while the effective tension near the End A (fairlead point) is 128.60 [kN], with a touch down point (TDP) of 55.98 [kN]. Conversely, in the 180° wave direction, the platform drifts far away from the touchdown point, which leads to elongation of dynamic cable and it causes tension in the system that increases to 198.92 [kN] at the fairlead point and 158.96 [kN] at the touch down point (TDP).

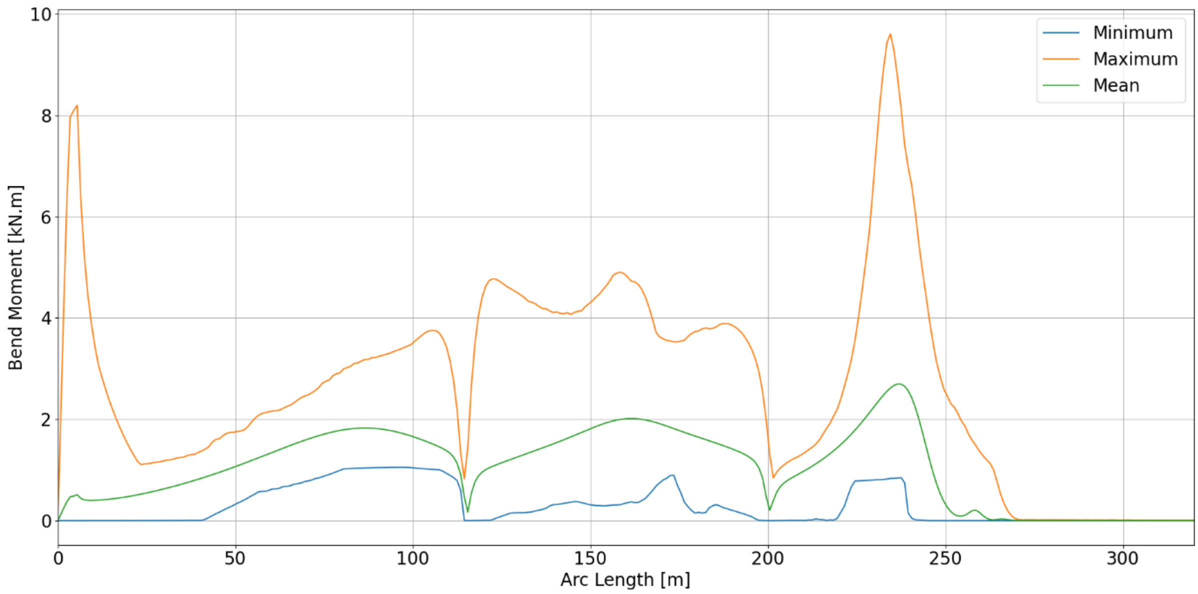

Figure 7.14 Extreme sea state: Bending Moment in 0° wave direction for dynamic cable

It can be seen from the above Figure 7.14, that the maximum bending moment of 9.6 [kNm] occurs in the last section of the power cable. In addition to the bending stiffener area, another peak of the maximum bending moment of 8.2 [kN] also appeared, due to large wave height the heave motion of the platform increased. In this case, the length of 5 [m] bend curved stiffener is considered as the reference section (analysis of the curved stiffener). In the arc length between 110 [m] and 200 [m], the buoyancy module is connected to the power cable, and the maximum bending moment in this area is 4.9 [kN].

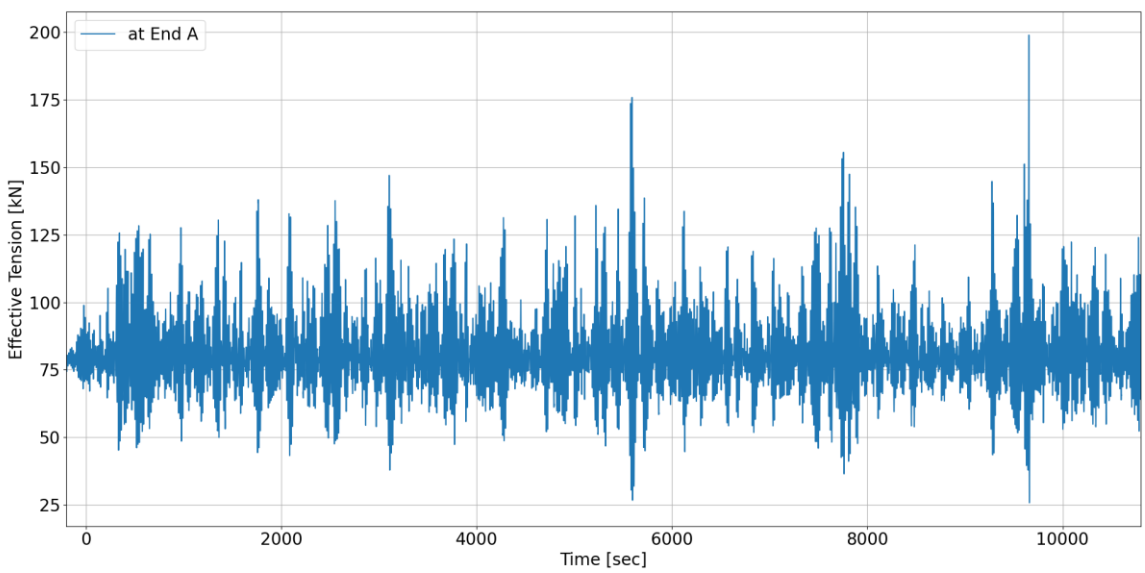

Figure 7.15 Extreme sea state: Effective tension at End A in 180° wave direction on the dynamic cable.

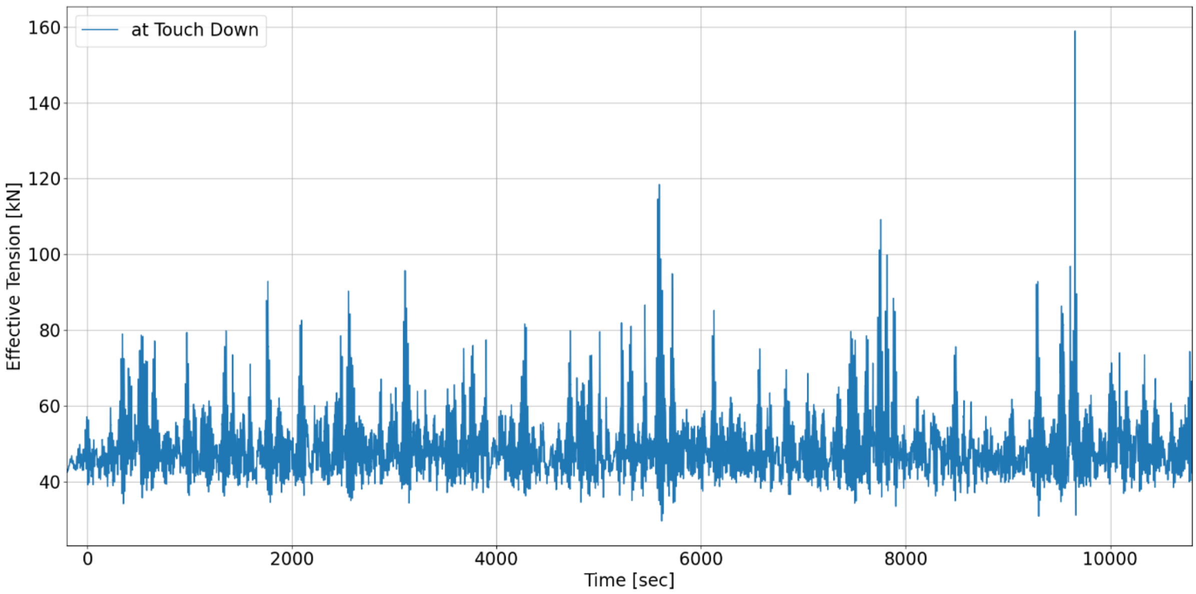

Figure 7.16 Extreme sea state: Effective tension at TDP in 180° wave direction on the dynamic cable.

From Figure 7.15 and Figure 7.16, it can be seen that the maximum tension on the dynamic cable occurs around 9000 seconds, where the A end is 199 [kN] and the touch down point (TDP) is 159 [kN]. At the End A (fairlead point) and the touch down point (TDP), the overall average tension of the rope is 120 [kN] and 65 [kN] respectively. The maximum effective tension absorbed by the mooring line at the End A (fairlead point) in the 0° to 180° wave direction is shown in Table 7.7.

Table 7.7 Extreme Sea State: maximum tension in mooring system

Wave Direction [deg]	Maximum Tension [kN]							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	1947.29	1320.62	1970.52	1330.01	10183.1	10121.15	1513.16	1522.31
30	1324.47	1872.31	3244.96	2022.16	3503.81	8397.84	1617.21	1626.39
60	4475.02	2244.47	8839.3	3679.88	2060.14	3232.61	1319.44	1283.48
90	1594.51	1785.67	10347.84	10005.78	1445.12	1902.64	1434.55	1851.95
120	2464.48	1409.21	3782.67	8515.96	2018.68	1335.71	2085.29	3086.06
150	2008.86	1312.9	2062.69	3215.84	2259.79	1700.39	3261.76	7789.72
180	1295.88	1903.57	1303.03	1887.13	1709.17	1509.91	9501.45	9539.98

From the above Table 7.7, the mooring line laid opposite to the wave direction absorbs the greatest amount of tension. The arrangement of the mooring line is shown in Figure 7.1. Mooring analysis. When the wave is heading at 0°, the maximum tension on the mooring lines 5 and 6 is 10183 [kN] and 10121 [kN], respectively. When the wave is heading at 90°, the maximum tension on the mooring lines 3 and 4 is 10347 [kN] and 10005 [kN], respectively, and when the wave is heading at 90°, the maximum tension on the mooring lines 7 and 8 is 9501 [kN] and 9539.98 [kN]when the wave is heading in 180°.

The maximum tension was noticed in the mooring line 3 in the 90° wave direction, and its time series of effective tension at End A (fairlead point) is shown in Figure 7.17. The time series for mooring lines 5 and 6 in 0°, mooring 4 in 90° and mooring lines 7 and 8 in 180° are shown in APPENDIX A.

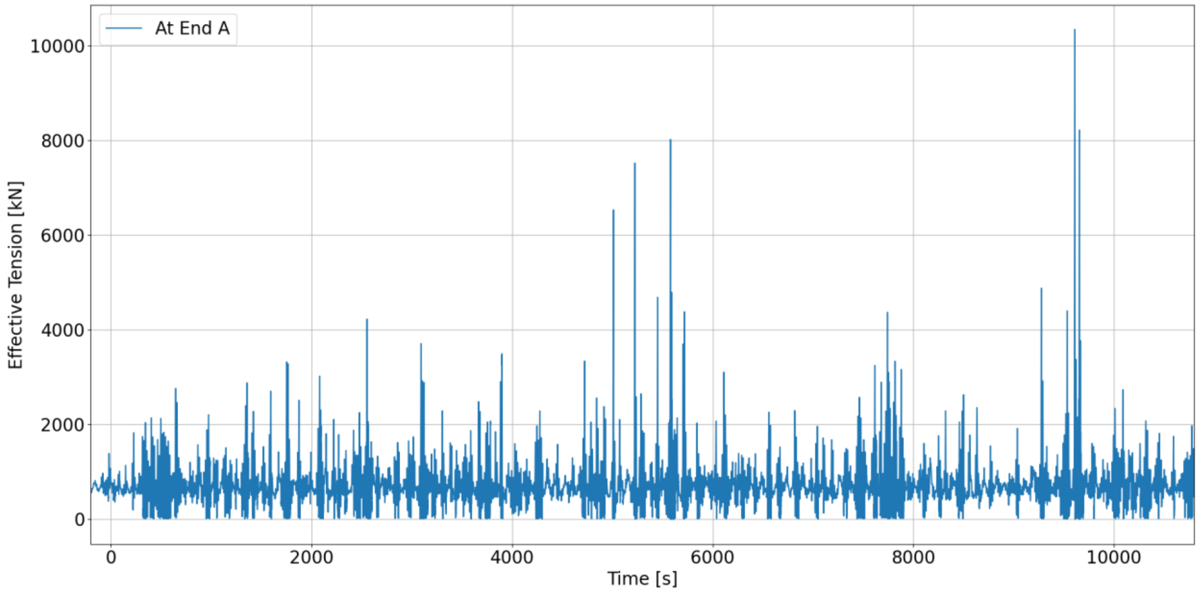

Figure 7.17 Extreme sea state: Tension in mooring line 3 at End A for 90° wave heading

Table 7.8 Extreme sea state: Floater motion

Wave Direction [deg]	Floater Motion					
	Max. Surge [m]		Max. Sway [m]		Max. Heave [m]	
	+ X axis	-X axis	+ Y axis	-Y axis	+ Z axis	-Z axis
0	16.56	11.15	0.05	0.02	11.07	13.76
30	13.48	6.64	7.62	3.91	10.70	13.49
60	8.09	3.79	13.32	6.74	10.65	13.48
90	0.43	0.00	16.68	11.55	11.04	13.65
120	4.26	7.79	13.34	6.66	10.67	13.51
150	7.13	13.19	7.58	3.92	10.71	13.49
180	9.98	16.25	0.02	0.03	11.00	13.78

It can be seen from Table 7.8 that at 0° wave direction, when the float drifts to the vicinity of the touch down point (TDP), the float absorbs the maximum surge motion of 16.56 [m] in the positive x-direction. This is the reason for the maximum bending moment on the dynamic cable. At 90°, the float absorbs the maximum rocking motion of 16.68 [m] in the positive y-direction because the float drifts later and will not affect the dynamic cable system. However, due to the elongation of the mooring line, the mooring lines 3 and 4 absorb the maximum tension. At 180°, when the float is away from the landing site, the float absorbs a maximum rocking motion of 16.25 [m] in the negative x-direction. This is the reason for the maximum tension on the dynamic cable. The average maximum heave motion is 11 [m] in the positive Z direction and 13.5 [m] in the negative Z-direction for all wave directions. This vertical movement of the float is deemed acceptable for the dynamic cable system.

As the conclusion of extreme sea conditions analysis, power cables and mooring systems can withstand such environmental conditions. In a dynamic cable system, the maximum bending moment and maximum tension are much lower than the allowable limit of the dynamic cable. The maximum allowable bending moment is 13.33 [kNm] and the minimum allowable breaking load is 2720 [kN] (see Table 5.1). In the mooring system, the maximum tension is also within the allowable range of the mooring chain under consideration, and the minimum allowable breaking load is 13570.00 [kN] (see Table 7.3).

7.3.2 Normal Sea State Condition

This section summarizes the dynamic analysis results of the optimized lazy wave configuration and optimized mooring system under normal sea conditions mentioned in Table 7.1.

For wave headings from 0° to 180°, the interval is 30°, and the running time is a 3-hour storm period. The maximum bending moment and effective tension of the dynamic cable system at End A (fairlead point) and touch down point (TDP) under the three load conditions, the maximum tension of the mooring system fairlead point and the maximum surge and heave of the floater are shown in Figure 7.18, Figure 7.19, Figure 7.20, Figure 7.21, Figure 7.22 and, Figure 7.23. As well as the detailed table for three load conditions, see APPENDIX B.

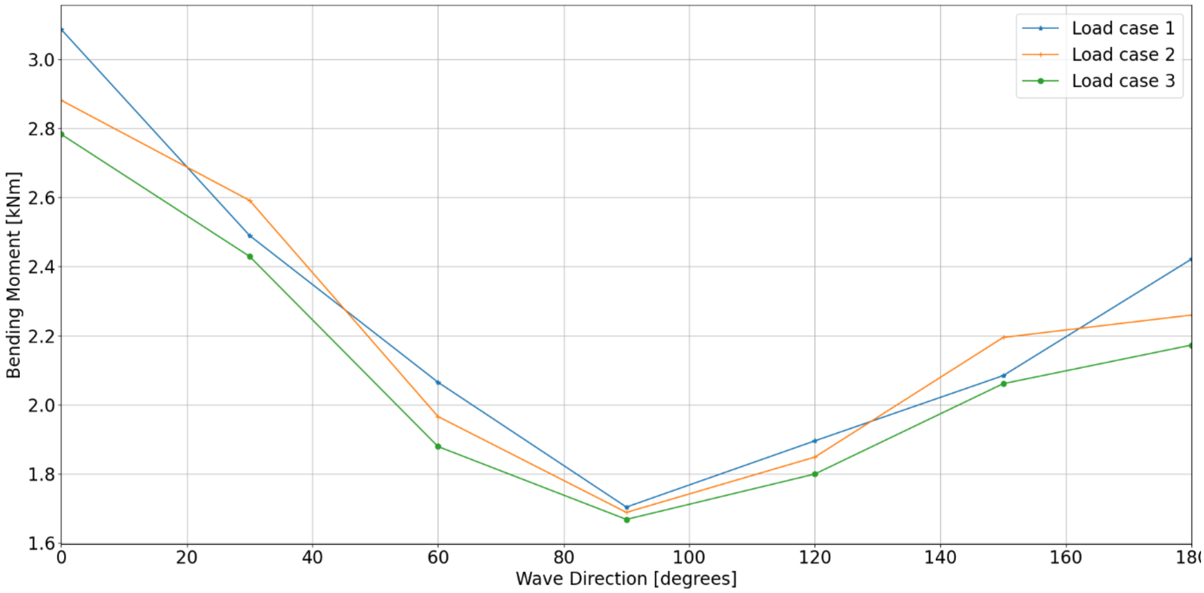

Figure 7.18 Normal sea state: Maximum Bending moment in dynamic cable

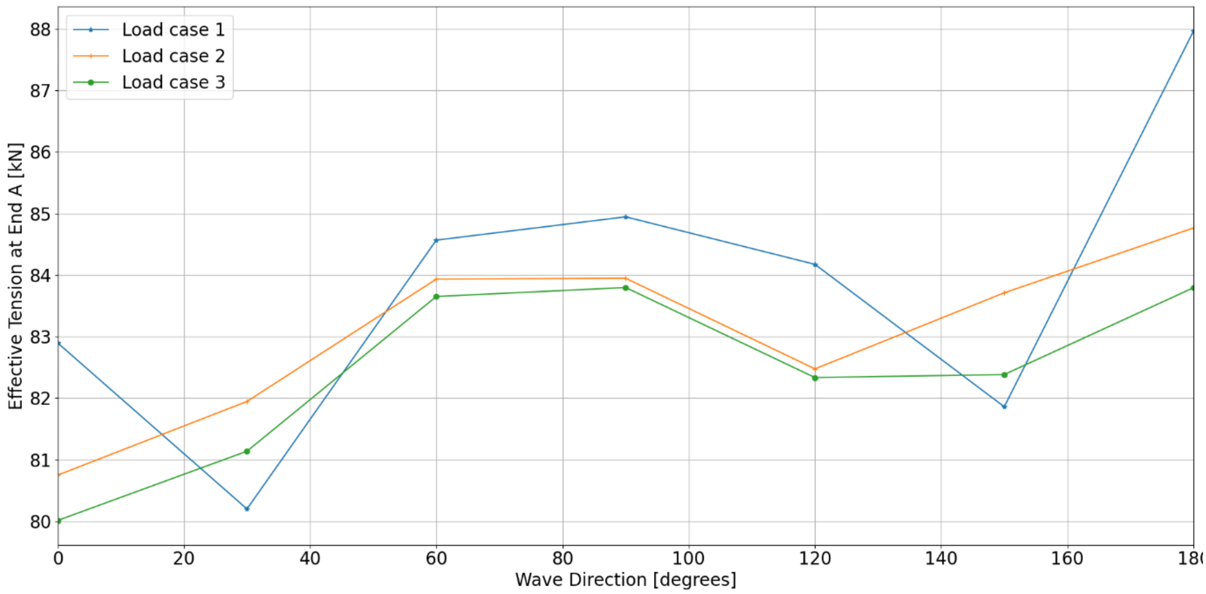

Figure 7.19 Normal sea state: Maximum effective tension at End A in dynamic cable

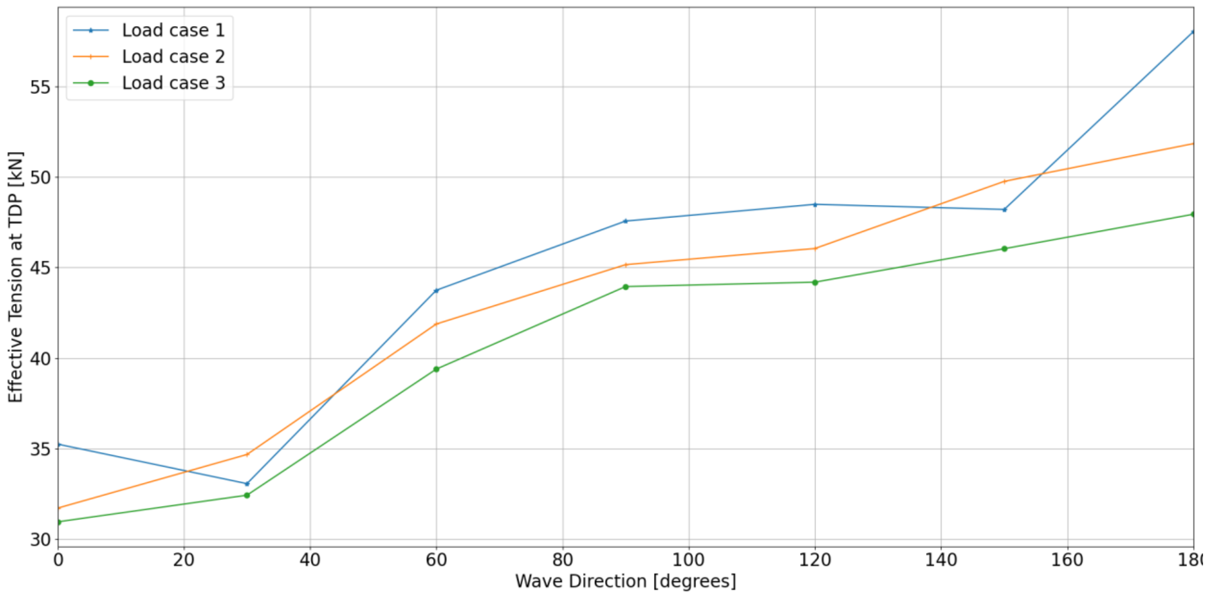

Figure 7.20 Normal sea state: Maximum effective tension at Touch down point (TDP) in dynamic cable

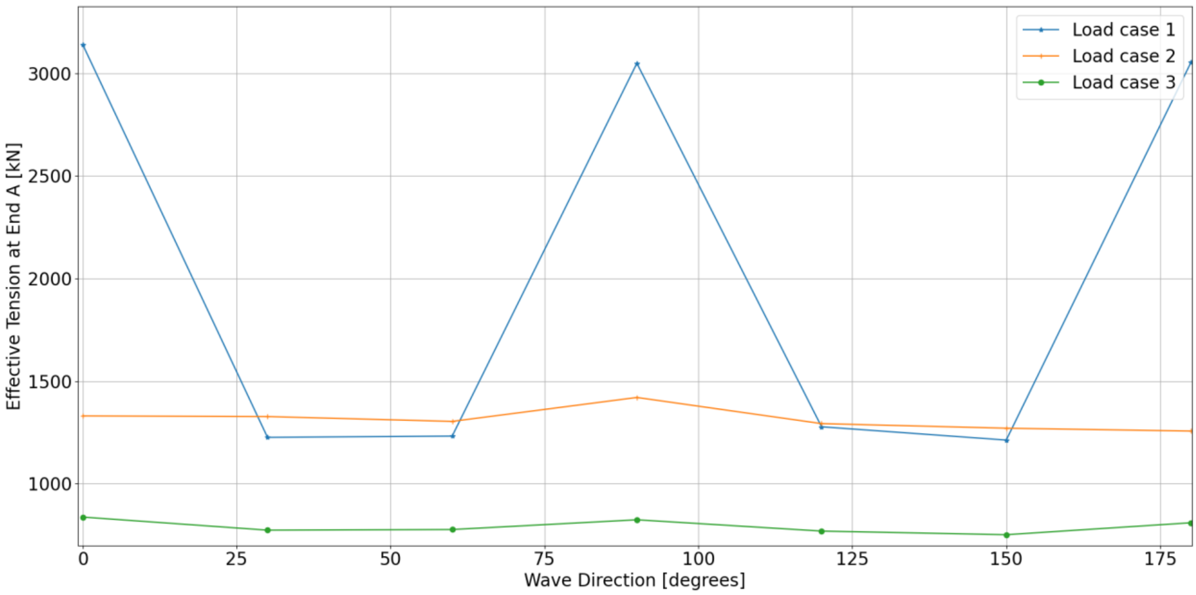

Figure 7.21 Normal sea state: Maximum effective tension at End A in mooring line

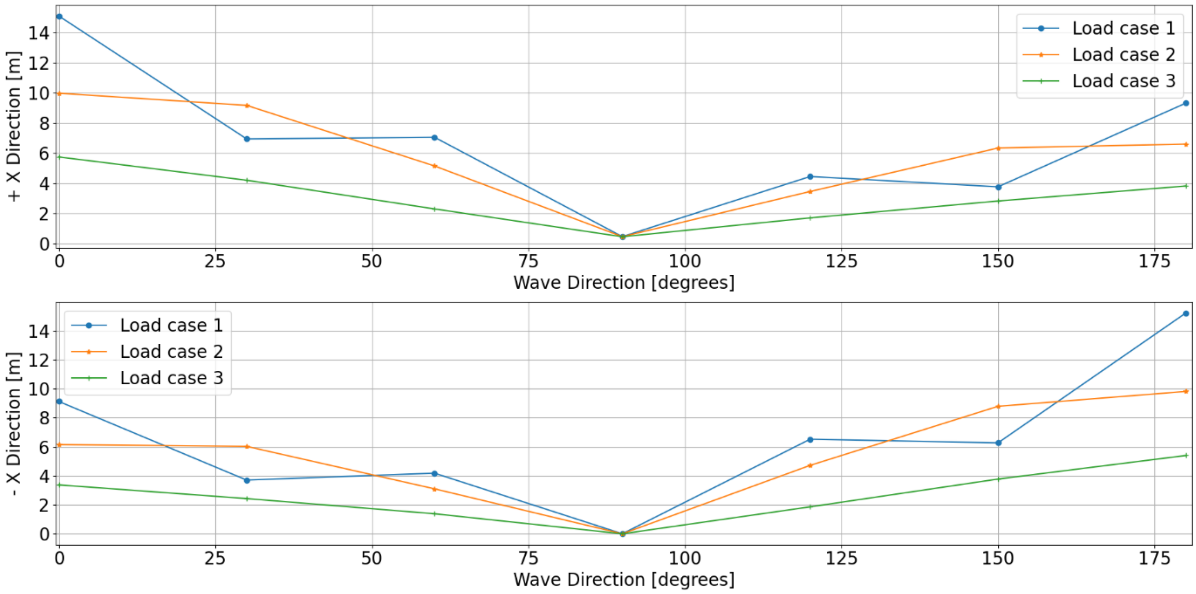

Figure 7.22 Normal sea state: Maximum surge motion in the floater

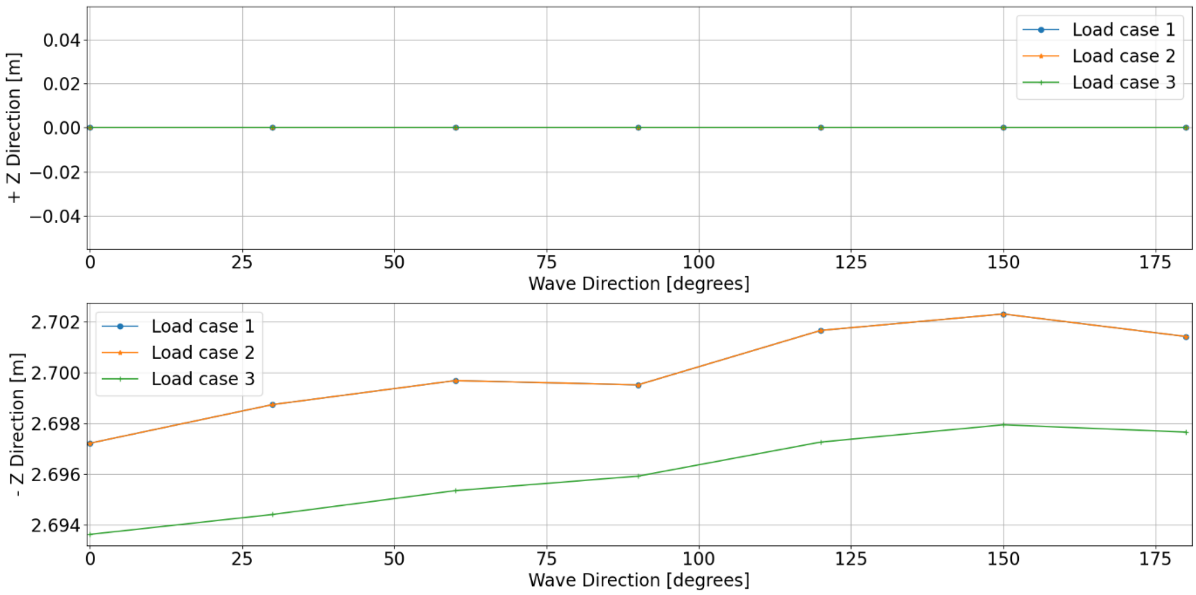

Figure 7.23 Normal sea state: Maximum heave motion in the floater

As can be seen from the above figures, load case 1 has a greater impact on the two systems. This is because the load case 1 has a shorter wave period of 3 seconds (i.e. the zero-crossing period (Tz)), so the translational movement of the floater has a greater impact on the dynamic cable and mooring system.

Compared with other load cases, in load case 1, the maximum bending moment of the dynamic cable occurs in the wave direction 0°, as shown in Figure 7.24.

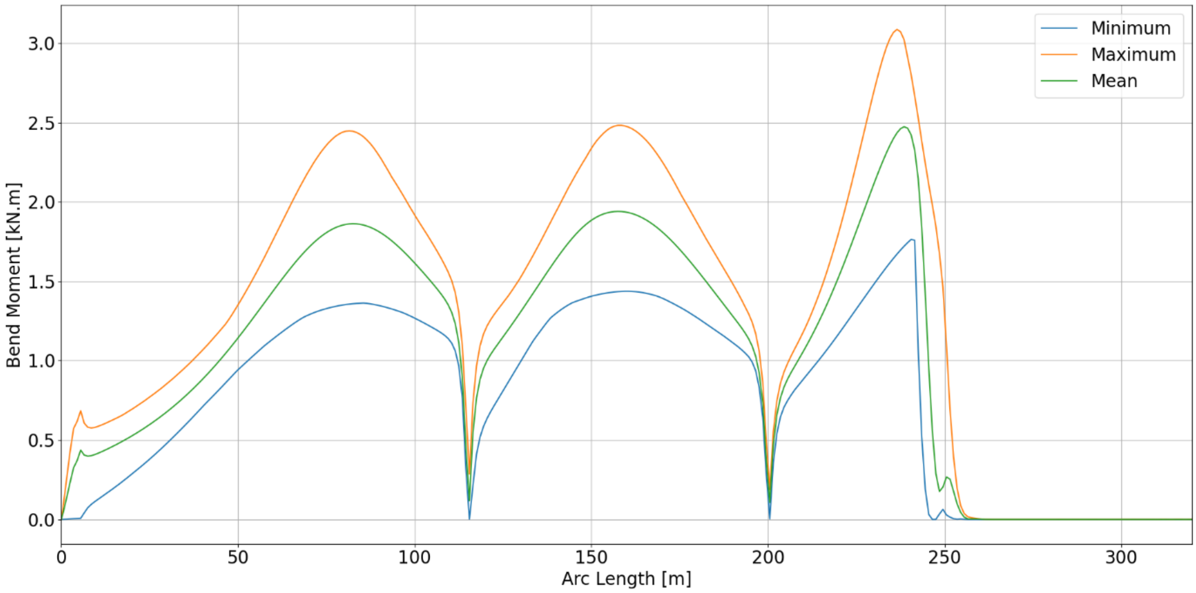

Figure 7.24 Normal Sea state: Load case 1 Bending Moment in 0° wave direction

From the above Figure 7.24, the maximum bending moment is 3.12 [kN.m] appears at the last arc length of the moving cable at 231 [m]; in addition to the buoyancy module area, there is also a peak bending moment of 2.5 [kN]. This is because the wave period is short, and the waves are continuously generated and sollecitate the floating section. It increases the impact movement of the float in the positive X direction, resulting in increase in bending moment due to reduction of tension in the cable.

In load case 1, the maximum effective tension on the dynamic cable occurs in the 180° wave direction. The effective tension time series of end A and the grounding point are shown in Figure 7.25 and Figure 7.26.

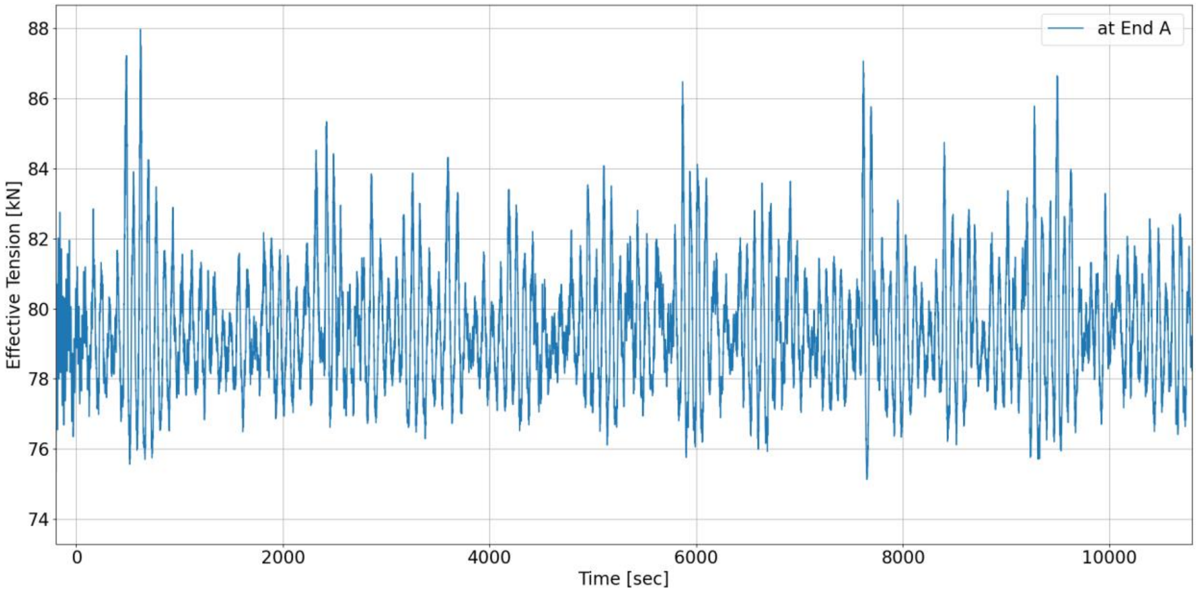

Figure 7.25 Normal Sea state: Load case 1 Effective Tension at End A in 180° wave direction

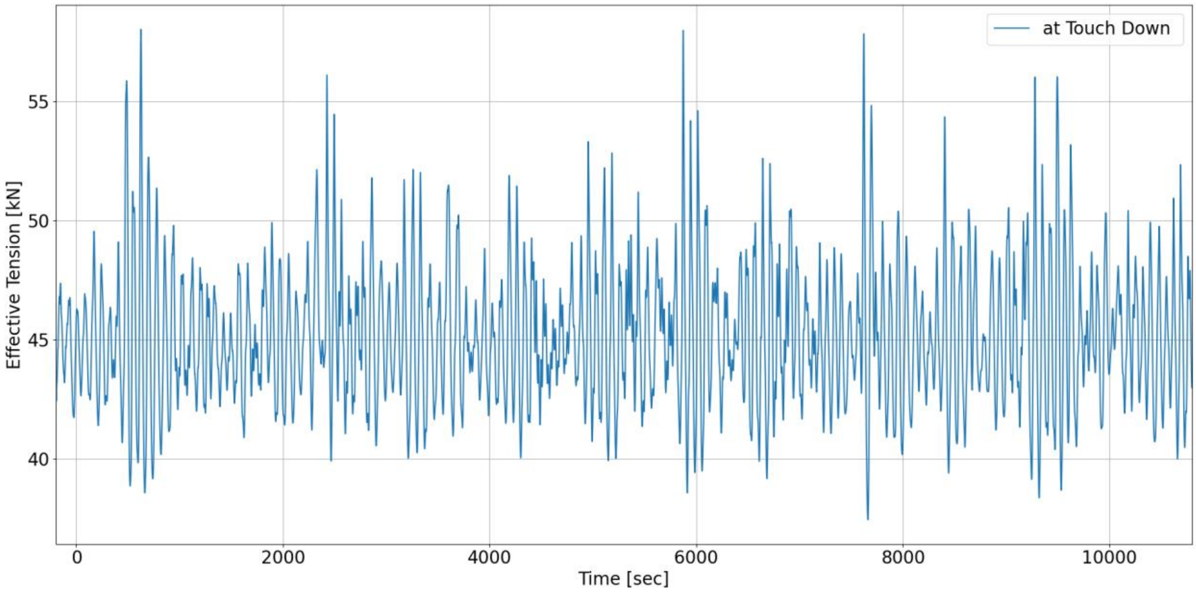

Figure 7.26 Normal Sea state: Load case 1 Effective Tension at TDP in 180° wave direction

From Figure 7.25 and Figure 7.26, it can be seen that the maximum tension at end A is 88 [kN], and the maximum tension at the touch down is 62 [kN], which occurs in a period of 621 seconds. The average maximum tension at the fairlead is 83 [kN], and the average maximum tension at the touch down point (TDP) is 48 [kN]. The reason for the increased tension is that the floats drift away from the touch down point (TDP).

It is also interesting from the Figure 7.21, that compared with other load cases, load case 1 has a greater impact. The mooring line laid opposite to the wave direction absorbs most of the load. Refer to Figure 7.1 for the layout of the mooring line.

For load case 1, the maximum tension on the mooring line with a wave direction of 0° to 180° is shown in Table 7.9.

Table 7.9 Normal sea state: Load case 1 maximum tension of mooring lines

Direction [deg]	Maximum Tension [kN]							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	762.17	666.16	765.40	664.33	3122.24	3140.32	1235.41	1234.80
30	767.93	882.17	1225.45	956.39	895.35	1201.91	804.19	694.89
60	749.19	869.30	1231.58	928.06	894.75	1223.64	845.84	711.57
90	1328.54	1330.57	3049.65	2968.89	663.37	748.50	642.62	712.41
120	888.38	749.78	939.86	1276.91	866.37	739.12	859.03	1141.47
150	879.53	758.89	933.54	1212.22	797.57	713.81	853.38	1080.78
180	667.31	763.67	666.57	765.96	1295.36	1296.23	3053.96	3052.80

It can be seen from Table 7.9, that when the wave is heading at 0°, the maximum tension on the mooring lines 5 and 6 is 3122 [kN] and 3140 [kN], respectively. When the wave is heading at 90°, the maximum tension on the mooring lines 3 and 4 is 3049 [kN] and 2968 [kN], respectively, and when the wave is heading at 90°, the maximum tension on the mooring lines 7 and 8 is 3054 [kN] and 3053 [kN] when the wave is heading in 180°.

The maximum tension appears at the mooring line 5 in the 0° wave direction, and its effective tension time sequence at end A is shown in Figure 7.27. Other time series of mooring line 6 for wave direction 0°, mooring lines 3 and 4 for wave direction 90°, and mooring lines 7 and 8 for wave direction 180° are shown in the APPENDIX C.

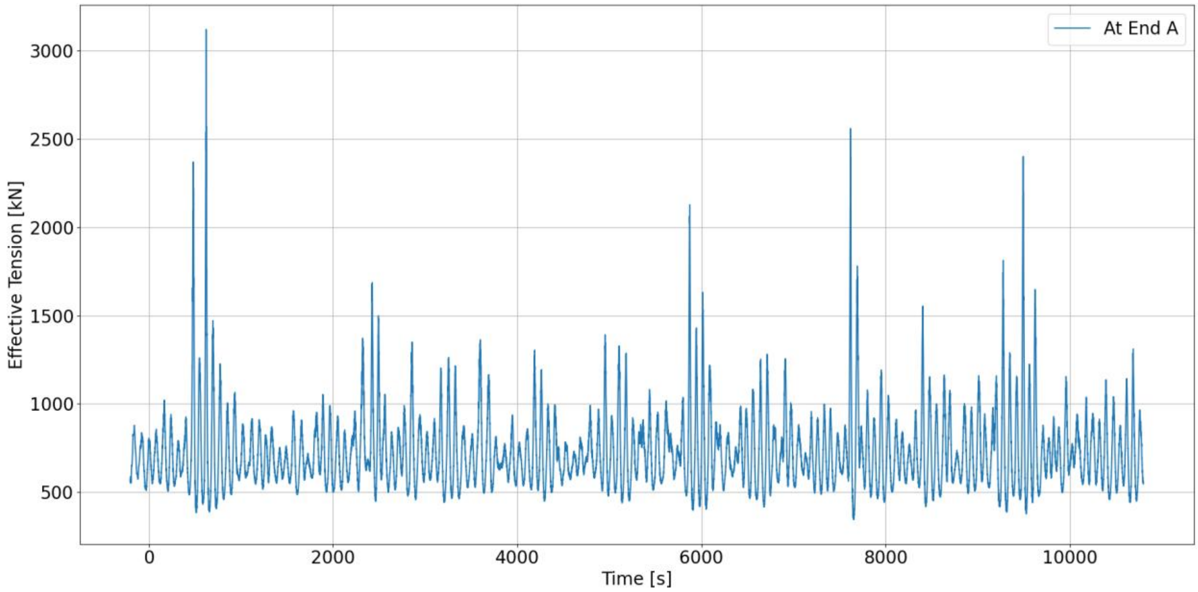

Figure 7.27 Normal sea state: Maximum tension in mooring line 5 in 0° wave direction for load case 1

It can be concluded from this analysis that the optimized dynamic cable and mooring system is completely stable for a significant wave height of 3.5 [m] for three different zero-crossing wave periods [Tz] of 3, 5.5 and 7 seconds. Since the platform experienced the greatest surge motion, the greatest impact was noticed in the lower wave period of 3 seconds. In general, the heave motion is controlled, and the maximum value is far below the allowable limit of the mechanical properties of the dynamic cable and mooring line.

8 CONCLUSION

According to this thesis, a dynamic power cable configuration and mooring system for a floating offshore wind power platform under extreme and normal environmental conditions are proposed. It provides a good starting point for further study of the detailed optimization of the two systems.

Initially, a dynamic cable configuration was set up, investigating four possible options for catenary configurations in OrcaFlex, and, based on the performed static analysis, the lazy wave configuration was selected. Then a sensitive analysis of the lazy wave configuration was carried out. The optimized catenary configuration of the dynamic cable has been found by performing several sensitivity on the optimal buoyancy module and the cable section length.

A preliminary mooring analysis was carried out on the catenary mooring system. An optimized mooring system under extreme environmental conditions was obtained by optimizing the chain diameter and the length of the mooring rope.

Finally, a coupled analysis of the dynamic power cable and mooring system was carried out, and it was found that both systems sustained the extreme environmental conditions (design condition). Moreover, in order to verify the behaviour of both systems during its normal life , the analysis was repeated for normal environmental conditions. It was noticed that the shorter wave period has a higher impact on the system than other load cases in normal conditions.

9 FUTURE WORK

This thesis is the starting point to model the dynamic cable and mooring system for offshore floating platforms. Further, for this research work to be successful, a long period of research work is required. An in-depth study and analysis will help with further development of both system. The topic's that are to be explored in future:

• Fatigue analysis for dynamic power cable.

• Marine growth analysis for dynamic cable and mooring chain

• Vortex induced vibration (VIV)

• Optimization of mooring lines and fatigue analysis

• Model Testing

• Full-Scale Testing

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APPENDIX A

Extreme sea state: Time series for mooring lines 5 and 6 in 0° wave direction, mooring lines 4 in 90° wave direction and mooring lines 7 and 8 in 180° wave direction.

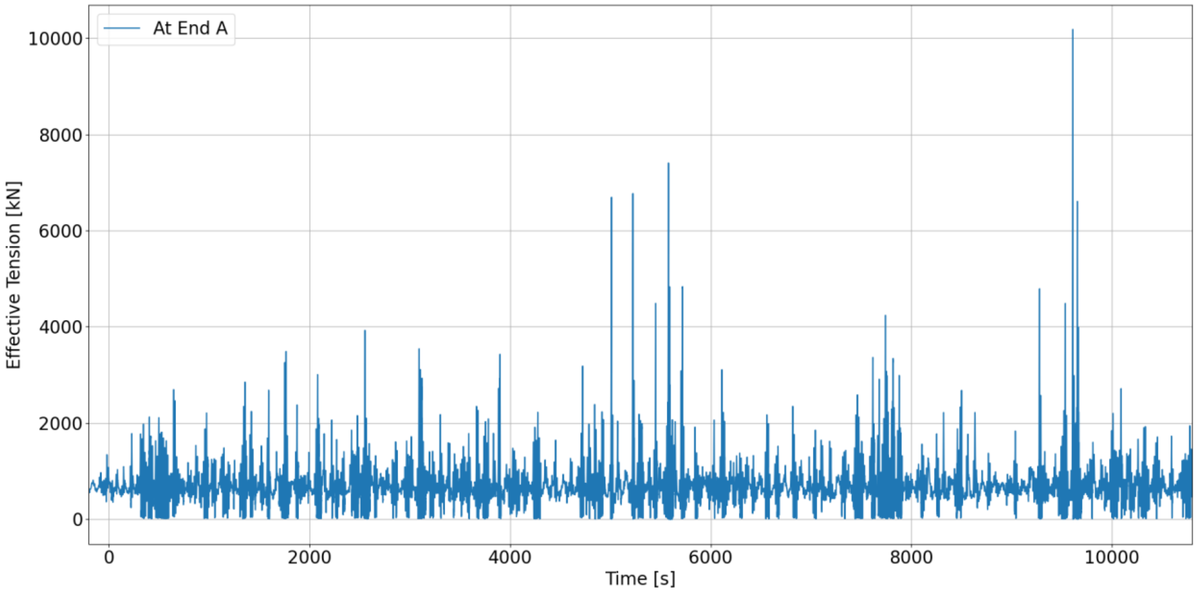

Figure 0.1 Extreme sea state: Effective tension of mooring line 5 in 0° wave direction

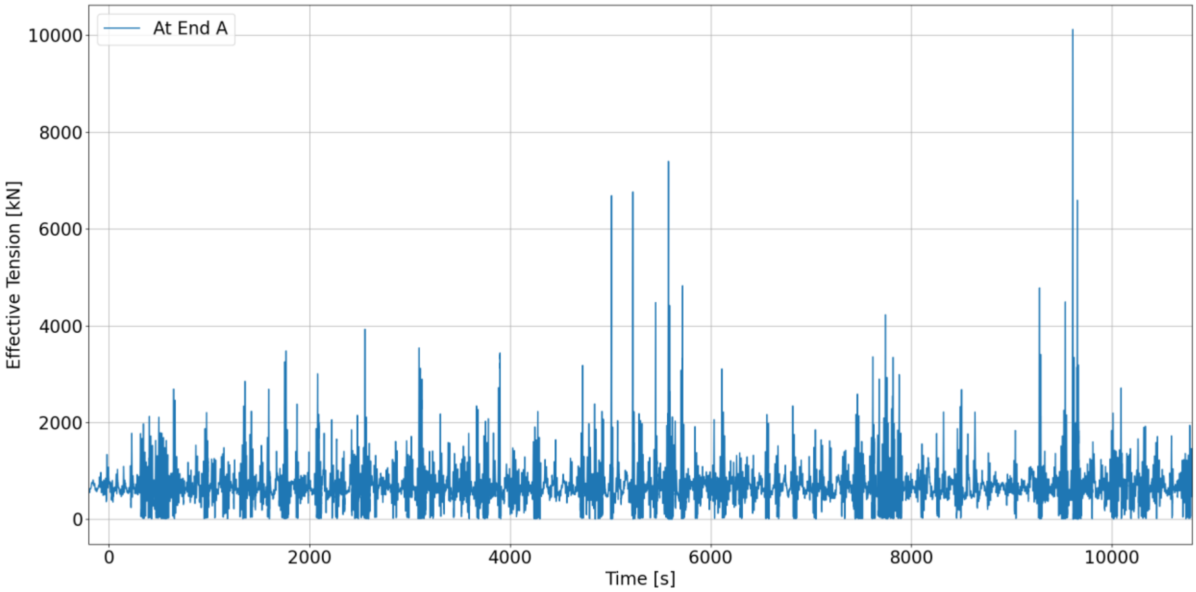

Figure 0.2 Extreme sea state: Effective tension of mooring line 6 in 0° wave direction

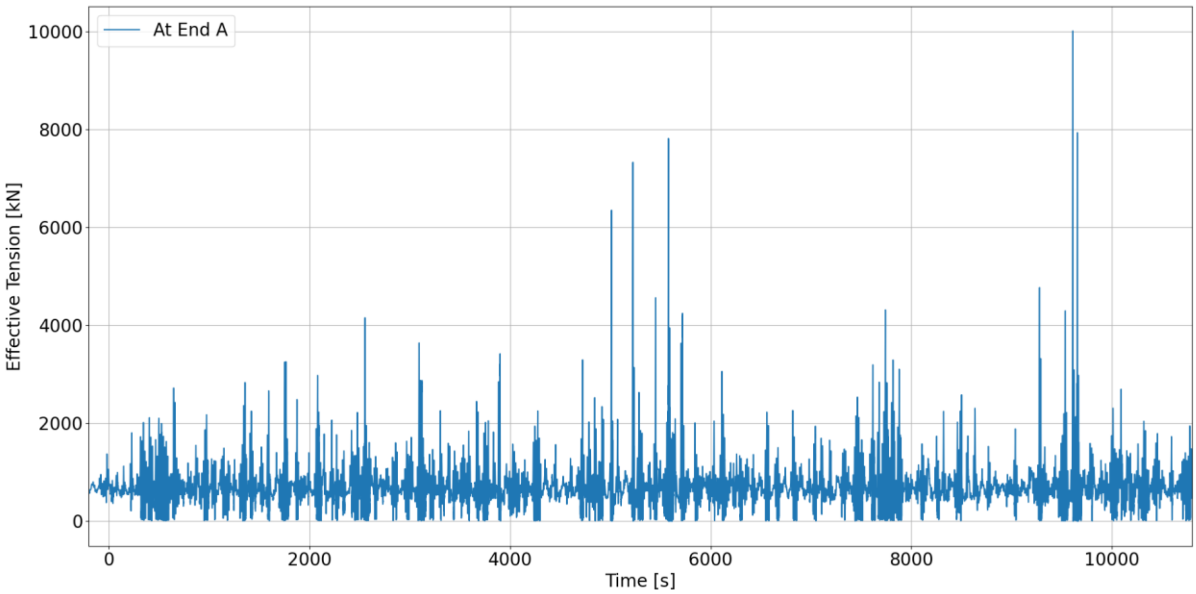

Figure 0.3 Extreme sea state: Effective tension of mooring line 4 in 90° wave direction

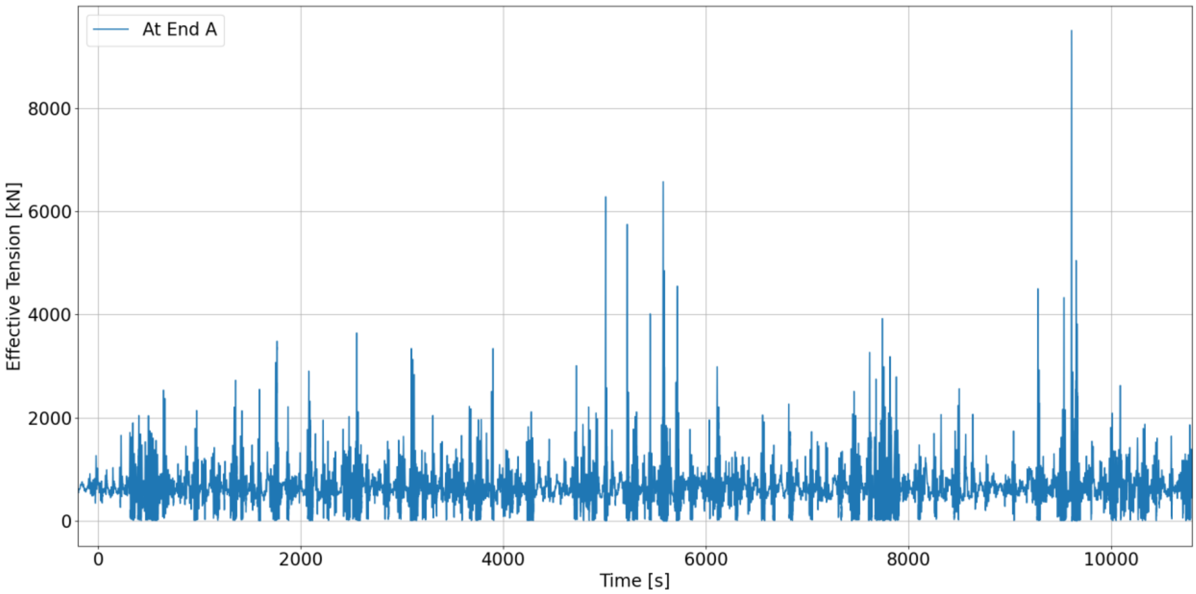

Figure 0.4 Extreme sea state: Effective tension of mooring line 7 in 180° wave direction

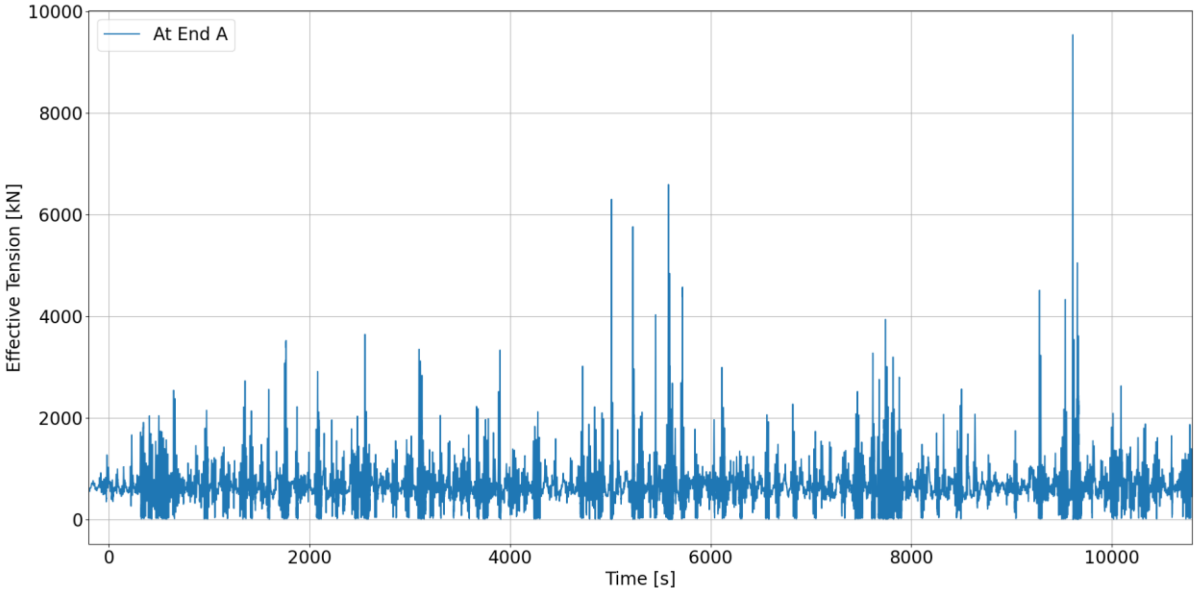

Figure 0.5 Extreme sea state: Effective tension of mooring line 8 in 180° wave direction

APPENDIX B

Normal sea state: Load case 1 (Hs: 3.5 [m] & Tz: 3 [sec])

Table 0.1 NSS: Load case 1 Bending moment and effective tension in dynamic cable

Dynamic Cable with Floater						
Direction [deg]	Bend Moment [kN.m]		Tension at End A [kN]		Tension at TDP [kN]	
	Max	Mean	Max	Min	Max	Min
0	3.09	0.99	82.90	71.36	35.25	19.51
30	2.49	1.00	80.20	73.00	33.07	24.92
60	2.07	0.97	84.57	75.36	43.75	30.80
90	1.70	0.92	84.95	77.07	47.57	39.31
120	1.90	0.92	84.17	75.74	48.49	39.89
150	2.08	0.91	81.86	74.15	48.21	40.10
180	2.42	0.87	87.97	73.99	58.03	37.46

Table 0.2 NSS: Load case 1 Floater motion

Floater Motion						
Direction [deg]	Surge		Sway		Heave	
	+ X axis	-X axis	+ Y axis	-Y axis	+ Z axis	-Z axis
0	15.12	9.12	0.04	0.03	0.00	2.70
30	6.95	3.70	6.94	4.53	0.00	2.70
60	7.06	4.18	6.87	4.22	0.00	2.70
90	0.45	0.00	14.37	9.56	0.00	2.70
120	4.45	6.52	7.10	4.36	0.00	2.70
150	3.76	6.27	6.83	4.42	0.00	2.70
180	9.33	15.22	0.03	0.01	0.00	2.70

Table 0.3 NSS: Load case 1 Effective tension in mooring lines

Mooring Chain								
Direction [deg]	Maximum Tension [kN]							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	762.17	666.16	765.40	664.33	3122.24	3140.32	1235.41	1234.80
30	767.93	882.17	1225.45	956.39	895.35	1201.91	804.19	694.89
60	749.19	869.30	1231.58	928.06	894.75	1223.64	845.84	711.57
90	1328.54	1330.57	3049.65	2968.89	663.37	748.50	642.62	712.41
120	888.38	749.78	939.86	1276.91	866.37	739.12	859.03	1141.47
150	879.53	758.89	933.54	1212.22	797.57	713.81	853.38	1080.78
180	667.31	763.67	666.57	765.96	1295.36	1296.23	3053.96	3052.80

Normal sea state: Load case 2 (Hs: 3.5 [m] & Tz: 5 [sec])

Table 0.4 NSS: Load case 2 Bending moment and effective tension in dynamic cable

Dynamic Cable with Floater						
Direction [deg]	Bend Moment [kN.m]		Tension at End A [kN]		Tension at TDP [kN]	
	Max	Mean	Max	Min	Max	Min
0	2.88	0.97	80.75	71.94	31.72	21.25
30	2.59	1.00	81.95	73.01	34.68	23.93
60	1.97	0.96	83.93	75.38	41.88	32.46
90	1.69	0.92	83.95	77.10	45.16	39.58
120	1.85	0.92	82.48	75.73	46.05	40.38
150	2.20	0.91	83.71	74.16	49.76	38.81
180	2.26	0.89	84.77	73.97	51.84	38.90

Table 0.5 NSS: Load case 2 Floater motion

Floater Motion						
Direction [deg]	Surge		Sway		Heave	
	+ X axis	-X axis	+ Y axis	-Y axis	+ Z axis	-Z axis
0	9.99	6.15	0.02	0.01	0.00	2.70
30	9.18	6.03	4.74	3.18	0.00	2.70
60	5.15	3.10	8.55	5.80	0.00	2.70
90	0.45	0.00	9.53	5.97	0.00	2.70
120	3.45	4.72	8.64	5.83	0.00	2.70
150	6.34	8.79	4.84	3.27	0.00	2.70
180	6.61	9.81	0.01	0.01	0.00	2.70

Table 0.6 NSS: Load case 2 Effective tension in mooring lines

Mooring Chain								
Direction [deg]	Maximum Tension [kN]							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	683.85	636.80	685.66	634.27	1329.96	1329.45	891.68	894.89
30	660.18	788.91	971.56	704.59	1058.24	1326.68	900.19	812.31
60	841.31	922.23	1303.18	1044.56	707.03	965.46	760.75	633.72
90	917.01	912.30	1420.01	1394.76	625.24	673.83	606.36	647.74
120	933.22	824.28	1057.83	1292.38	777.13	658.99	689.75	924.17
150	810.93	665.83	708.18	971.13	923.58	851.38	1008.42	1269.96
180	639.73	682.45	640.22	680.57	940.43	939.43	1253.26	1256.10

Normal sea state: Load case 3 (Hs: 3.5 [m] & Tz: 7 [sec])

Table 0.7 NSS: Load case 3 Bending moment and effective tension in dynamic cable

Dynamic Cable with Floater						
Direction [deg]	Bend Moment [kN.m]		Tension at End A [kN]		Tension at TDP [kN]	
	Max	Mean	Max	Min	Max	Min
0	2.78	0.97	80.01	71.71	30.96	22.43
30	2.43	0.99	81.14	72.79	32.43	25.81
60	1.88	0.96	83.65	75.27	39.39	34.15
90	1.67	0.92	83.80	77.13	43.95	39.75
120	1.80	0.93	82.33	75.74	44.19	41.24
150	2.06	0.92	82.38	74.16	46.04	40.23
180	2.17	0.89	83.80	73.97	47.94	40.00

Table 0.8 NSS: Load case 3 Floater motion

Floater Motion						
Direction [deg]	Surge		Sway		Heave	
	+ X axis	-X axis	+ Y axis	-Y axis	+ Z axis	-Z axis
0	5.75	-3.37	0.01	-0.01	0.00	-2.69
30	4.20	-2.43	1.94	-1.37	0.00	-2.69
60	2.30	-1.38	3.74	-2.33	0.00	-2.70
90	0.44	0.00	5.15	-3.05	0.00	-2.70
120	1.70	-1.86	3.78	-2.33	0.00	-2.70
150	2.82	-3.77	1.95	-1.40	0.00	-2.70
180	3.82	-5.40	0.01	0.00	0.00	-2.70

Table 0.9 NSS: Load case 3 Effective tension in mooring lines

Mooring Chain								
Direction [deg]	Maximum Tension [kN]							
	Mooring 1	Mooring 2	Mooring 3	Mooring 4	Mooring 5	Mooring 6	Mooring 7	Mooring 8
0	635.00	606.63	636.28	605.21	836.49	836.11	696.36	698.34
30	615.88	644.90	699.06	635.12	721.20	772.84	665.30	651.27
60	667.52	679.26	775.91	709.16	629.99	696.58	623.08	596.45
90	710.57	707.52	823.34	814.56	598.27	621.60	584.37	604.78
120	681.43	666.23	713.46	768.29	645.57	617.95	613.69	666.51
150	650.31	618.09	641.28	696.76	688.94	674.02	700.19	750.60
180	609.28	632.24	609.41	631.67	724.79	723.90	807.59	808.83

APPENDIX C

Normal sea state: Load case 1 Time series for mooring lines 6 in 0° wave direction, mooring lines 3 and 4 in 90° wave direction and mooring lines 7 and 8 in 180° wave direction.

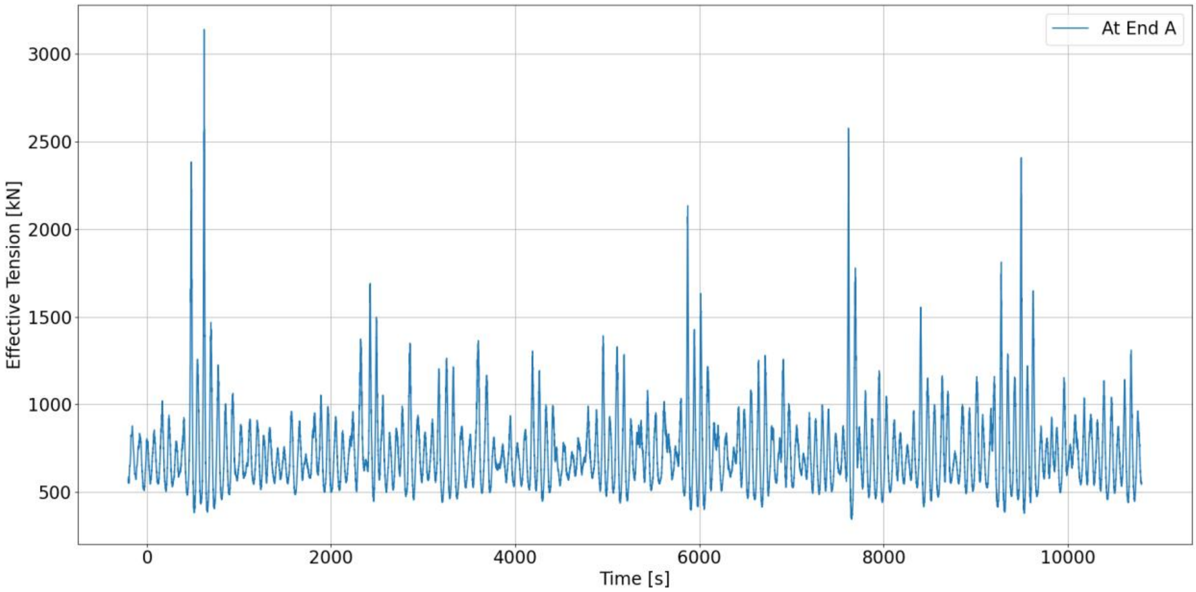

Figure 0.1 Normal sea state: Maximum tension in mooring line 6 in 0◦ wave direction for load case 1

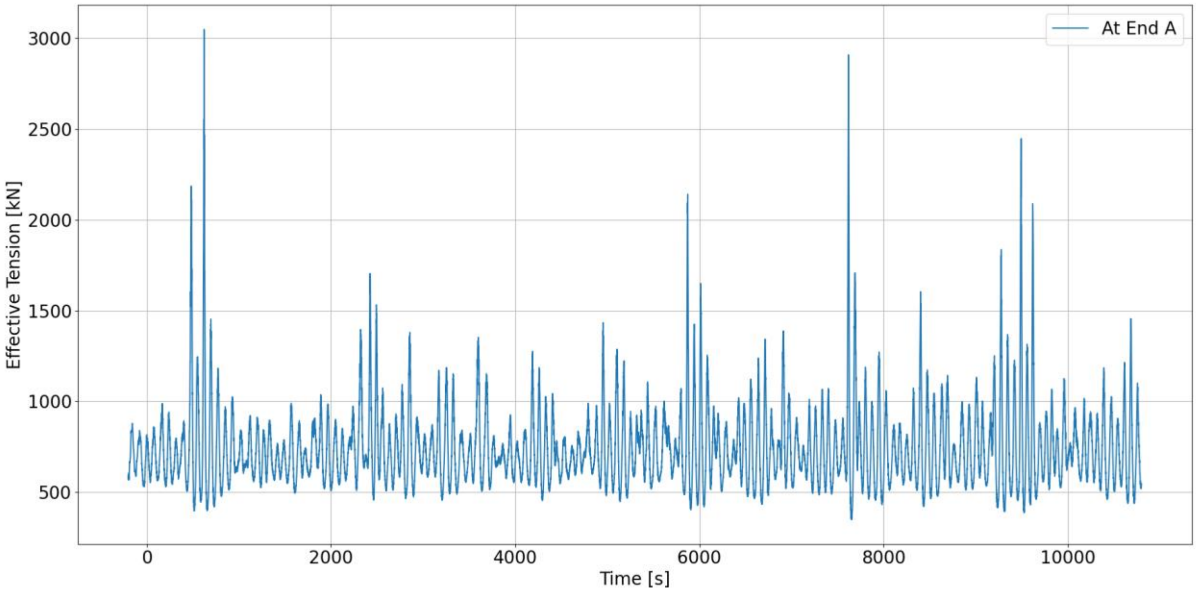

Figure 0.2 Normal sea state: Maximum tension in mooring line 3 in 90 degrees wave direction for load case 1

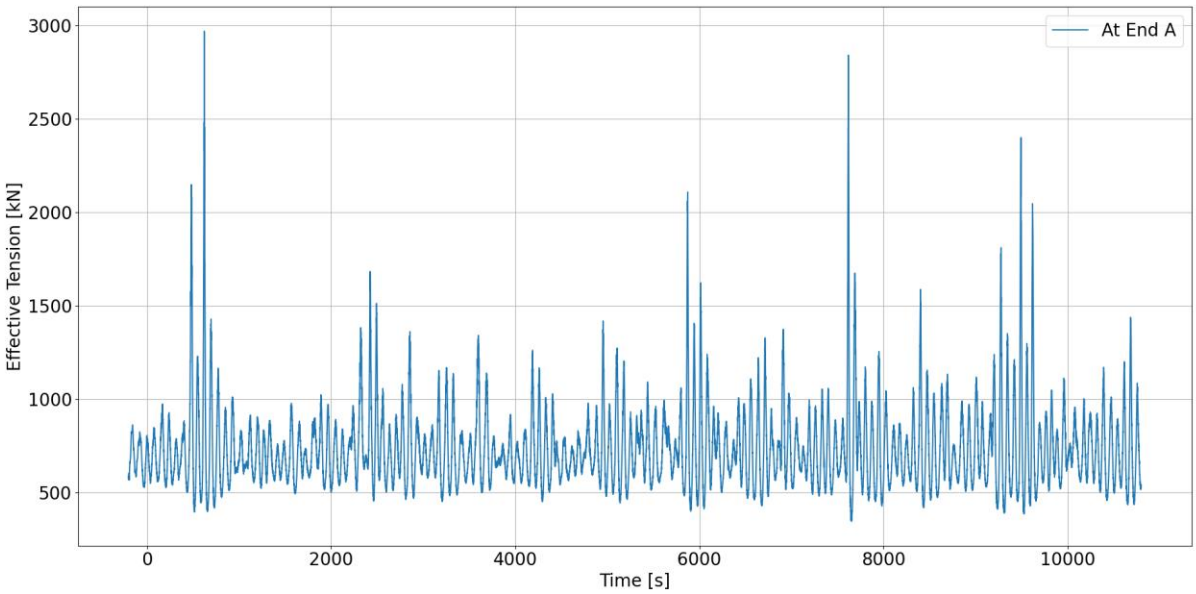

Figure 0.3 Normal sea state: Maximum tension in mooring line 4 in 90◦ wave direction for load case 1

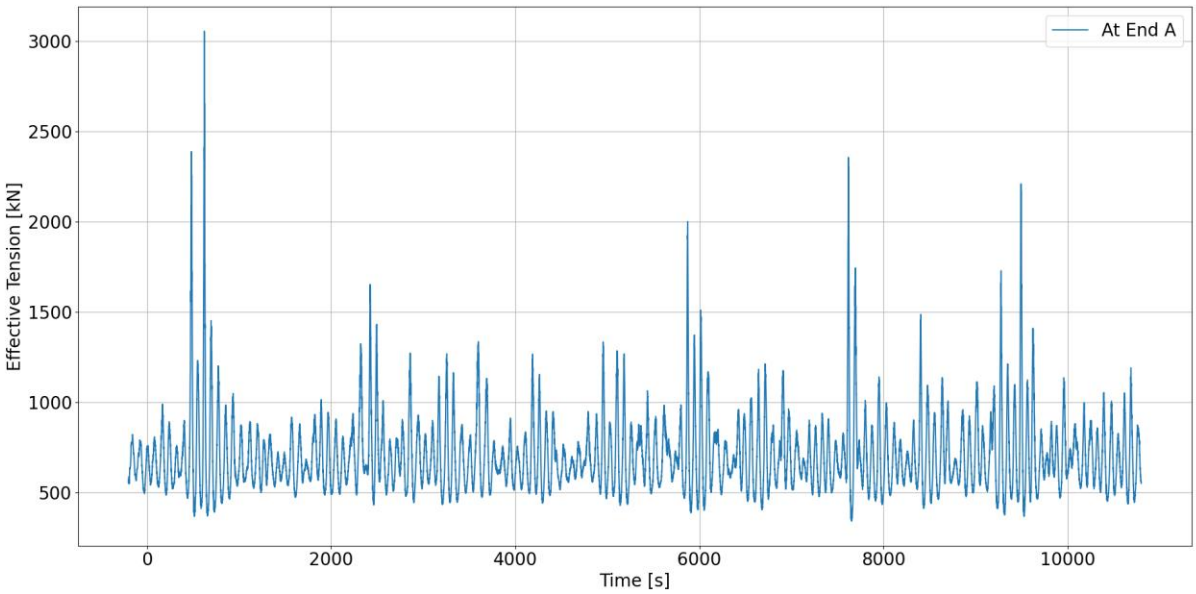

Figure 0.4 Normal sea state: Maximum tension in mooring line 7 in 180◦ wave direction for load case 1

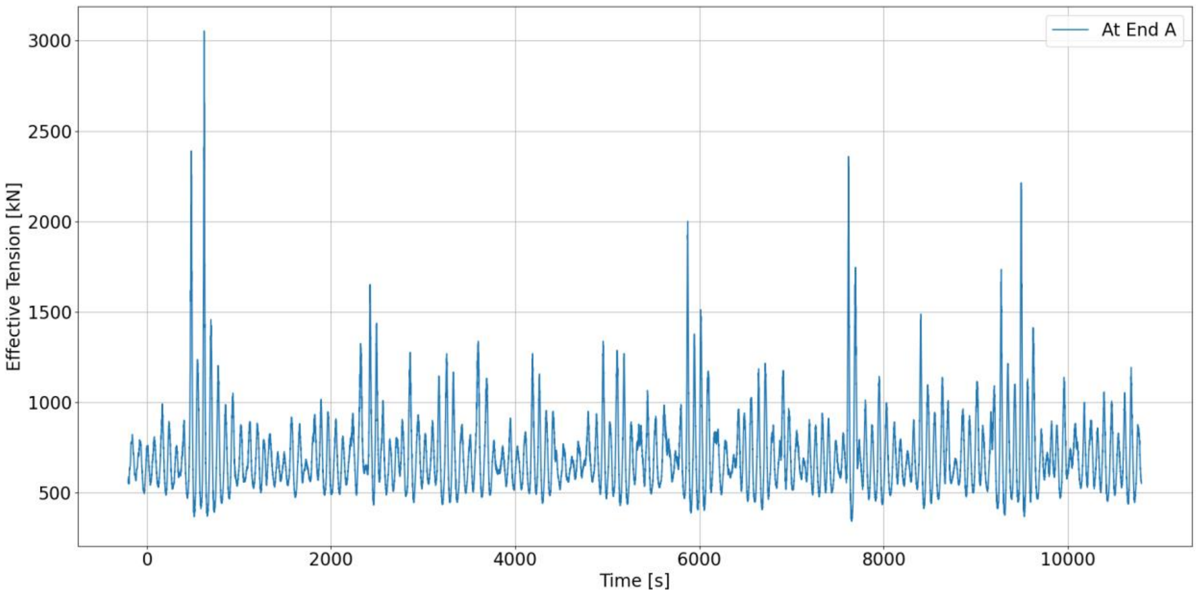

Figure 0.5 Normal sea state: Maximum tension in mooring line 8 in 180◦ wave direction for load case 1