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Study of Dynamic Cables Layout of Floating Wind Turbines to Optimize Installation and Cost

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by

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LIST OF ABBREVIATIONS

BEM	Boundary element method
CAPEX	Capital expenditure
CBM	Condition based maintenance
CFD	Computational fluid dynamics
DAS	Distributed acoustic sensing
DLC	Design load case
DPS	Dynamic positioning system
DSS	Distributed strain sensing
DTS	Distributed temperature sensing
EIA	Environmental impact assessment
EMI	Electromagnetic interference
EPR	Ethylene propylene rubber
ESS	Extreme sea state
FEM	Finite element method
FOWP	Floating offshore wind platform
FOWT	Floating offshore wind turbine
FSI	Fluid structure interaction
GBF	Gravity based foundation
HOWT	Higher order wave theory
IEA	International energy agency
LWT	Linear wave theory
MBR	Minimum bend radius
MBL	Maximum breaking load
OPEX	Operational expenditure
OTDR	Optical time domain reflectometry
PD	Partial discharge
ROV	Remotely operated vehicles
TLP	Tension leg platform
UV	Ultraviolet
XLPE	Cross linked polyethylene

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ABSTRACT

Offshore wind turbines have revolutionized renewable energy, harnessing stronger and more consistent winds at sea compared to land. These massive structures generate substantial electricity with minimal environmental impact, making them a cornerstone in the global shift toward sustainable energy. Their rapid expansion underscores their growing importance in the transition to a cleaner, resilient energy future.

A significant leap in this technology is the transition from fixed to floating offshore wind structures, enabling power generation in deeper, wind-rich ocean areas. This shift requires dynamic cables capable of enduring the motion of these structures and harsh sea conditions without compromising transmission efficiency. Among the various configurations of dynamic cables, catenary and lazy wave designs are critical.

This document presents a comprehensive comparative analysis of two dynamic power cable configurations, catenary and lazy wave, for a 15 MW semi-submersible floating offshore wind turbine (FOWT). Conducted across varying water depths from 50 to 200 meters, the study aims to identify the most suitable configuration for optimizing operational efficiency and reliability under challenging marine conditions.

Each layout has its pros and cons depending on water depth and structure properties, and this thesis will conclude with the best-fit layout for various water depth. This document analyses these two configurations for a catenary moored semi-submersible structure, focusing on the high-motion and load conditions under extreme environments.

Data for this analysis is provided by Iberdrola and Seaplace. The study examines environmental conditions at 0° and 180° directions to capture maximum tension and structure excursion. Utilizing a 15 MW floating structure from the Orcina platform, aligned with current projects, Seaplace's internal tool designs the mooring using two-dimensional static analysis. This incorporates wind, current, and wave coefficients, as detailed in Section 8.1. Both catenary and lazy wave layouts maintain consistent lengths, properties, and anchor points, with the lazy wave configuration including ancillaries.

Using a catenary system as the reference scenario, the FOWT is moored to provide a robust mooring for critical analysis. Through extensive simulations and evaluations, this study extracts essential insights into the performance and feasibility of both cable layouts. Input

data, sourced from the data provided by Iberdrola and Seaplace, ensures practical relevance and alignment with real-world parameters.

Simulations with OrcaFlex software extract maximum tension and minimum bending radius for each configuration. These parameters help determine the optimal layout. For water depths exceeding 100 meters, the lazy wave configuration outperforms the catenary due to its reduced hanging length, which lowers loads at the hang-off point. In both configurations, maximum loads occur at the hang-off point, while the minimum bending radius occurs at the touchdown point, manageable with appropriate ancillaries. Under extreme conditions, the lazy wave's buoyant section can also experience a minimum bend radius.

Key criteria, including structural integrity, stability in extreme environments, and operational effectiveness, are rigorously assessed for each cable configuration. The analysis also examines the sea-keeping of floating structures under extreme conditions regards to the reference project. Specifically, it evaluates the dynamic cable bend radius and tension to determine the optimal cable layout.

The research focuses on comparing these dynamic cable layouts across different water depths, aiming to draw conclusions regarding installation and cost efficiency. A 450 MW wind farm serves as the reference model for the cost estimation analysis, detailed later in the report. By synthesizing empirical findings with theoretical models; this document provides actionable recommendations for stakeholders involved in offshore wind energy projects.

This analysis highlights the importance of selecting the appropriate dynamic cable configuration to ensure the efficiency, safety, and longevity of floating offshore wind structures, advancing renewable energy technology.

The study serves as a valuable resource for decision-makers, engineers, and researchers seeking to advance the design and deployment of semi-submersible floating offshore wind structures. Ultimately, this study contributes to sustainable energy solutions in offshore environments. These considerations collectively lead to a robust conclusion, providing valuable insights for the design and implementation of offshore wind farms.

1. INTRODUCTION

Floating offshore wind structures, a groundbreaking technology, extend the reach of wind energy into deeper and more wind-rich areas of the ocean. By mounting turbines on floating platforms, this new approach overcomes the depth limitations of traditional fixed installations, potentially vast new areas for energy generation. Offshore wind structures can be broadly categorized mainly into three main types: gravity-stabilized platforms, mooring line-stabilized platforms, and buoyancy-stabilized platforms. A critical aspect of offshore wind farms, whether fixed or floating, is the efficient transportation of generated power to shore. The current standard electrical configuration currently involves an inter-array voltage of 66 kV alternating current (AC). In floating wind farms, the inter-array cables traverse the water column and are subject to the motion of the floating platforms, wave excitation, and currents. These dynamic cables present unique challenges and require robust design and installation strategies to ensure reliability and longevity.

After modelling the structure for various depths, analysis was conducted to ensure the motion and RAOs of the structure are within acceptable limits. This step was crucial before implementing the cable layouts. The analysis models ensure a close resemblance to the practicality of today's offshore sectors. The detailed design of the mooring was not the focus; instead, the aim was to compare the dynamic cable layouts that follow the same structural and mooring characteristics, differing only in cable layout for water depths.

The simulations focus on structure motions, accelerations, cable tensions, and bend radius. Manufacturer catalogues and information from Seaplace and Iberdrola were referenced to ensure in-line relevance to current market conditions, providing developers with insights into future challenges. Limit values for the structure under extreme environmental conditions were taken from the offshore site considered, detailed in later sections. The analysis, conducted with a catenary mooring floating offshore structure under extreme environmental conditions, aimed to research the major challenging conditions impacting the structure, mooring, and cables. The installation procedures and cost reduction strategies are detailed in the final part of the document based on the analysis results. The study concludes with the optimal layout best suited for different water depths, considering both CAPEX and OPEX, offering valuable insights for the efficient and reliable design of dynamic cable systems in floating offshore wind structures.

2. OFFSHORE WIND STRUCTURES

The offshore wind energy sector is making tremendous progress due to the increasing demand for renewable energy. Fixed offshore structures, suitable for shallow water depths up to 50 meters so far, are being installed across various parts of Europe being nowadays a commercial reality. However, as more of these shallow water areas are utilized, the demand for floating offshore wind structures might rise in the coming years. These floating structures can be installed in water depths starting from 30 meters. The primary challenge with floating structures is station keeping, which requires detailed analysis and design of moorings to ensure the structures remain stable under varying conditions with reference to the *DNV-ST-0119,2021*. Offshore wind turbine structures are categorized based on their method of installation and the water depth they are designed for. Here are the main types:

2.1. Bottom-Fixed Structures

Bottom fixed offshore structures in wind energy are foundational platforms that anchor wind turbines to the seabed, providing stability and durability in marine environments.

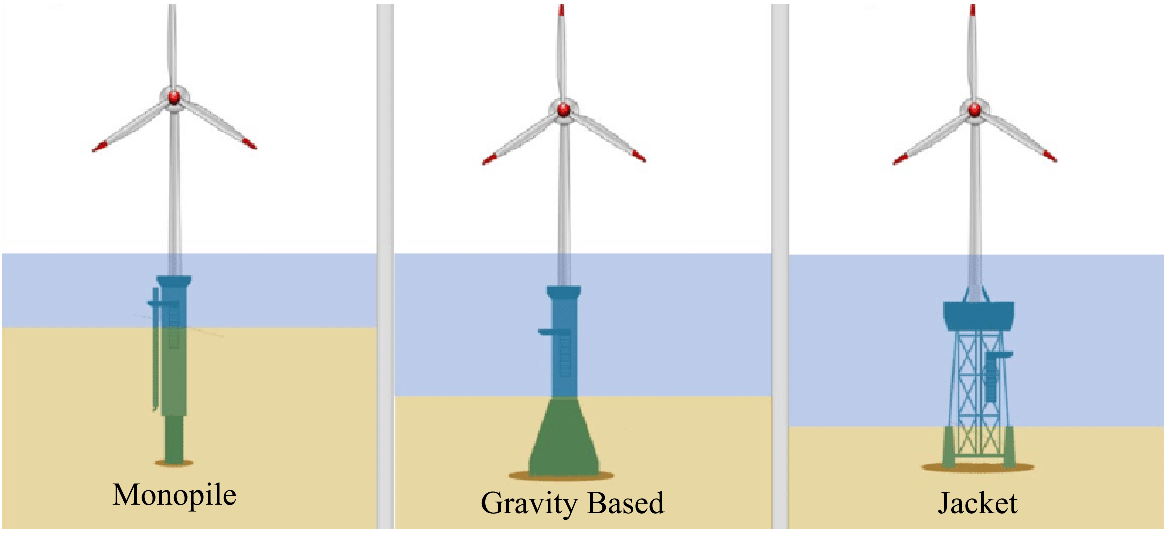


Figure 2.1: Bottom fixed structures [*Source: Francisco and Alferdo, 2020.*]

These structures, including monopiles, gravity-based foundations, and jackets, are predominantly used in shallow to intermediate waters, typically up to 50 meters deep, shown in Figure 2.1.

Bottom-fixed foundations in offshore wind energy provide a stable and reliable base for dynamic cables, crucial for transmitting electricity from wind turbines to shore or central offshore substations. These foundations fix dynamic cables securely, reducing mechanical stress from ocean currents, waves, and tidal forces. This stability allows for precise cable routing and the effective use of protective measures like bend restrictors and stiffeners, minimizing wear and tear. Additionally, secure fixing facilitates easier monitoring, maintenance, and repairs, extending the cables' lifespan. The stable conditions around bottom-fixed foundations enhance the overall reliability and efficiency of the offshore wind energy system.

2.1.1. *Monopile*

A monopile is one of the most used foundations for offshore wind turbines due to its economics and manufacturing technologies that have allowed the installation of the monopoles in deepest water than a decade ago. The main components of the monopile includes the pile, transition piece and scour protection. Monopile structures are characterized by a single, large-diameter steel tube that is driven deep into the seabed.

Monopiles are a proven technology with a solid track record. However, they have some notable disadvantages. Monopiles are limited to relatively shallow waters and are not suitable for deeper waters due to stability issues. They also face challenges such as scour potential and environmental impacts, which need to be carefully managed especially during the installation phase.

2.1.2. *Jacket*

The jacket foundation is a type of offshore wind structure commonly used in moderate to deep waters. It provides stability and support for wind turbines in challenging marine environments, offering a durable and reliable solution. Characterized by a lattice framework of welded steel tubes, jacket structures have a broad base for stability and are suitable for water depths ranging from 30 to 50 meters.

Jacket foundations have several advantages, including stability in deeper waters compared to monopiles, a robust design, versatility, and longevity. Despite being more complex and costly to manufacture, their suitability for challenging marine environments makes them a popular choice for many offshore wind projects. However, they also present installation challenges and have associated environmental impacts that need to be addressed.

The major components of jacket structures include the main legs, bracing members, and the transition piece. With ongoing advancements in design and installation techniques, jacket foundations continue to play a significant role in the expansion of offshore wind energy worldwide.

2.1.3. *Gravity-Based Structures*

A gravity-based foundation (GBF) is a type of offshore structure used to support wind turbines in shallow to moderate water depths, relying on its own weight to anchor securely to the seabed. This eliminates the need for additional anchoring or pile-driving equipment. GBFs typically consist of large concrete or steel bases that rest on the seabed and are held in place by their own weight. They are suitable for water depths of up to 50 meters.

The main components of gravity-based structures are the base, support structure, and transition piece. These foundations offer a stable and reliable solution for supporting offshore wind turbines in shallow to moderate water depths. While GBFs can be cumbersome to transport and install compared to other foundation types, their simplicity, stability, and minimal environmental impact make them a viable option for many offshore wind projects.

GBFs have several advantages, including the lack of need for seabed penetration, simple installation, stability, longevity, and minimal environmental impacts. However, they also have disadvantages, such as being very heavy and requiring substantial transportation and installation efforts. Despite these challenges, gravity-based foundations remain an effective choice for offshore wind energy projects.

2.2. Floating Structures

Floating offshore wind structures are innovative solutions designed for deep water locations where traditional bottom-fixed foundations are impractical. Anchored to the seabed with mooring lines, these floating platforms provide stability and support for wind turbines, harnessing wind energy in challenging marine environments. Their ability to operate in deeper waters opens up vast new areas for offshore wind development, making them a key technology for the future expansion of renewable energy. They are anchored to the seabed with mooring lines. The various floating structures are as shown in Figure 2.2.

Semi - submersible Tension Leg Platform Spar Buoy

Figure 2.2: Floating structures [*Source: Corewind*]

2.2.1. *Spar Buoy*

A spar buoy is a type of floating offshore structure used to support wind turbines in deep water locations, typically in water depths over 20 meters. It is designed to provide stability and support for wind turbines while floating on the surface of the water, utilizing a long cylindrical structure that extends far below the water surface to achieve stability through its deep draft. The main components of a spar buoy structure are the buoyancy, mooring system, and transition piece.

Spar buoys offer a viable solution for supporting wind turbines in deep water locations where traditional fixed foundations are not feasible. Their stability, scalability, and minimal environmental impact make them a promising option for large-scale offshore wind projects. However, spar buoys need deep sheet water for installation of turbine. For that, Spar buoys are not suitable for many places out of Norway where they were developed taking advantage of the sheltered deep water of fiords. Disruptive design, such as semi-spar with pendulums and dire installation methods could expand the areas where the spars can be installed.

2.2.2. *Semi-Submersible*

A semi-submersible is a type of floating offshore structure used to support wind turbines in deep water locations, typically in water depths over 50 meters. Designed to partially submerge below the water's surface, semi-submersibles provide stability and support for wind turbines in challenging marine environments. The main components of a semi-submersible structure are the platform, columns, and mooring systems. Semi-submersibles offer a viable solution for supporting wind turbines in deep water locations where traditional fixed foundations are not feasible. They provide good stability, are easier to install compared to spar buoys, and are flexible in accommodating different water depths. Additionally, their scalability makes them suitable for large-scale offshore wind projects. However, semi-submersibles also have disadvantages. They are more susceptible to wave action compared to spar buoys, having a more complex design. Despite these challenges, the advantages of semi-submersibles, such as stability, ease of installation, and versatility, make them a crucial option in the development of offshore wind energy.

2.2.3. *Tension Leg Platform*

A Tension Leg Platform (TLP) is a type of floating offshore structure used to support wind turbines in deep water locations, typically in water depths deeper than 120 meters depending on the size of the turbines. It utilizes a system of vertical tethers or tendons to provide stability and support for the platform, ensuring it remains in position despite wave action and currents. The main components of a TLP are the platform, tethers, temporary buoyancy tanks, and mooring systems. TLPs offer several advantages, including minimal vertical motion, stability in various sea conditions, suitability for deep waters, and scalability for large-scale offshore wind projects. However, they also present challenges, such as requiring precise installation of tendons, and complex installation methods. Despite these challenges, the stability and effectiveness of TLPs make them a valuable option in the development of offshore wind energy.

2.3. Selection Criteria

The choice of structure depends on several factors with reference to the *Maria Ikhennicheu, and Mattias Lynch, 2020*:

- Water Depth: Bottom-fixed structures are suitable for shallow waters, while floating structures are required for deeper waters.
- Soil Conditions: The seabed composition can affect the feasibility of certain foundation types, such as monopiles or gravity-based structures.
- Wave and Wind Conditions: The local environmental conditions influence the stability and durability of the structure.

- Cost: Budget constraints and economic considerations play a significant role in selecting the appropriate structure.

Bottom-fixed structures, including monopiles, jackets, and gravity-based foundations, are ideal for shallow to moderate depths, providing stability and cost-efficiency. Floating structures, such as spar buoys, semi-submersibles, and TLPs, extend the viability of offshore wind energy to deeper waters, leveraging advanced anchoring and mooring technologies to maintain stability. Each structure type has its unique advantages and limitations, and the choice depends on specific site conditions and project requirements with reference to the *DNV-ST-0119,2021*.

2.4. Mooring of the structure

Floating offshore wind structures rely on various mooring layouts to anchor and stabilize the platforms in deep water environments. These layouts are designed to ensure the stability of the platforms and provide support for the wind turbines even in challenging marine conditions. Below detailed are some different types of moorings commonly used in floating offshore wind structures:

In Single-Point Mooring (SPM), the platform is anchored to the seabed using a single mooring point, typically a turret or a single anchor. SPM systems allow the platform to weathervane around the mooring point, adjusting its orientation with changing wind and wave directions. This layout is often used in smaller-scale floating wind projects and can provide cost-effective mooring solutions but require specific configurations of the control system of turbine and bespoke analysis of the load cases.

Spread Mooring uses multiple anchor points distributed around the platform to provide stability and support. Anchor lines or chains are connected to the platform at various attachment points, spreading the load and preventing excessive movement. Spread mooring layouts offer enhanced stability. However, they require careful positioning and alignment of the anchor points to ensure proper tension distribution. Various types in this are:

2.4.1. *Catenary Mooring System*

A catenary mooring system utilizes a series of anchor lines that are attached to the floating offshore structure and extend to the seabed. These anchor lines, typically made of steel cables or chains, are connected to the floating platform at one end and anchored to the seabed at the other. They are designed with enough slack to allow them to sag under their own weight and the tension from the platform, forming a catenary shape as shown in Figure 2.3.

This catenary shape provides natural buoyancy and stability to the floating platform, allowing it to adjust its position in response to waves, currents, and wind. The weight of the anchor lines and the tension applied to them help keep the platform centred and prevent excessive movement. Additionally, the flexible nature of the catenary allows the mooring system to absorb energy from waves and currents, reducing the impact on the platform and enhancing its stability. Catenary mooring systems are well-suited for shallow to moderate water depths and offer a cost-effective solution for floating offshore structures.

2.4.2. *Taut or Semi-Taut Mooring System*

A taut mooring system shares similarities with the catenary system but features less slack in the anchor lines, resulting in a more tensioned configuration. In this system, the anchor lines are tensioned to reduce sagging and maintain a more upright position, providing increased stiffness and stability to the mooring system and allowing for better control of the platform's position. Compared to the catenary system, the semi-taut mooring system offers reduced dynamic movement because the tension in the anchor lines limits the platform's range of motion.

This increased stiffness makes taut mooring systems suitable for deeper water depths and environments with stronger currents and wave action. However, semi-taut mooring systems require careful design and engineering to ensure that the tension in the anchor lines is optimized for the specific environmental conditions and operational requirements. Unlike catenary mooring systems, where the mooring lines have significant slack and form a curve, taut mooring systems have tensioned lines that are nearly straight, providing a more rigid connection between the floating structure and the seabed as shown in Figure 2.3. Taut mooring systems typically utilize multiple anchor lines, often made of steel cables or synthetic ropes, which extend from the floating structure directly to the seabed.

Taut mooring systems require mechanisms to tension the anchor lines and maintain the desired level of tension throughout the operation of the floating structure. The tensioned configuration of taut mooring systems provides increased stiffness and stability to the floating structure, minimizing its movement in response to external forces such as waves and currents.

This enhanced stability makes taut mooring systems well-suited for deep water environments and locations with strong currents and wave action.

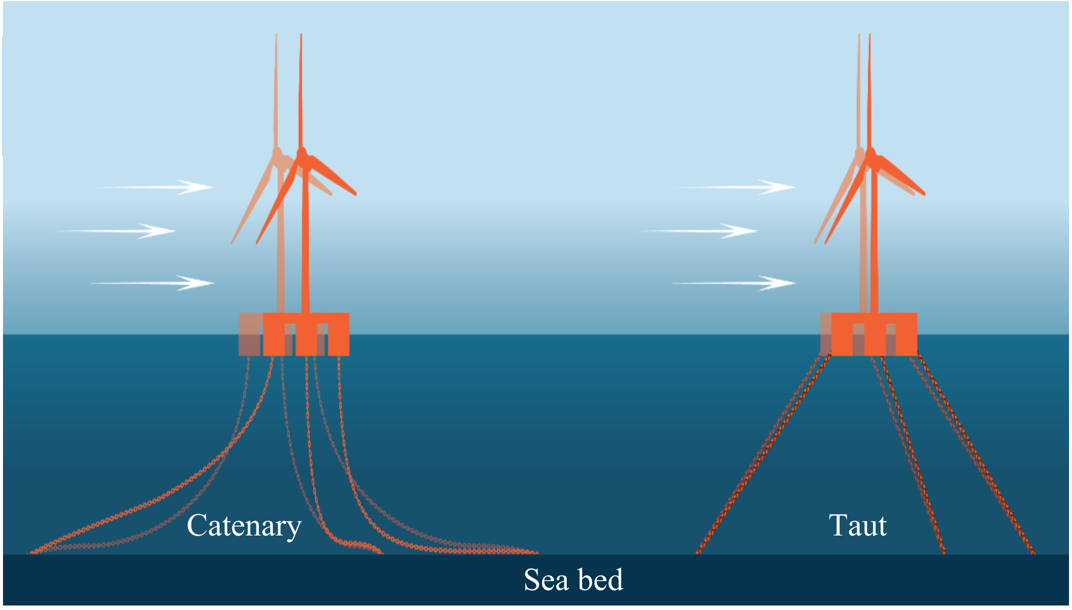


Figure 2.3: Catenary and Taut mooring [*Source: Bridon Bekaert Rope Group*]

In conclusion, the varied mooring systems – catenary and taut - play crucial roles in anchoring floating offshore wind structures across different water depths and environmental conditions. Catenary mooring systems, with their natural buoyancy and flexibility, excel in shallow to moderate waters, providing cost-effective stability while absorbing energy from waves and currents. Taut mooring systems offer enhanced stiffness and control, suitable for deeper waters and more dynamic marine environments where minimizing platform movement is essential. Taut mooring systems, characterized by their taut, nearly straight lines, ensure rigorous stability in deep waters with strong currents, leveraging tension to maintain platform position with minimal displacement.

The study focuses on the catenary mooring layout of semi-submersible structures, recognizing that this configuration imposes greater movements and loads on the structure compared to other mooring configurations. By selecting the catenary mooring layout, the study aims to address the critical case scenario, which can serve as a basis for understanding and analysing the performance of other mooring layouts. This approach ensures a comprehensive examination of the dynamic behaviour and structural response of semi-submersible platforms under challenging marine conditions with reference to the *DNV-ST-0119,2021*.

3. SEMI-SUBMERSIBLE FOWT

The semi-submersible floating offshore wind structure stands as a pioneering advancement in renewable energy, meeting the escalating global demand for sustainable power solutions in deeper ocean waters. The EU outlook into the wind capacity is illustrated in Figure 3.1. Unlike conventional fixed-bottom turbines, which are constrained to shallow waters up to 50 meters deep, semi-submersible platforms are engineered to operate effectively in significantly deeper marine environments with reference to *BVG, 2023*. These innovative platforms rely on sophisticated buoyancy and mooring systems to maintain stability, even amidst challenging sea conditions, positioning them ideally for tapping into wind resources far offshore where wind speeds are consistently higher and more reliable.

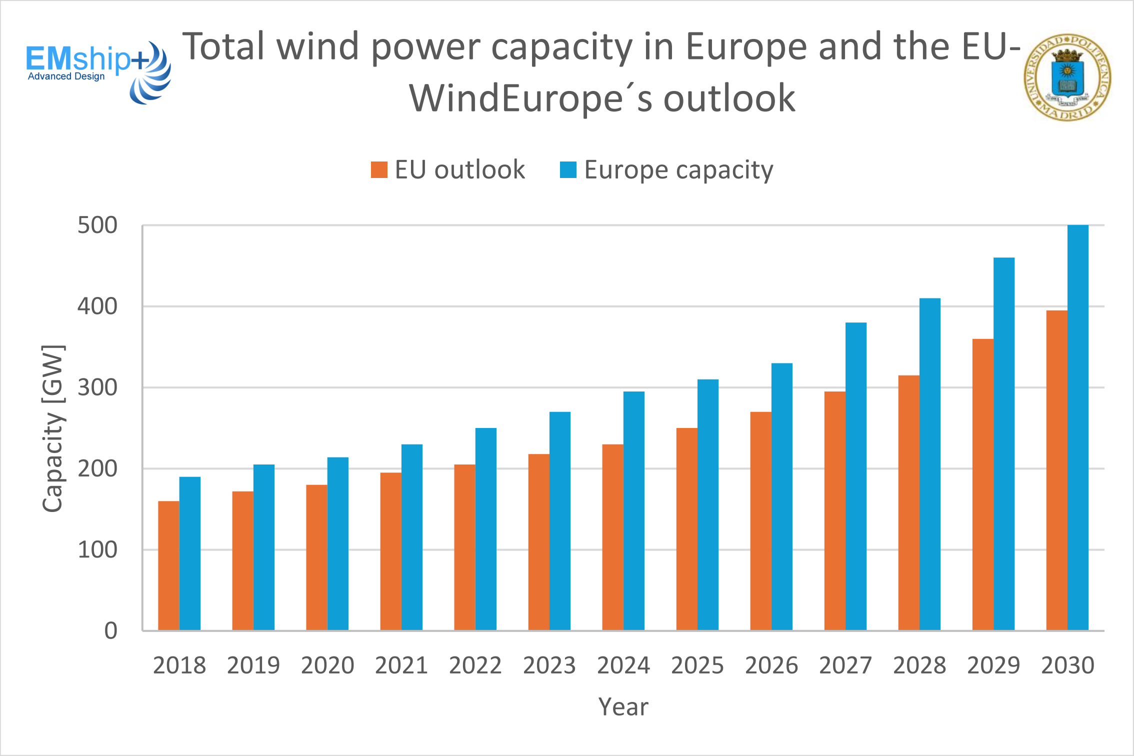


Figure 3.1: Wind capacity in Europe and EU WindEurope outlook [*Source: WindEurope*]

This technological leap not only expands the geographical reach of offshore wind energy but also capitalizes on the abundant wind resources available in deeper waters, where traditional installations are impractical. By leveraging their robust design and adaptive mooring technologies, semi-submersible structures promise enhanced efficiency and durability, setting a new standard for offshore wind power generation. As renewable energy initiatives continue to prioritize sustainability and resilience, the semi-submersible platform emerges as a pivotal solution, driving forward the transition to cleaner energy sources and contributing significantly to global efforts in combating climate change.

3.1. Current Demand in Europe

Europe is at the forefront of the global push towards renewable energy, driven by ambitious climate goals and a commitment to reducing carbon emissions as mentioned in Figure 3.1. WindEurope plans for 393 GW of wind power capacity by 2030, which is below the EU's 2030 target of 425 GW with reference to the *WindEurope, 2024*. However, it is expected that by 2030, a total of 500 GW of wind power capacity will be installed in Europe. The region's demand for semi-submersible floating offshore wind structures has surged due to several key factors:

- Abundant Wind Resources:

  Europe's extensive coastline and deep offshore waters provide ideal conditions for floating wind farms. Countries such as the United Kingdom, Norway, and Spain are particularly well-positioned to benefit from this technology, with numerous sites identified for potential development with reference to *BVG, 2023*.

- Environmental and Policy Drivers:

  The European Union's Green Deal and various national policies aim to achieve net-zero carbon emissions by 2050. Floating offshore wind technology is critical to meeting these targets, as it enables access to untapped wind resources in deeper waters, beyond the reach of fixed-bottom turbines with reference to *BVG, 2023*.

- Technological Advancements:

  Recent advancements in floating platform design, materials, and mooring systems have made semi-submersible structures more viable and cost-effective. Innovations in digital modelling and simulation tools, such as OrcaFlex, have also enhanced the precision and reliability of design and installation processes with reference to *BVG, 2023*.

- Economic Opportunities:

  The development of floating offshore wind farms might present significant economic opportunities, including job creation in engineering, manufacturing, and maintenance sectors. Additionally, it’s energy independence and security in certain regions by diversifying energy sources with reference to *BVG, 2023*.

3.2. Significance of Semi-Submersible Designs

As technological advancements might continue to enhance the feasibility and efficiency of these platforms, they could be poised to play a role in Europe's energy transition with reference to *BVG, 2023*. By tapping into the vast wind resources available offshore, semi-submersible floating wind structures offer a potential pathway to achieving climate goals and ensuring a resilient, sustainable energy future for some regions of Europe. For all the above-mentioned reasons, the analysis is carried out for the semi-submersible floating offshore structure designed for a 15 MW turbine. The model available in the Orcina resource was developed as part of the International Energy Agency's Wind Task 37, featuring a three-bladed rotor with nacelle and hub assembly. This model served as the reference for the required simulation model. The mooring design is conducted using Seaplace's internal tool, which is suitable for simulation purposes. The tool utilizes wind and wave forces to estimate the static equilibrium of the structure, with inputs including structural properties and environmental conditions.

4. POWER CABLE

Dynamic cables in offshore wind structures play a crucial role in connecting the offshore wind turbines to the onshore grid, ensuring the transfer of generated electricity. These cables must withstand the challenging marine environment, including dynamic loads caused by waves, currents, and the movement of floating wind platforms. The main suppliers of inter array power cables are Hellenic cables, JDR cable systems - shown in Figure 4.1, LS cable & system, Nexans, Prysmian and Sumitomo Electric.

Figure 4.1: Power cable [*Source: JDR*]

4.1. Types of Dynamic Cables

4.1.1. *Inter-array Cables*

Inter-array cables, also known as intra-array or inter-turbine cables, are essential components of offshore wind farms. They connect individual wind turbines to each other and to the offshore substation, creating a network that collects the generated electricity before transmitting it to shore via export cables as shown in Figure 4.2. These cables typically operate at medium voltage levels, ranging from 33kV to 66kV, and are designed to ensure minimal power loss and efficient transmission of electricity with reference to *José Ignacio Rapha, and José Luis Dominguez-Garcia, 2021*.

The structure of inter-array cables includes a conductor, usually made of copper or aluminium, for high conductivity. Insulation is typically provided by XLPE (cross-linked polyethylene), which is favoured for its excellent electrical properties and resistance to high temperatures. Steel wire armouring offers mechanical protection against physical damage from seabed conditions, marine life, and fishing activities. An outer protective sheath, made from robust materials, safeguards the cable against abrasion and corrosion with reference to *DNV-ST_0359,2021*.

To withstand the dynamic mechanical stresses caused by ocean currents, waves, and the installation process, inter-array cables are designed with significant mechanical strength. Flexibility is crucial, especially for handling the movement of floating wind platforms. Efficient thermal management is also essential to dissipate the heat generated by electrical resistance, preventing overheating and ensuring the longevity and reliability of the cables.

The installation of inter-array cables begins with detailed seabed surveys to identify the optimal cable route, avoiding obstacles and minimizing environmental impact. Factors such as seabed conditions, water depth, and potential hazards are carefully considered. Specialized vessels, equipped with dynamic positioning systems, are used for precise cable laying. Techniques like ploughing, trenching, or burial secure the cables in place and protect them from external damage. Additionally, protective measures such as rock dumping, concrete mattresses and protective casings are employed to shield the cables from physical damage and ensure their stability.

The installation and operation of inter-array cables pose several challenges. Minimizing disturbance to marine ecosystems during installation and ensuring compliance with environmental regulations and guidelines is crucial. The cables must also be designed for long-term durability in harsh marine conditions, with robust construction to withstand mechanical stresses and prevent electrical faults. Maintenance and repair are challenging due to the difficulty of accessing and repairing cables in deep and turbulent waters. Remotely operated vehicles (ROVs) and other specialized equipment are often used for inspection and maintenance.

Advancements in materials and technology have led to significant improvements in inter-array cables. The development of advanced materials for better insulation, armouring, and sheathing has enhanced their performance and longevity. The integration of sensors and real-time monitoring systems allows for early detection of issues, and data analytics and AI are used for predictive maintenance and fault detection. Innovative installation techniques, including improved cable laying vessels and equipment, have made installation more efficient and precise. Advances in trenching and burial methods have also enhanced cable protection.

Several case studies highlight the importance and effectiveness of inter-array cables. The London Array Wind Farm, one of the world's largest offshore wind farms, utilizes a network of inter-array cables to connect 175 turbines to offshore substations. This project demonstrates the critical role of robust cable design and installation in large-scale offshore wind projects. Another example is the Gemini Offshore Wind Park in the North Sea, which uses advanced inter-array cable technology to connect 150 turbines. This project showcases the challenges and solutions in managing dynamic mechanical stresses and environmental impact.

4.1.2. *Export Cables*

Export cables are a critical component in offshore wind farms, responsible for transmitting the collected electricity from the offshore substation to the onshore grid as shown in Figure 4.2. These high-voltage cables play a crucial role in ensuring the efficient and reliable delivery of power generated by offshore wind turbines.

Export cables typically operate at high voltage levels, often up to 220kV or more, to facilitate the efficient long-distance transmission of electricity. They are designed to handle large amounts of electrical power while minimizing losses. The structure of these cables is complex, comprising a conductor (usually made of copper or aluminium for high conductivity), insulation (often XLPE for its excellent electrical properties and resistance to high temperatures), armouring (steel wire for mechanical protection against physical damage), and an outer sheath (made from robust materials to protect against abrasion and corrosion) with reference to *DNV-ST_0359,2021*.

The installation of export cables begins with meticulous route planning, involving detailed seabed surveys to identify the optimal path that avoids obstacles and minimizes environmental impact. The seabed conditions, water depth, and potential hazards are key considerations in this planning phase. Specialized vessels equipped with dynamic positioning systems are used for the precise laying of these cables. Techniques such as ploughing, trenching, or burial secure the cables and protect them from external damage.

To ensure the stability and security of export cables, various protective measures are implemented. Rock dumping, concrete mattresses and protective casings are used to shield the cables from physical damage. These measures help in maintaining the integrity of the cables amidst challenging seabed conditions and potential threats from marine activities with reference to *José Ignacio Rapha, and José Luis Dominguez-Garcia, 2021*.

The challenges associated with export cables are significant. Ensuring minimal disturbance to marine ecosystems during installation is crucial, and compliance with environmental regulations and guidelines is mandatory. The cables must be designed for long-term durability to withstand the harsh marine conditions, including mechanical stresses from currents and waves. Maintenance and repair pose another set of challenges due to the difficulty of accessing and repairing cables in deep and turbulent waters.

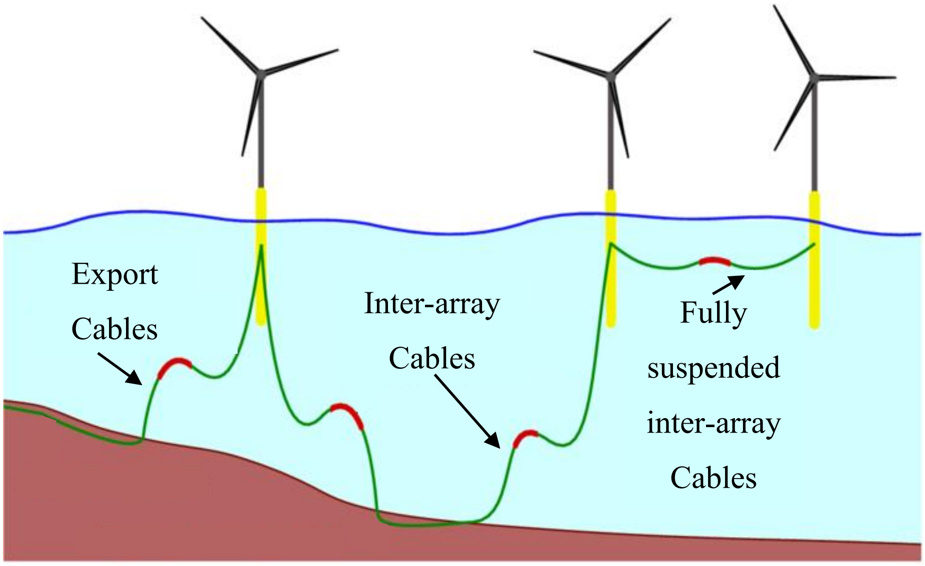


Figure 4.2: Types of offshore power cables [*José Ignacio Rapha, and José Luis Dominguez-Garcia, 2021*]

Advancements in technology and materials have significantly improved the performance and reliability of export cables. Innovations in material science have led to the development of better insulation, armouring, and sheathing materials, enhancing the cables' durability and efficiency. The integration of sensors and real-time monitoring systems has allowed for early detection of potential issues, enabling predictive maintenance and reducing the risk of unexpected failures. Data analytics and artificial intelligence are increasingly being used to monitor and maintain the health of export cables; further improving their reliability. Several case studies demonstrate the importance and effectiveness of export cables in offshore wind projects. The Hornsea Project One, for example, is one of the largest offshore wind farms in the world, utilizing high-voltage export cables to transmit power from the offshore substation to the onshore grid. This project showcases the critical role of robust cable design and installation in the successful operation of large-scale offshore wind farms. Another example is the Beatrice Offshore Wind Farm, which uses advanced export cable technology to connect its turbines to the grid, highlighting the challenges and solutions in managing the transmission of electricity over long distances. Export cables are essential for the efficient and reliable operation of offshore wind farms. Their design and installation require careful consideration of electrical and mechanical properties, environmental impact, and long-term durability.

4.2. Cable Layouts

Here’s an overview of various cable layouts commonly used as shown in Figure 4.3:

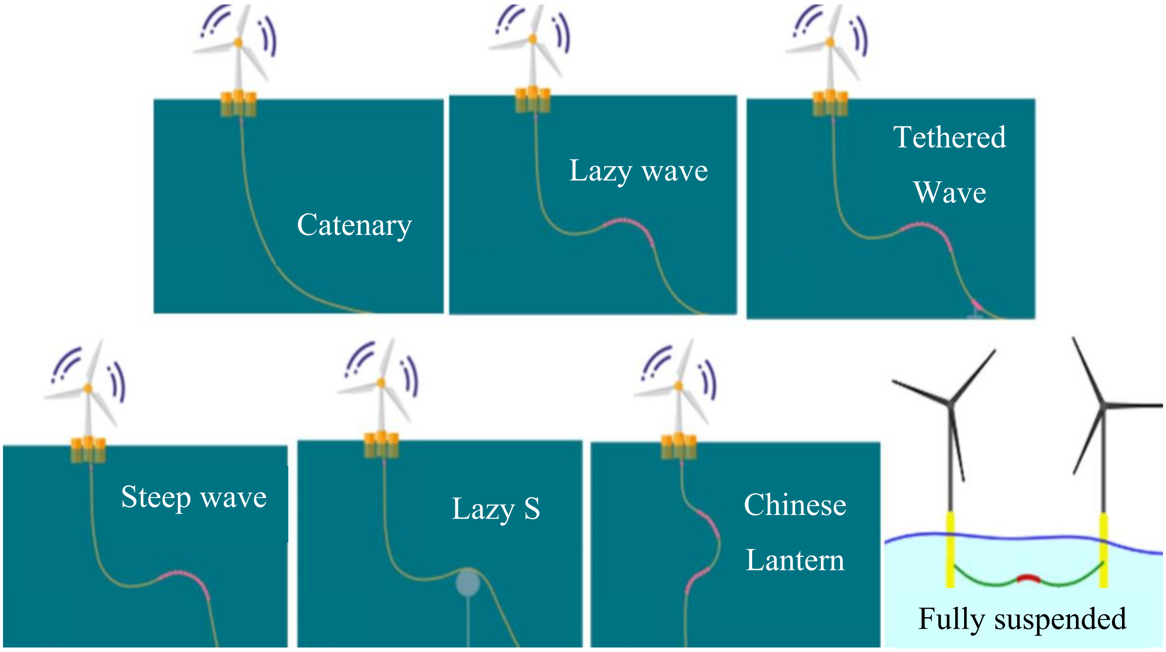


Figure 4.3: Various dynamic cable layouts[*Source: Siobhan Doole, and José Luis Dominguez, 2023*]

4.2.1. *Catenary or Free hanging*

In a catenary or free-hanging layout, cables are suspended in a curve between two fixed points, typically between the offshore wind turbine and the seabed. This configuration follows the natural curve dictated by gravity and the tension forces between the endpoints. The advantages of a catenary cable layout include lower capital expenditure (CAPEX) due to simple installation with minimal additional structures, such as supports or tensioning equipment.

The natural suspension of the cables allows for some movement and flexibility, accommodating tidal movements and minor seabed shifts without compromising stability. Additionally, catenary layouts are generally easier and quicker to install compared to more complex configurations, which can reduce project timelines and costs.

However, catenary layouts also have disadvantages to consider. They are suitable for shorter distances due to limitations in cable span and tension, which may restrict their application in larger-scale offshore wind projects. Maintenance challenges arise as these cables are exposed to elements and potential wear, requiring more frequent inspections and upkeep to ensure continued reliability.

Moreover, there is a risk of seabed interference in areas with irregular topography or dynamic seabed conditions, which could impact the integrity and performance of the cables over time. Despite these drawbacks, catenary cable layouts remain a viable choice for offshore wind installations where their advantages align with project requirements and environmental conditions are favourable.

4.2.2. *Lazy wave*

The lazy wave cable layout involves suspending the cable in a sinusoidal shape using buoyancy modules or floats at regular intervals, which helps manage dynamic forces and reduces cable fatigue. This configuration offers several advantages: first, it effectively reduces fatigue by minimizing dynamic stresses on the cable, thereby extending its operational lifespan. Second, the layout allows for moderate movement with waves and currents, enhancing flexibility and reducing strain on the cable over time. Additionally, the consistent sinusoidal shape maintains stability, reducing the risk of cable damage compared to other configurations.

However, the lazy wave layout also presents challenges. Its installation is more complex than simpler configurations, requiring precise deployment of buoyancy modules or floats along the cable length. This complexity can lead to higher capital expenditure (CAPEX) due to the additional cost of buoyancy modules and the increased installation time and effort.

Furthermore, maintenance of the buoyancy modules is necessary, requiring periodic inspections and upkeep to ensure continued performance and durability of the cable system.

Despite these challenges, the lazy wave cable layout remains a preferred choice in offshore installations where reducing cable fatigue and managing dynamic forces are critical considerations. Its ability to enhance cable longevity and stability makes it suitable for various offshore wind projects, balancing the initial investment with long-term reliability and performance.

4.2.3. *Tethered wave or reverse pliant wave*

The tethered wave cable layout utilizes tensioned cables to maintain a sinusoidal shape, employing tensioners or anchor points to control cable movement and ensure shape stability. This configuration offers distinct advantages in offshore wind installations: firstly, it provides greater control over cable movement, enhancing stability and reducing the risk of damage from dynamic forces.

By minimizing dynamic stresses and fatigue on the cable, the tethered wave layout contributes to extending its operational lifespan. Additionally, this layout is suitable for longer distances between turbines and substations, accommodating larger-scale offshore wind projects effectively. However, the tethered wave layout also presents challenges. Its implementation involves higher initial capital expenditure (CAPEX) due to the need for tensioners or anchor points along the cable length, adding to project costs.

Moreover, the maintenance of tensioners and anchor points requires specialized expertise and regular inspections to ensure optimal performance and reliability. Furthermore, the installation process is more complex compared to free-hanging layouts, requiring meticulous planning and execution to achieve the desired shape stability and functionality.

Despite these challenges, the tethered wave cable layout remains a preferred choice in offshore wind energy for its ability to enhance control, reduce fatigue, and support longer cable spans between turbines and substations. The investment in robust installation and maintenance practices ensures that this layout continues to meet the demanding requirements of offshore wind projects, contributing to sustainable energy generation in marine environments.

4.2.4. *Steep wave*

The steep wave cable layout is designed with a pronounced sinusoidal shape, particularly suited for longer cable spans in offshore wind installations. This layout utilizes heavy weight or tension elements to maintain its steep configuration and minimize cable movement, offering several advantages. It supports long-span capability, making it suitable for extended distances between turbines and substations while reducing dynamic stresses and fatigue on the cable. The stable configuration of the steep wave layout ensures consistency in shape, thereby lowering the risk of damage during operation.

However, adopting a steep wave layout comes with challenges. The initial capital expenditure (CAPEX) is higher due to the requirement for heavier weight or tension elements, which escalate installation costs. The complex nature of installation demands specialized equipment and expertise to deploy the heavy elements effectively. Moreover, the layout's limited flexibility compared to other configurations may increase strain on the cables during extreme weather conditions, necessitating careful consideration of environmental factors and operational constraints.

Despite these drawbacks, the steep wave cable layout remains a strategic choice for offshore wind projects aiming to maximize distance coverage between turbines and substations while prioritizing cable longevity and stability. Investing in robust deployment practices and ongoing maintenance efforts ensures that this layout continues to meet performance expectations and contributes to the reliable generation of renewable energy from offshore wind farms.

4.2.5. *Lazy S*

The lazy S layout represents a hybrid approach, combining elements from both lazy wave and catenary configurations to optimize performance in offshore wind installations. This layout incorporates gentle curves in the cable path, allowing for movement flexibility while maintaining stability.

The advantages of the lazy S layout include balanced flexibility, providing moderate adaptability to varying environmental conditions while reducing dynamic stresses and fatigue on the cable. It also offers a moderate level of installation complexity, balancing initial capital expenditure (CAPEX) and installation efforts compared to more complex configurations. However, adopting a lazy S layout involves considerations. While it requires moderate

CAPEX, careful planning and precise deployment of cable curves are essential to achieve optimal performance and longevity.

Maintenance requirements include periodic inspections to ensure continued stability and functionality of the layout. Environmental factors must also be carefully managed to mitigate potential impacts on the shape and stability of the cable over time. Overall, the lazy S layout represents a versatile choice for offshore wind projects, effectively balancing flexibility, stability, and installation considerations. By leveraging the strengths of both lazy wave and catenary layouts, it supports reliable and efficient energy generation from offshore wind farms while addressing operational challenges and environmental considerations.

4.2.6. *Chinese lantern*

The Chinese lantern cable layout is characterized by hanging the cable in a series of gentle curves or loops, resembling the shape of a lantern. This layout offers several advantages in offshore wind installations. Firstly, it effectively manages dynamic forces by distributing them evenly along the cable length, thereby enhancing overall stability.

The flexibility of the lantern configuration allows for movement and adjustments in response to changing environmental conditions, minimizing strain and optimizing performance. Additionally, the Chinese lantern layout reduces fatigue on the cable, contributing to its extended operational lifespan. However, adopting a Chinese lantern layout involves challenges. The installation process requires precise deployment of loops or curves, which can increase complexity compared to simpler cable configurations.

This precision in deployment contributes to higher initial capital expenditure (CAPEX) due to additional costs associated with deploying and maintaining the lantern configuration over time. Furthermore, ongoing maintenance is necessary to ensure the integrity and effectiveness of the loops, requiring periodic inspection and upkeep to address any potential issues that may affect performance.

In summary, while the Chinese lantern cable layout offers significant benefits in managing dynamic forces, enhancing flexibility, and reducing cable fatigue, careful planning and investment are essential to navigate the complexities of installation and maintenance effectively. By addressing these considerations, offshore wind projects can capitalize on the advantages of this innovative layout to achieve reliable and sustainable energy generation from offshore wind farms.

4.2.7. *Fully suspended*

The fully suspended cable layout involves suspending the cable in a straight line from point to point without touching the seabed, minimizing contact and potential damage from external factors. This configuration offers distinct advantages in offshore wind installations. Firstly, it reduces wear and tear on the cable by eliminating interactions with the seabed, enhancing longevity and reliability. Nevertheless, the dynamic loads and behaviour of the cables is uncertain due to the lack of references.

The straightforward installation process requires simple deployment without additional structures or support elements, which can streamline project timelines and costs. Additionally, the fully suspended layout demands less maintenance compared to configurations that involve seabed contact, further reducing operational costs over the lifespan of the installation. However, adopting a fully suspended layout presents certain challenges. Its limited flexibility makes it less adaptable to environmental changes and movements compared to configurations that allow for some movement and adjustment.

Longer spans may require additional support structures or tension elements to maintain stability, potentially increasing initial capital expenditure (CAPEX). Furthermore, reducing seabed interaction may have environmental implications, requiring careful consideration of potential impacts on marine life and habitats affected by the installation.

Even though the fully suspended cable layout offers advantages in minimizing wear, simplifying installation, and reducing maintenance, careful planning is essential to address challenges related to flexibility, cost, and environmental impact. By balancing these considerations, offshore wind projects can leverage the benefits of this configuration to achieve efficient and sustainable energy generation in marine environments.

Choosing the appropriate dynamic power cable layout in offshore wind farms involves evaluating trade-offs between initial costs (CAPEX), ongoing operational expenses (OPEX), installation complexity, and environmental considerations. Each layout offers unique advantages and disadvantages based on the specific project requirements, environmental conditions, and operational constraints.

Proper planning, engineering expertise, and advanced technology play crucial roles in selecting and deploying the optimal cable layout to ensure efficient and reliable energy transmission in offshore wind installations.

4.3. Design Factors of Dynamic Power Cable

4.3.1. *Floater Motions and Horizontal Excursions*

Designing dynamic cables for offshore wind applications hinges on accounting for the significant motions and horizontal excursions of floating wind turbine platforms. These platforms, subject to waves, currents, and wind, experience pitch (up and down), roll (side to side), and yaw (rotation) movements, which impose dynamic loads on the connecting cables. Dynamic cables require high flexibility to accommodate these movements effectively. This flexibility prevents excessive stress or fatigue, which can lead to premature wear, mechanical failure, or reduced electrical performance. Engineers achieve this by carefully selecting materials and construction techniques that balance strength with elasticity. Typically, specialized polymers for insulation and high-strength metals for armouring are used to ensure durability and flexibility with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

The design process includes detailed analysis of expected environmental conditions and operational parameters. This analysis predicts the range and intensity of floater motions and horizontal excursions, allowing engineers to optimize cable design for reliability and longevity, thereby minimizing maintenance and operational disruptions. Managing floater motions and horizontal excursions is crucial for dynamic cables in offshore wind farms. By designing cables with sufficient flexibility and resilience, engineers enhance the overall performance and durability of offshore wind energy systems, ensuring efficient and sustainable electricity transmission from offshore turbines to onshore facilities.

4.3.2. *Environmental Conditions*

Offshore wind farms face harsh environmental conditions, including saltwater exposure, UV radiation, temperature variations, and severe weather. These challenges demand careful selection of durable and high-performance cable materials. Cables must resist corrosion, UV degradation, and thermal expansion. Marine-grade stainless steel is often used for armouring to combat corrosion, while robust polymers like cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) are chosen for insulation. XLPE and EPR provide essential electrical integrity and mechanical strength, offering thermal stability and resilience against UV radiation; ensuring cables withstand temperature fluctuations and maintain long-term performance. Integrating these materials into cable design ensures that offshore dynamic cables endure environmental stresses, reliably transmitting electricity from wind turbines to onshore substations. This approach enhances operational reliability and supports the sustainable growth of offshore wind energy with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

4.3.3. *Marine Growth*

Marine growth significantly impacts dynamic cables in offshore wind farms, affecting performance and longevity. Organisms like algae, barnacles, and mussels attach to cables, increasing drag, weight, and operational risks. To mitigate these effects, dynamic cables use anti-fouling measures such as specialized coatings and materials that resist biological attachment. These measures help reduce marine growth, maintaining optimal cable performance. Materials for the outer sheath and armouring often include polymers or coatings that deter marine organisms, preventing excessive weight gain and mechanical damage with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

Regular inspection and maintenance are crucial. Underwater inspections using remotely operated vehicles (ROVs) assess fouling levels and the effectiveness of anti-fouling measures. Cleaning or treatment protocols may be implemented to remove marine growth and restore cable performance. Environmental sustainability is a key consideration, favouring biodegradable coatings or passive methods that discourage marine growth without chemical intervention. Effectively managing marine growth enhances the performance and reliability of dynamic cables in offshore wind farms, reducing maintenance costs and extending the cables' operational lifespan. These measures ensure cables maintain optimal efficiency and durability in the demanding marine environment with reference to *Siobhan Doole, and José Luis Dominguez, 2023*.

4.3.4. *Mechanical and Fatigue Stress*

Dynamic power cables in offshore wind farms endure significant mechanical and fatigue stresses due to the harsh marine environment. These stresses include tension during installation, dynamic loading from ocean currents and waves, and the motion of floating platforms or turbines, causing the cables to bend, twist, and stretch. To handle these stresses without compromising structural integrity, cables are designed with materials that offer high tensile strength and flexibility. Key design considerations include using robust conductor materials and flexible armouring. Armouring materials and configurations are selected to distribute mechanical forces evenly and minimize stress concentrations along the cable length.

Fatigue resistance is crucial, as cables must withstand cyclic loading over time without significant degradation.

Durable materials like cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) are commonly used for their ability to handle repetitive stress with reference to *Siobhan Doole, and José Luis Dominguez, 2023*. High tensile strength is achieved by reinforcing conductors with copper or aluminium and incorporating steel wire or aramid yarn armouring. These measures ensure that the cables can resist the forces encountered during installation and operation, maintaining their structural integrity and performance in the demanding marine environment.

4.3.5. *Electrical Performance*

Ensuring high electrical performance is vital for dynamic power cables in offshore wind farms to efficiently transmit electricity from turbines to onshore substations. This requires conductors with high electrical conductivity, effective insulation to prevent energy loss, and shielding against electromagnetic interference (EMI). Dynamic power cables use copper or aluminium conductors to minimize power loss and ensure high conductivity. Insulation materials like cross-linked polyethylene (XLPE) provide superior electrical properties and thermal stability, reducing energy loss over the cable's lifespan with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*. XLPE is preferred for its high dielectric strength and resistivity, preventing electrical breakdown and ensuring reliable performance.

Robust shielding protects against EMI, maintaining signal integrity and minimizing disruptions to power transmission. These cables are designed to withstand high voltage levels, with comprehensive testing and adherence to strict standards to verify insulation effectiveness under varying environmental conditions with reference to *Siobhan Doole, and José Luis Dominguez, 2023*. By integrating high-quality materials, advanced insulation technologies, and effective shielding, dynamic power cables optimize energy transmission efficiency and reliability, supporting the sustainable generation of offshore wind energy.

4.3.6. *Thermal Management*

Effective thermal management is critical to prevent overheating and maintain optimal operating temperatures for dynamic cables in offshore wind farms. Thermal stresses can arise from electrical resistance and environmental temperature fluctuations, necessitating design solutions with excellent thermal conductivity and heat dissipation properties. Dynamic power cables generate significant heat during operation due to electrical resistance. Effective thermal management is essential to prevent overheating, which could lead to mechanical failure and reduced lifespan with reference to *Siobhan Doole, and José Luis Dominguez, 2023*. This involves selecting materials that efficiently dissipate heat and maintain structural integrity over a wide temperature range.

Advanced polymer materials and specialized construction techniques enhance the cable's ability to manage thermal expansion and contraction. Materials are chosen for their superior thermal conductivity and resistance to heat-related stresses. Additionally, thermal management strategies may include integrating cooling systems or heat dissipation features within the cable design to regulate internal temperatures, ensuring safe operation under varying conditions. By implementing robust thermal management solutions, offshore wind farm operators can enhance the reliability and longevity of dynamic power cables, optimizing energy transmission efficiency from offshore turbines to onshore substations.

4.3.7. *Corrosion Resistance*

Corrosion resistance is crucial for dynamic power cables in marine environments. Exposure to seawater can cause corrosion and material degradation, so these cables are designed with corrosion-resistant materials and protective coatings. Marine-grade metals like stainless steel are commonly used for armouring, providing robust protection against corrosion. The outer sheath typically consists of durable polymers that resist environmental elements, ensuring long-term durability despite prolonged saltwater and atmospheric exposure.

Protective measures such as sacrificial anodes and corrosion inhibitors further enhance resistance. Sacrificial anodes, made from materials like zinc or aluminium, corrode preferentially to protect the cable's metal components with reference to *Siobhan Doole, and José Luis Dominguez, 2023*. Corrosion inhibitors applied to cable surfaces or incorporated into coatings, help mitigate corrosion and extend the cable's lifespan. Effective corrosion resistance ensures that dynamic power cables maintain reliability and performance over extended periods, reducing maintenance needs and costs. This enhances the overall efficiency and sustainability of offshore wind energy projects.

4.3.8. *Installation and Deployment Challenges*

Installation and deployment challenges are crucial design factors for dynamic cables in offshore wind farms due to the complexities of marine environments. These factors include water depth, seabed topography, and weather conditions, which significantly influence installation methods and strategies.

Dynamic cables must withstand installation stresses from methods like ploughing, trenching, or burial, depending on seabed characteristics. The design ensures cables maintain structural integrity and performance throughout their operational life despite these initial stresses.

Specialized equipment, such as cable-laying vessels and remotely operated vehicles (ROVs), facilitates precise installation and deployment. These tools handle the unique demands of offshore conditions; ensuring cables are securely positioned on the seabed and efficiently connected to wind turbines and onshore substations with reference to *BVG, 2023*.

Environmental considerations and regulatory requirements are also factored in to minimize disruption to marine ecosystems during installation. This includes best practices for seabed protection and mitigation of underwater noise and disturbance with reference to *Siobhan Doole, and José Luis Dominguez, 2023*.By addressing these challenges in the design phase, engineers optimize the reliability and longevity of dynamic cables. Robust design considerations ensure cables withstand installation stresses and operate effectively, supporting efficient electricity transmission from offshore wind turbines to onshore infrastructure.

4.3.9. *Safety and Risk Mitigation*

Safety and risk mitigation are crucial design factors for dynamic cables in offshore wind farms, operating in remote and challenging environments. These cables prioritize safety through various features and strategies aimed at minimizing risks during installation, maintenance, and operation. Robust connectors ensure secure and reliable connections, designed to withstand harsh marine conditions and prevent accidental disconnection with reference to *Siobhan Doole, and José Luis Dominguez, 2023*.

Redundant systems provide backup pathways for electrical transmission, enhancing reliability and ensuring continuous power delivery in case of component failure. Fail-safe mechanisms automatically activate in response to abnormal conditions or emergencies, such as overloading or equipment malfunction, to prevent accidents or damage. Adherence to international safety standards and regulations throughout the cable lifecycle ensures that design; installation, maintenance, and operation practices meet established safety criteria, protecting personnel and equipment from offshore hazards. By incorporating robust safety features and adhering to rigorous safety standards, dynamic cable designs minimize risks, enhance operational reliability, and safeguard workers in offshore wind energy projects. This proactive approach ensures safe operations, supporting the sustainable growth and efficiency of offshore wind energy generation.

4.4. Cable Ancillary

Cable ancillaries shown in Figure 4.4, such as bend restrictors, stiffeners, and buoyancy modules, play a critical role in protecting dynamic cables in offshore wind energy systems.

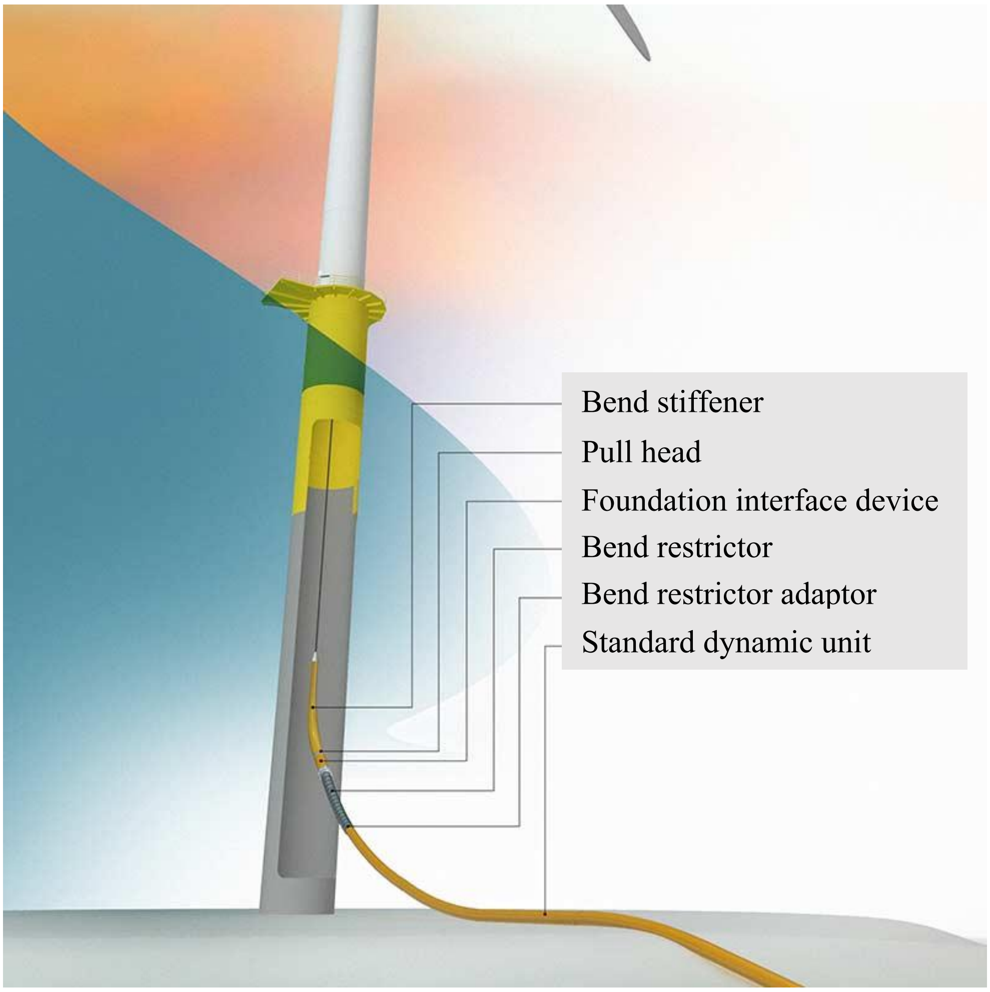


Figure 4.4: Dynamic cable ancillaries [*Source: BVG Associates*]

These components minimize mechanical stress, prevent excessive bending, and ensure proper buoyancy, enhancing the durability and performance of the cables. By effectively managing the physical demands of the marine environment, cable ancillaries help extend the lifespan of dynamic cables and maintain the reliability of power transmission from offshore wind turbines.

4.4.1. *Bend stiffeners*

A bend stiffener is crucial in offshore dynamic cable systems used in marine telecommunications and energy production. It provides vital structural support and protection to flexible pipes, umbilical, and dynamic cables where they encounter high bending stresses at connection points with rigid structures like floating platforms or subsea installations.

Made from durable materials like polyurethane, bend stiffeners gradually increase the stiffness of cables or pipes from their flexible ends to where they meet the rigid structure. This design helps distribute bending loads smoothly, preventing damage from excessive curvature in harsh marine environments. The catalogue summary of bend stiffener is detailed in Annex A.2.Bend stiffeners are pre-installed on cables or pipes before deployment, secured at connection points, and engineered not to impede dynamic movement. In offshore wind farms, they ensure reliable power transmission by preventing excessive bending at critical points like where cables exit turbine bases, thereby reducing maintenance needs as shown in Figure 4.5.

Figure 4.5: Bend stiffener [*Source: Kalyan Offshore*]

Advantages include extending the service life of cables and pipes, preventing costly failures, and enhancing safety by maintaining critical connections' integrity with reference to *IEC*

60840, 2020. Types include static for installation protection, dynamic for operational lifespan protection, and split stiffeners for facilitating installation processes. These components are essential for ensuring the longevity and reliability of offshore energy production and marine communication networks in challenging marine environments.

4.4.2. *Bend restrictor*

A dynamic bend restrictor is crucial in offshore marine applications to protect cables and umbilical from excessive bending. Unlike bend stiffeners, which gradually increase stiffness, bend restrictors physically limit the bend radius to prevent sharp bends and maintain structural integrity. Made from durable materials like polyurethane, they are customizable and installed at critical points along cables to prevent damage from environmental forces with reference to *IEC 60840, 2020*. Benefits include enhanced cable protection, extended service life, reduced maintenance costs, and increased reliability in offshore operations.

Bend restrictors ensure continuous and dependable performance of offshore systems in energy production and telecommunications, essential for operations in dynamic marine environments as shown in Figure 4.6.

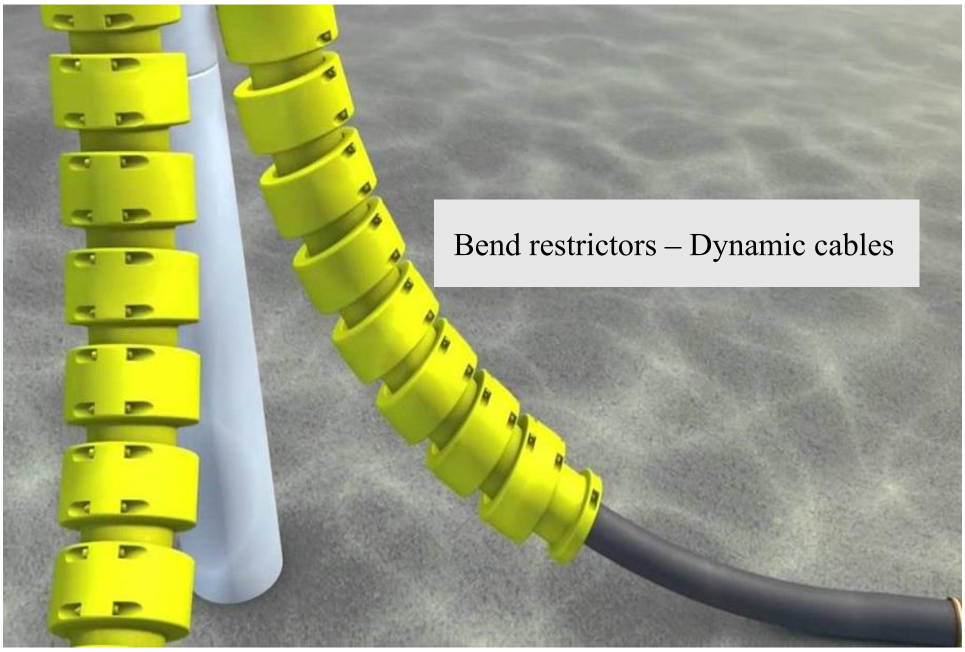


Figure 4.6: Bend restrictor [*Source: TMS*]

The bend restrictors are of polyurethane, steel or can be hybrid. Some of the manufacturers and their brochures are mentioned in Annex A.2.

4.4.3. *Bell mouth*

A bell mouth is essential in offshore dynamic cable systems to smoothly guide cables where they enter or exit structures like subsea equipment or platforms. Its primary role is to minimize stress and potential damage by providing a gradual transition for the cable. This component typically features tapered cones that create a flared, bell-shaped opening.

Starting wide and narrowing down to match the cable diameter, it ensures a seamless passage that prevents sharp bends and mechanical strain. Bell mouths find application in offshore oil and gas for guiding risers and umbilical, in renewable energy for transitioning wind turbine cables, and in marine telecommunications for cable laying operations.

They offer advantages such as potentially replacing more complex bend protection systems, thereby simplifying installation and reducing costs. However, bell mouths may not be suitable for highly dynamic environments due to potential wear from cable movement against their walls. They also require adequate space and careful design to ensure effective cable guidance without sharp bends as shown in the Figure 4.7.

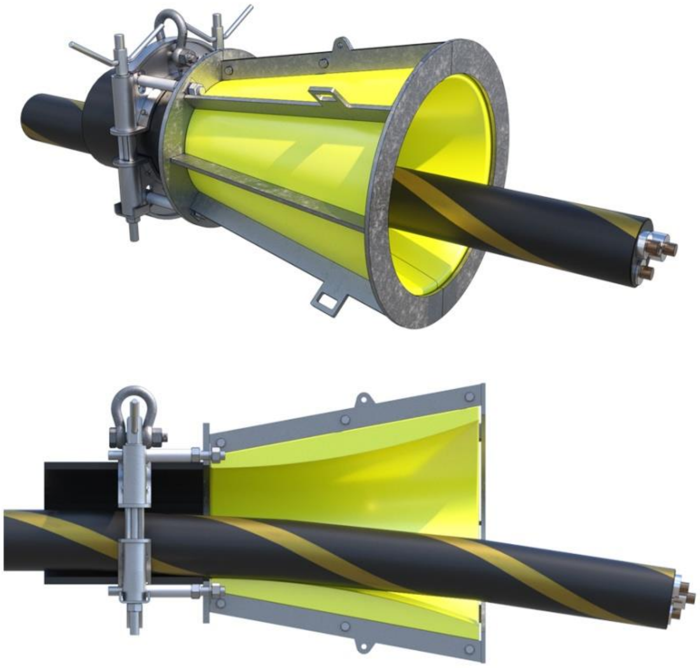


Figure 4.7: Bell Mouth [*Source: Bein Engineering*]

In summary, bell mouths serve as effective solutions for guiding cables through critical transitions offshore with reference to *IEC 60840, 2020*. Their ability to facilitate smooth transitions and potentially streamline system design makes them valuable, though considerations like environmental dynamics and space constraints must be carefully evaluated for optimal use.

4.4.4. *Bend stiffener latching*

The bend stiffener latching mechanism is crucial in offshore dynamic cable systems, securely fastening bend stiffeners to floating structures like platforms or floaters. Its main role is to transfer bending moments and shear forces from the cable's dynamic movements to the structure, ensuring stability and integrity. This mechanism is designed to withstand extreme and fatigue loading conditions through rigorous material testing and technology qualification.

Installation methods range from manual with divers to semi-automatic using ROVs and fully automatic systems controlled remotely. Diverless systems, relying solely on ROVs or automation, enhance safety and efficiency, particularly in hazardous or deep-water environments. They minimize human risk during installation and maintenance, improving overall operational safety.

Key benefits include enhanced load transfer reliability, reduced cable damage risk, extended operational life, and efficiency gains with reference to *IEC 60840, 2020*. By employing advanced automation and robust designs, these mechanisms play a vital role in maintaining cable integrity and operational continuity in challenging offshore conditions.

4.4.5. *Hang off*

The hang-off is a critical component in offshore installations, crucial for anchoring dynamic cables at the top of the I-Tube or directly to support structures on floating platforms. Its primary role is to effectively manage and transfer mechanical loads, particularly tension, from the cable to the platform while ensuring the cable's integrity.

Designed to handle dynamic tension loads generated by cable movements, the hang-off typically consists of two steel half-shells that enclose and secure the cable head with reference to *IEC 60840, 2020*. This setup efficiently transfers mechanical forces to the platform, protecting the cable from damage and maintaining its operational integrity as shown in Figure 4.8.

Figure 4.8: Hang off [*Source: VOS Prodect*]

4.4.6. *Buoyancy module*

Buoyancy modules are crucial components in offshore dynamic cable systems, particularly in deep-water environments. They generate upward force to manage the cable's position and configuration, crucial for setups like the Lazy Wave configuration that reduce mechanical stresses. Typically, buoyancy modules consist of buoyant half-shells secured around the cable with corrosion-resistant straps or bolts, along with internal clamps that attach directly without damaging the cable's outer layer.

Their primary function is to counteract the cable's weight, ensuring precise control over its vertical alignment and curvature in the water column. By strategically placing buoyancy modules along the cable, specific configurations can be achieved to optimize performance and minimize stress. Design considerations include protecting the cable with internal clamps that fit its minimum outer diameter, while accounting for maximum tensile loads and long-term creep resistance. Buoyancy modules are essential in deep-water offshore operations, supporting installations in oil and gas platforms, renewable energy setups, and marine communication systems with reference to *IEC 60840, 2020*. They play a critical role in maintaining the integrity and longevity of dynamic cable systems by managing configurations and reducing operational stresses effectively as shown in the Figure 4.9.

Figure 4.9: Buoyancy Module [*Source: Saderet Limited*]

4.4.7. *Other equipment*

Some other equipment that are also part of dynamic cables in offshore are:

- DMA / Anchors: Dead Man anchors are typically used to secure dynamic cables in configurations such as the Pliant Wave. These anchors provide a stable base to prevent unwanted movement.
- Protective Sleeves: Protective sleeves are employed at the cable's touchdown points to mitigate potential abrasion issues caused by dynamic motions, shown in Figure 4.10.

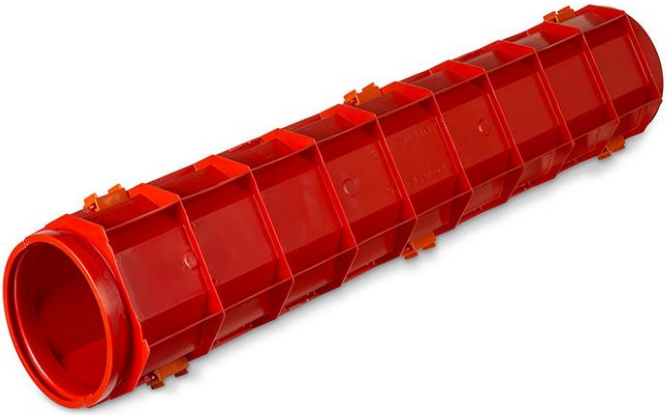


Figure 4.10: Protective sleeve [*Source: Electroplast*]

- Helical Strakes: Helical strakes are used to reduce or eliminate the risk of Vortex-Induced Motions (VIM), shown in Figure 4.11. These devices are attached to the cable to disrupt vortex shedding patterns, thereby preventing oscillations that could lead to cable fatigue with reference to *IEC 60840, 2020*.

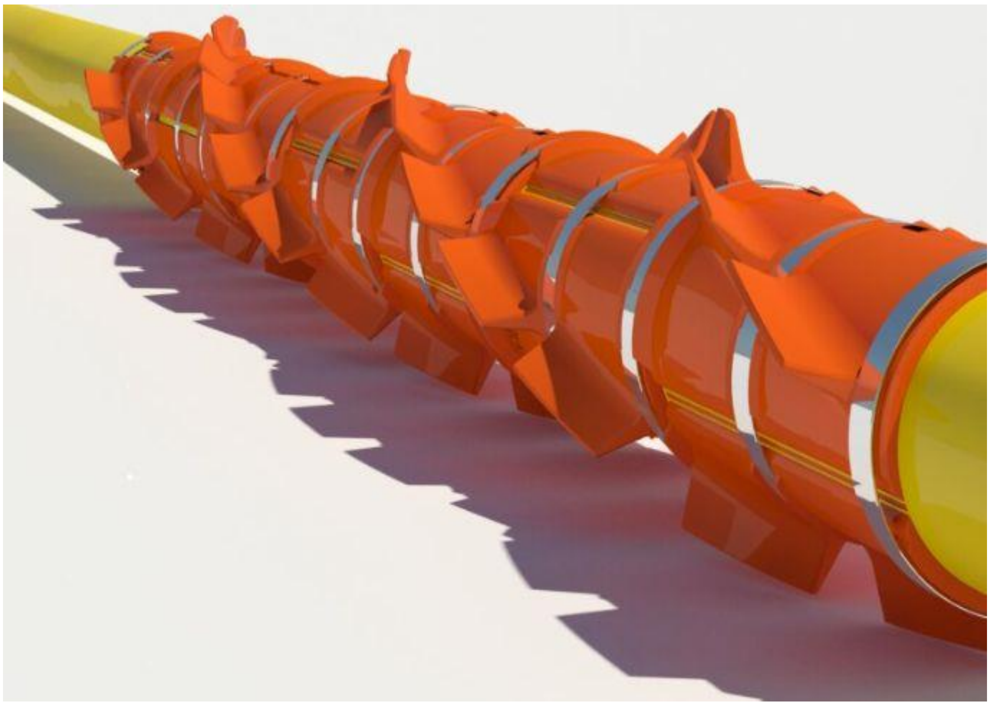


Figure 4.11: Strake [*Source: CRP subsea*]

4.5. Configurations for different offshore wind structures

The selection of each dynamic cable layout in floating offshore wind structures is meticulously tailored to match specific characteristics such as water depth, environmental conditions, platform motion dynamics, and installation feasibility. Engineers prioritize choosing the optimal configuration to ensure the cables endure operational challenges, facilitating efficient electricity transmission from wind turbines to onshore substations. These considerations are pivotal in bolstering the reliability, safety, and longevity of offshore wind energy systems.

4.5.1. *Spar buoy*

In offshore engineering, dynamic cable configurations like catenary and lazy wave designs are crucial for the stability and efficiency of Spar buoys. The catenary configuration, where cables hang in a natural curve from the platform to the seabed, effectively accommodates vertical movements, reducing dynamic loads and enhancing flexibility, especially in moderate water depths with flat seabed terrain with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

Alternatively, the lazy wave configuration arranges cables in a controlled wave-like pattern, managing vertical movements from waves and currents while maintaining adequate tension without excessive stress. Both configurations optimize the performance and longevity of dynamic cables for Spar buoys, ensuring reliable and successful offshore operations.

4.5.2. *Semi- submersible or Floating structure*

In offshore engineering, dynamic cable configurations for semi-submersible platforms, such as catenary, tethered wave, and lazy wave layouts, optimize stability and reliability. The catenary configuration is cost-effective in shallow waters, while the lazy wave layout is more suitable for depths over 100 meters. The tethered wave configuration anchors cables at intervals to the seabed, forming controlled waves that minimize horizontal movement and enhance stability, particularly for semi-submersibles with significant pitch and roll motions.

The lazy wave design, with its gentle S-shaped curve, accommodates the platform's dynamic movements and maintains consistent tension. Selecting the appropriate cable layout based on water depth and operational conditions is crucial for the long-term performance of semi-submersible offshore platforms with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

4.5.3. *Tension leg platform*

In offshore engineering, TLPs use specific dynamic cable configurations to optimize stability and reliability. TLPs typically employ a fully suspended cable layout, where cables are tautly anchored to the seabed via tension legs. This ensures constant tension and stability, ideal for deepwater installations where minimizing vertical movement is crucial.

Alternatively, the steep wave layout features a steep slope from the platform to the seabed, accommodating vertical movements from waves and currents with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*. This design minimizes cable stress while maintaining integrity, ensuring reliable performance in varying marine conditions.

4.6. Case Studies and Applications

Hywind Scotland's use of specially designed dynamic cables for floating platforms demonstrates the innovation required to support new wind energy solutions in challenging environments. Meanwhile, Borssele Wind Farm highlights the importance of advanced cable technology and real-time monitoring systems in ensuring efficient and reliable energy transmission.

4.6.1. *Hywind Scotland*

Hywind Scotland, the world first floating wind farm, represents a pioneering application of dynamic power cable technology. Located off the coast of Scotland, this wind farm utilizes specially designed dynamic cables to manage the unique challenges associated with floating structures. Unlike traditional fixed-bottom wind turbines, floating platforms are subject to more significant movement due to waves, currents, and wind. The dynamic cables used in Hywind Scotland are engineered for increased flexibility and robustness to handle these dynamic loads. They feature advanced composite materials and flexible joints that allow them to move with the floating platforms without sustaining damage. The success of Hywind Scotland demonstrates the feasibility of floating wind farms and highlights the critical role of innovative cable design in supporting the deployment of wind energy solutions in deeper waters where fixed-bottom turbines are not viable with reference to *Source: Hywind Scotland*.

4.6.2. *Borssele Wind Farm*

Borssele Wind Farm, located in the North Sea off the coast of the Netherlands, employs state-of-the-art dynamic power cables designed to withstand the harsh marine environment and ensure optimal performance. The cables used in Borssele Wind Farm are constructed with high-strength materials and advanced polymers that offer excellent electrical properties and thermal stability. They are also equipped with real-time monitoring systems that continuously track critical parameters such as temperature, pressure, and mechanical strain. This data is analysed using advanced data analytics and artificial intelligence to predict potential issues and enable proactive maintenance. The robust design and advanced monitoring capabilities of the cables at Borssele Wind Farm ensure efficient energy transmission and enhance the overall reliability and lifespan of the wind farm's infrastructure with reference to *Source: Borssele Wind Farm*.

5. ANALYSIS THEORY

5.1. Wave theory

In offshore wind structure analysis, two primary wave theories are utilized: linear wave theory (LWT) and higher-order wave theories (HOWT). The selection between these theories depends on the specific needs of the analysis. Linear wave theory (LWT) is often chosen for Preliminary Design and Quick Assessments due to its simplicity and computational efficiency. It provides reasonable estimates of wave-induced loads under regular wave conditions, making it suitable for initial evaluations. In contrast, higher-order wave theories (HOWT) are preferred for Detailed Design and Assessment. These theories account for non-linear wave effects and are more accurate in predicting wave-induced loads in complex sea states. HOWT is crucial for ensuring the structural integrity and safety of offshore wind platforms under realistic wave conditions, providing deeper insights necessary for detailed engineering analyses.

5.1.1. *Linear Wave Theory*

Linear wave theory (LWT) is a foundational approach in offshore engineering, simplifying fluid dynamics equations based on potential flow theory. It presumes sinusoidal wave profiles and neglects non-linear effects like wave steepness and interactions between waves. LWT's computational efficiency makes it ideal for preliminary design and quick assessments of wave-induced loads on offshore structures. It calculates wave characteristics such as height, wavelength, period, and celerity (speed), crucial for understanding wave interactions with structures like wind turbines and oil rigs. However, LWT's accuracy diminishes for steep waves and complex sea states where non-linear effects become significant. It doesn't accurately predict wave behaviour in conditions with large wave amplitudes or intense weather. Despite these limitations, LWT remains indispensable in initial feasibility studies and conceptual designs, providing essential insights into wave forces and structural responses during the early stages of offshore structure planning and evaluation.

5.1.2. *Higher-Order Wave Theory*

Higher-order wave theory (HOWT) addresses non-linear effects such as wave steepness, asymmetry, and wave-wave interactions that are crucial in offshore environments with steep waves. They include Stokes and Airy wave theories, as well as computational fluid dynamics (CFD), providing more accurate predictions compared to linear wave theory (LWT). HOWT describes wave dispersion and incorporates non-linear dispersion effects through additional terms, offering precise formulas for wave characteristics like shape and wave breaking. This makes HOWT essential for detailed design and assessment of offshore structures such as floating wind turbines and oil platforms, where accurate predictions of wave forces and structural responses are critical. However, using HOWT requires more computational resources and expertise due to the complexity of its equations and the need to solve higher-order differential equations. Despite these challenges, HOWT's ability to simulate realistic sea conditions accurately is indispensable for ensuring the safety, stability, and performance of offshore structures in harsh marine environments.

5.1.3. *Theory in OrcaFlex*

OrcaFlex employs advanced numerical techniques that extend beyond linear wave theory (LWT) to simulate offshore marine systems under complex wave conditions. While specific algorithms are proprietary, OrcaFlex incorporates higher-order wave theories (HOWT) and numerical methods to account for non-linear wave effects such as steepness, kinematics, and wave shape variations. It accurately models wave dispersion, reflecting the different speeds of waves with varying wavelengths. This advanced approach ensures OrcaFlex provides realistic predictions of wave-induced forces and responses, surpassing the capabilities of simpler linear methods. Engineers and researchers rely on OrcaFlex for detailed design, analysis, and optimization of floating offshore structures in the renewable energy sector and other marine applications.

5.2. Hydrodynamic classifications

Hydrodynamics plays a crucial role in the analysis and design of offshore floating wind structures, encompassing various aspects that are essential for understanding their behaviour in marine environments.

5.2.1. *Wave-Structure Interaction, Radiation and Diffraction*

Wave-Structure Interaction Analysis in offshore engineering focuses on two key aspects: radiation and diffraction. In Radiation Analysis, it examines how waves are generated by the motion of offshore structures in calm seas. It predicts how these waves propagate into the surrounding water, considering the structure's movements. Methods like the Boundary Element Method (BEM) or Finite Element Method (FEM) are typically used to model wave generation and propagation from the structure. While in Diffraction Analysis, it studies how waves are altered or diffracted when encountering offshore structures. It calculates changes in wave direction and energy distribution around the structure, influenced by its size, shape, and orientation relative to incoming waves. Similar numerical methods like BEM or FEM are employed to simulate how waves are scattered or diffracted by the presence of the structure. Both radiation and diffraction analyses employ sophisticated numerical techniques to solve equations governing wave propagation and interaction. These simulations help predict wave patterns, energy distribution, and forces acting on the structure. Such analyses are crucial for designing and assessing offshore structures, including floating wind turbines, ensuring their stability, integrity, and performance under varying wave conditions. Advancements in computational fluid dynamics (CFD) and numerical modelling have improved the accuracy and efficiency of these analyses. By simulating complex wave-structure interactions, engineers can optimize offshore installations to enhance energy production and operational safety in challenging marine environments.

5.2.2. *Morison Equation*

The Morison equation is a foundational tool in hydrodynamics for calculating wave-induced forces on submerged bodies, including offshore structures like floating wind turbines. It incorporates three main components: drag force, inertia force, and added mass force, which collectively estimate the total force exerted by waves on the structure. Reference to this section is made to the OrcaFlex software manual. Drag force accounts for resistance from water on the structure's surface area, while inertia force arises from water particle acceleration around the structure. Added mass force considers the extra mass of water displaced by the structure's motion. Together, these components enable calculation of instantaneous wave forces based on wave characteristics and structural parameters. Initially developed for simple cylindrical shapes, the Morison equation has evolved to handle more complex geometries using empirical coefficients and experimental data adjustments. While effective for estimating wave loads in linear wave conditions, it does not account for higher-order wave effects and nonlinear interactions seen in extreme sea states.

The Morison equation can be written as mentioned in Eq. (5.1),

$$F = \left(C_m * \Delta * a_f\right) + \left(\frac{1}{2} * \rho * C_d * A * v_f^2\right) \tag{5.1}$$

Where, the first term is the inertia term and the second is the drag term. Also, other terms used are,

F is the fluid force per unit length on the body

C_m is the inertia coefficient for the body

Δ is the mass of fluid displaced by the body

a_f is the fluid acceleration relative to earth

ρ is the density of water

C_d is the drag coefficient for the body

A is the drag area

$v_f$is the fluid velocity relative to earth

In practice, engineers use the Morison equation in software like OrcaFlex, where it is adapted to include added mass coefficients and consider dynamic conditions involving moving bodies. This extended form enhances accuracy in predicting forces on submerged components of offshore structures, aiding in design optimization and ensuring structural integrity and operational safety in dynamic marine environments as mentioned in Eq. (5.2),

$$F = \left(C_m * \Delta * a_f - C_a * \Delta * a_b\right) + \left(\frac{1}{2} * \rho * C_d * A * v_r^2\right) \tag{5.2}$$

The terms are as detailed,

$C_a$is the added mass coefficient for the body

$a_b$is the body acceleration relative to earth

$v_r$is the fluid velocity relative to the body

5.2.3. *Dynamic Analysis*

Dynamic Analysis related to Coupled Fluid-Structure Interaction (FSI) is crucial for evaluating the behaviour of floating wind turbines in marine environments. This approach integrates Computational Fluid Dynamics (CFD) with Structural Dynamics to simulate how environmental forces like waves and wind affect turbine motions, stresses, and fatigue loads. Coupled FSI involves bidirectional interaction between the turbine and surrounding fluid. CFD solves the Navier-Stokes equations to model fluid flow around the turbine, while Structural Dynamics predicts the mechanical response of turbine components to external forces. Key objectives of this simulation include predicting turbine motions (pitch, roll, and heave) for assessing operational safety and stability. It also calculates stresses and strains in turbine parts due to wave and wind loading, aiding in fatigue life assessment and design optimization. Moreover, it estimates fatigue loads over time, guiding maintenance schedules and operational limits. By simulating under realistic conditions, FSI helps design robust turbines that withstand offshore challenges, ensuring safety, performance, and efficiency in energy production. This approach supports advancements in offshore renewable energy technology, contributing to sustainable energy solutions for the future.

5.2.4. *Hydrodynamic Stability and Performance*

Hydrodynamic Stability and Performance are crucial aspects in evaluating floating offshore wind structures, ensuring they withstand wave-induced motions like pitch, heave, and roll while maximizing energy production efficiency. Engineers use numerical simulations and analytical methods to predict how these platforms respond to wave forces and moments. Hydrodynamic Stability Analysis involves assessing stability metrics such as metacentric height and restoring moments under varying sea conditions. This analysis integrates factors like buoyancy effects, damping mechanisms, and platform geometry to optimize design for enhanced stability and operational reliability. Robust designs are essential in offshore wind to endure the marine environment and maintain continuous energy generation. Classification of hydrodynamic bodies in floating wind structure analysis encompasses methodologies such as radiation and diffraction analysis, Morison equation applications, dynamic FSI simulations, and stability assessments. These approaches enable the design of resilient and efficient turbines capable of harnessing wind energy effectively in challenging offshore environments. This comprehensive approach supports the feasibility, safety, and sustainability of offshore wind energy projects, advancing global efforts towards clean energy solutions.

6. CRITERIA AND AXIS FOR ANALYSIS

The applicable criteria that need to be focused on are the motion, acceleration and tilt that happen for the structure for the considered environment condition. The analysis has been carried out for extreme environment condition passed on for the academic purpose from Seaplace and Iberdrola. Accelerations are restricted by the turbine manufacturer. Most turbine manufacturers specify a horizontal nacelle accelerations limit during production. This shall not be interpreted as a strict criterion, but rather as an indication about the likelihood of WTG overload. As a rule of thumb, we limit the maximum offset to the 30% of the water depth. The NORDFORSK criteria are referenced for evaluating floating offshore wind turbines (FOWT) under extreme environmental conditions with reference to *Marion Zu, and Karl Garme, 2024*. The criteria used for the reference project are also applied to this study's simulation evaluation. The simulation results are evaluated based on these criteria to ensure that the structure meets the safety and performance standards required for extreme conditions as summarized in below Table 6.1:

Table 6.1: Criteria for the simulation [Industry experience]

Acceleration extreme	[0.4*g]	3.9 m/s²
Offset	-	30% depth
Tilt extreme	RMS = 15 °	Peak = 20 °

The axis for the analysis is as mentioned in Figure 6.1.

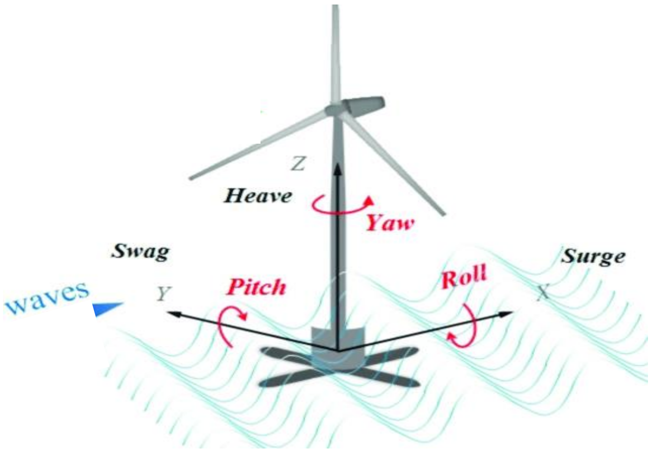


Figure 6.1: Axis for the analysis [*Source: Ziwen Chen, and Xiaodong Wang, 2021*]

7. ENVIRONMENT CONDITIONS

The environment condition taken for the analysis of study on the dynamic cable was extreme sea state. In the context of DNV rules, extreme sea state refers to the most severe combination of environmental conditions that a marine structure, such as an offshore platform or vessel, is expected to encounter for 50 years return period. DNV's Design Load Cases (DLC) are pivotal for evaluating the structural integrity and safety of marine structures under diverse environmental conditions, especially extreme sea states. These scenarios represent the most severe combinations of wave height, wave period, wind speed, current velocity, and other factors crucial for designing and assessing marine structures with reference to *DNV-ST-0437, 2024*.

Criteria for selecting extreme sea states are guided by DNV rules, incorporating factors like geographical location, water depth, historical data, and risk assessments. These conditions are characterized by exceptionally high significant wave heights, long wave periods, and strong wind speeds, tailored to specific design criteria and operational requirements. Analysis of extreme sea states involves evaluating structural responses such as wave-induced motions, wave loads on the structure, and resulting stresses and deformations. Designing for these conditions necessitates incorporating safety margins to ensure structures can withstand the most severe environmental challenges expected throughout their operational lifetimes, accounting for uncertainties in environmental data and loading assumptions.

The JONSWAP irregular wave spectrum is adopted for analysing waves, defined by project requirements. Widely recognized for its realism and accuracy in depicting irregular waves and swell, it is favoured for sea keeping analyses of offshore floating structures. The spectrum's adaptability and endorsement by regulatory bodies, classification societies, and industry standards further enhance its utility. Key parameters within the JONSWAP spectrum include the peak enhancement factor (γ), set at 3.3, and the ratio of wave period (T) to the square root of significant wave height (Hs) maintained at 4. This ratio, T/(√ Hs), plays a crucial role in characterizing wave shape and behaviour, aiding in understanding wave dynamics and energy distribution across different frequencies and wave heights.

According to *DNV-ST-0437, 2024*guidelines, Extreme Sea States (ESS) are defined as combinations of the most demanding waves and wind speeds, considering directionality variations. The simulation considers the 50-year wave, 50-year wind, and 5-year current speed scenarios, with waves, wind, and current combination aligned collinearly. Extreme sea state values shared for the simulation are mentioned in the following Table 7.1.

Table 7.1: Extreme load case parameters

Parameter	Value	Unit
Significant wave height (Hs)	10.5	m
Peak period (Tp)	12	s
Gamma (ϒ)	3.3	-
Wind speed (Vw)	42	m/s
Current speed (Vc)	1	m/s

The OrcaFlex analysis aimed to evaluate the cable system's response under extreme sea state conditions. Two analysis scenarios were conducted: one at 0 degrees, focusing on maximum excursion, and another at 180 degrees, examining maximum tension load as mentioned in Figure 7.1. These scenarios provided valuable insights into the system's response to extreme wave, wind, and current loading, as well as its structural integrity and safety under extreme conditions. The direction for the simulations is as mentioned in below Figure 7.1 with wind turbine facing the direction of wind:

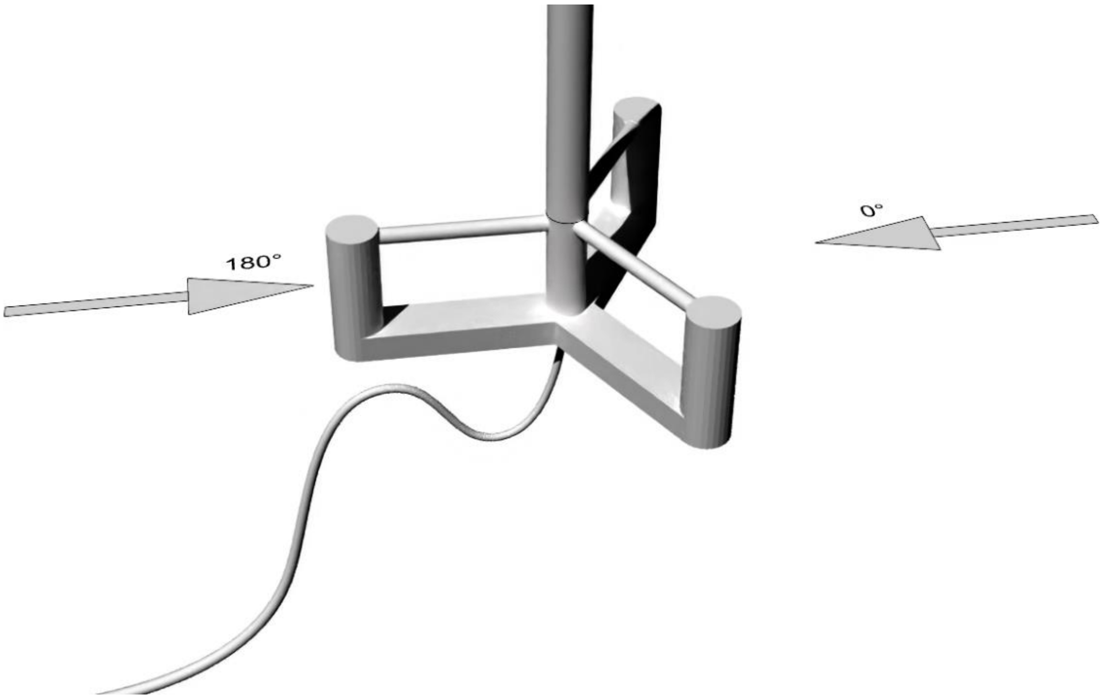


Figure 7.1: Environmental direction

8. METHODOLOGY

The simulation model utilized in this study was derived from the Orcina resource, specifically the OC4 15 MW floating offshore wind turbine. The analysis involved modifying the mooring of structure according to varying water depths. Drawing practical insights from previously launched projects, it was observed that the catenary layout proves efficient for shallow waters, up to a certain depth beyond which the lazy wave configuration becomes more effective. Consequently, simulations were conducted for water depths ranging from 50m to 200m, with the initial step involving mooring modifications to accommodate each depth. The model base is as shown in Figure 8.1

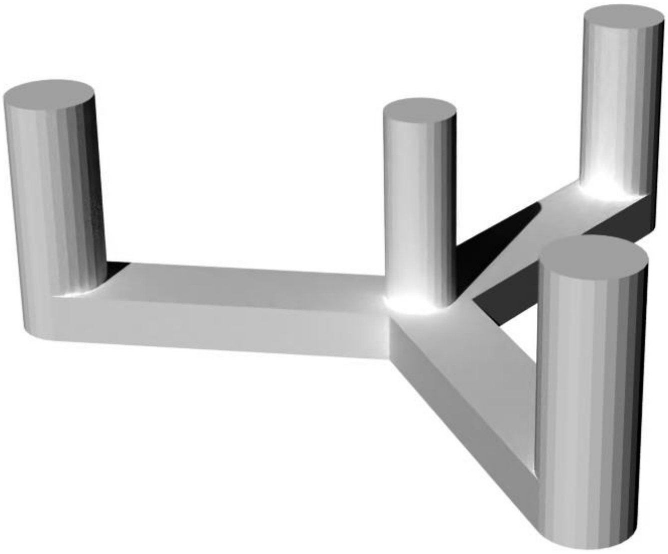


Figure 8.1: FOWT base structure – Rhinoceros

8.1. Mooring of the FOWT

The mooring layout for different depths was obtained using the Sea Place internal tool, which is confidential. This tool helps estimate mooring using a 2-dimensional equilibrium analysis, requiring inputs of the structure, wind coefficients, current coefficients, and line characteristics from manufacturers. The wind area and current area, as mentioned in Figure 8.2 and Figure 8.3, are used to estimate the current and wind coefficients in the tool. The structure details, primarily the main particulars, are also input into the tool. Mooring is focused on the system convergence in the calculation, indicating the structure's station-keeping for a particular water depth. The mooring stiffness for each depth was adjusted to closely resemble the parent model, facilitating a reasonable comparison. Catenary mooring lines were selected due to their expected maximum excursion, which significantly impacts dynamic cables compared to other mooring types with reference to *Manuel U. T. Rentschler, and Frank Adam, 2020*. Additionally, conclusions drawn from simulations of the catenary mooring structure are critical for extreme sea state scenarios, justifying their selection.

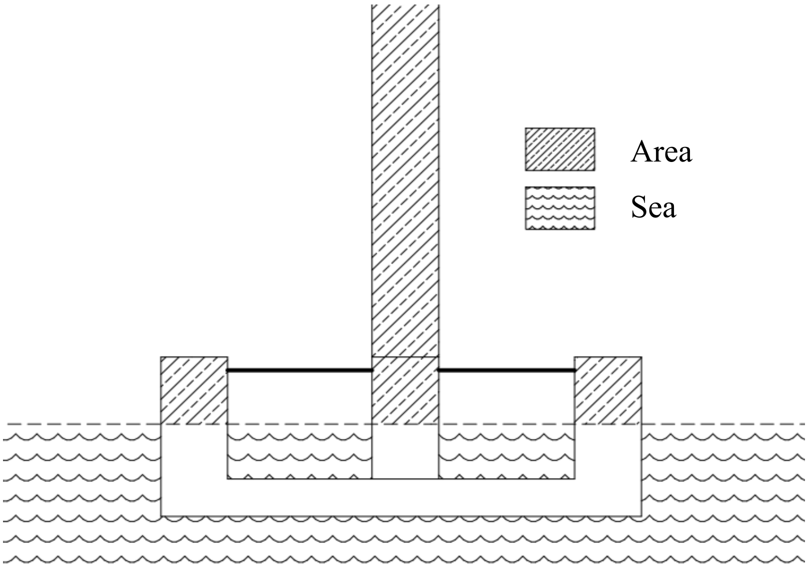


Figure 8.2: Wind area for wind coefficient

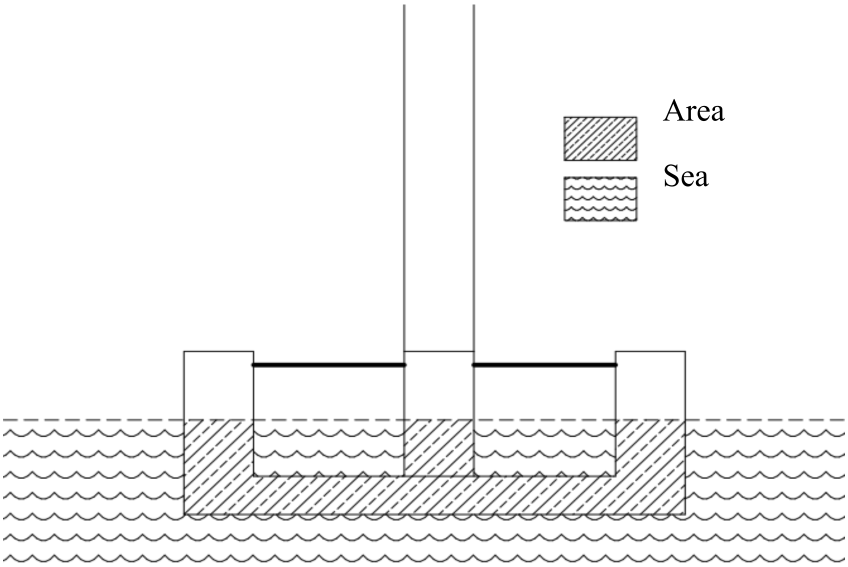


Figure 8.3: Current area for current coefficient

8.2. Dynamic Cable Layout

Dynamic cable configurations studied included catenary and lazy wave layouts, reflecting current demand. For each water depth, two models were created—one for catenary and the other for lazy wave. To ensure consistency, the lazy wave configuration was initially modelled and simulated, with the resulting anchor and touchdown points maintained for subsequent catenary analysis.

The first lazy wave layout is designed for a specific water depth, as shown in the Figure 8.4. The ratio for the hang-off, buoyancy, and laid sections was initially set as 1:1:2 with reference to *Manuel U. T. Rentschler, and Frank Adam, 2020*.

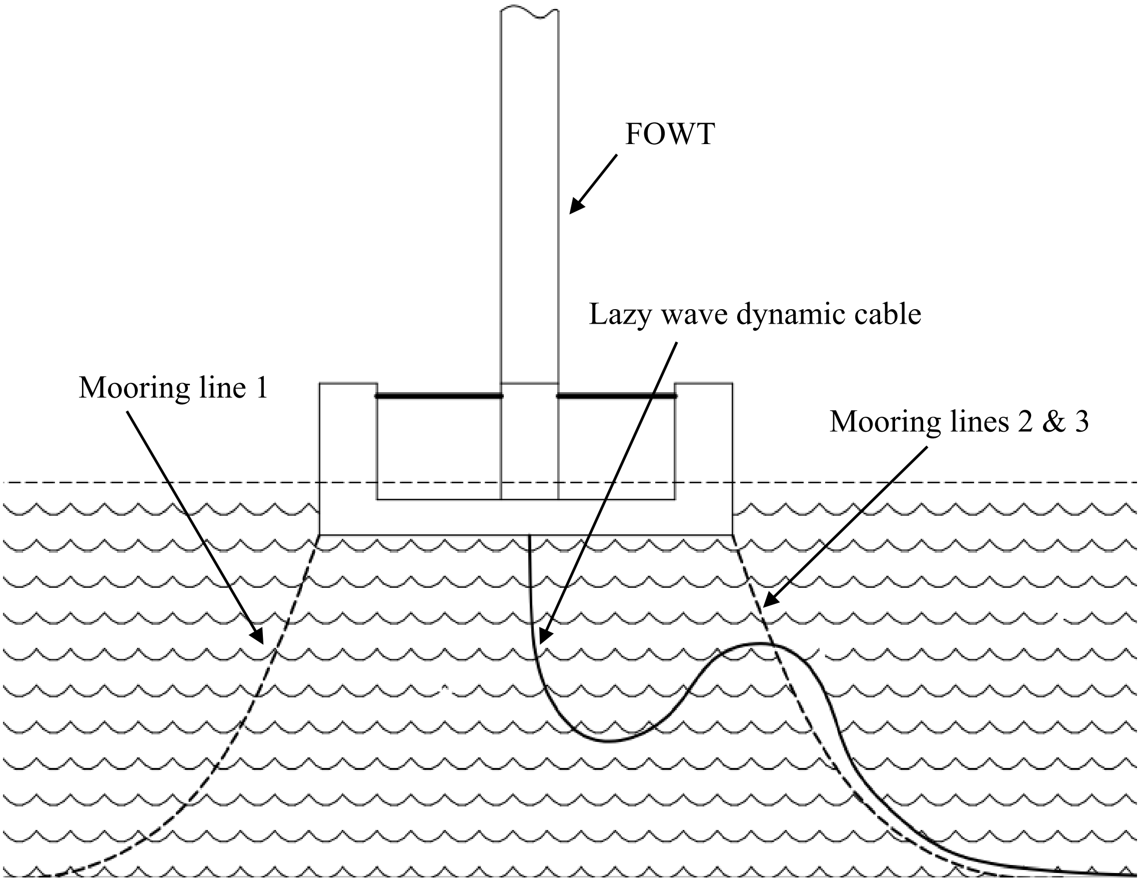


Figure 8.4: Lazy wave cable layout for simulation

The static analysis is carried out once the initial lazy wave layout is provided. The anchor point and cable length are adjusted to achieve static equilibrium in OrcaFlex. Once the static analysis is satisfactory, a time domain dynamic analysis is conducted for a brief period of 150 seconds to check for any corrections. The focus is on ensuring that the cable does not perform the station-keeping function of the structure, which is the property of the mooring line. This ensures that the cable functions solely as the power transmission system without serving the mooring purpose.

Once the analyses are satisfactory, a 1-hour period simulation is run. The simulation results are then evaluated to meet the comparison requirements of the study, which are explained in later sections. Once the lazy wave layout is completed for a specific water depth, the buoyancy modules are removed, resulting in a catenary shape for the cable as shown in the Figure 8.5. No changes are made to any other characteristics from the previous analysis, ensuring that the comparison remains sensible.

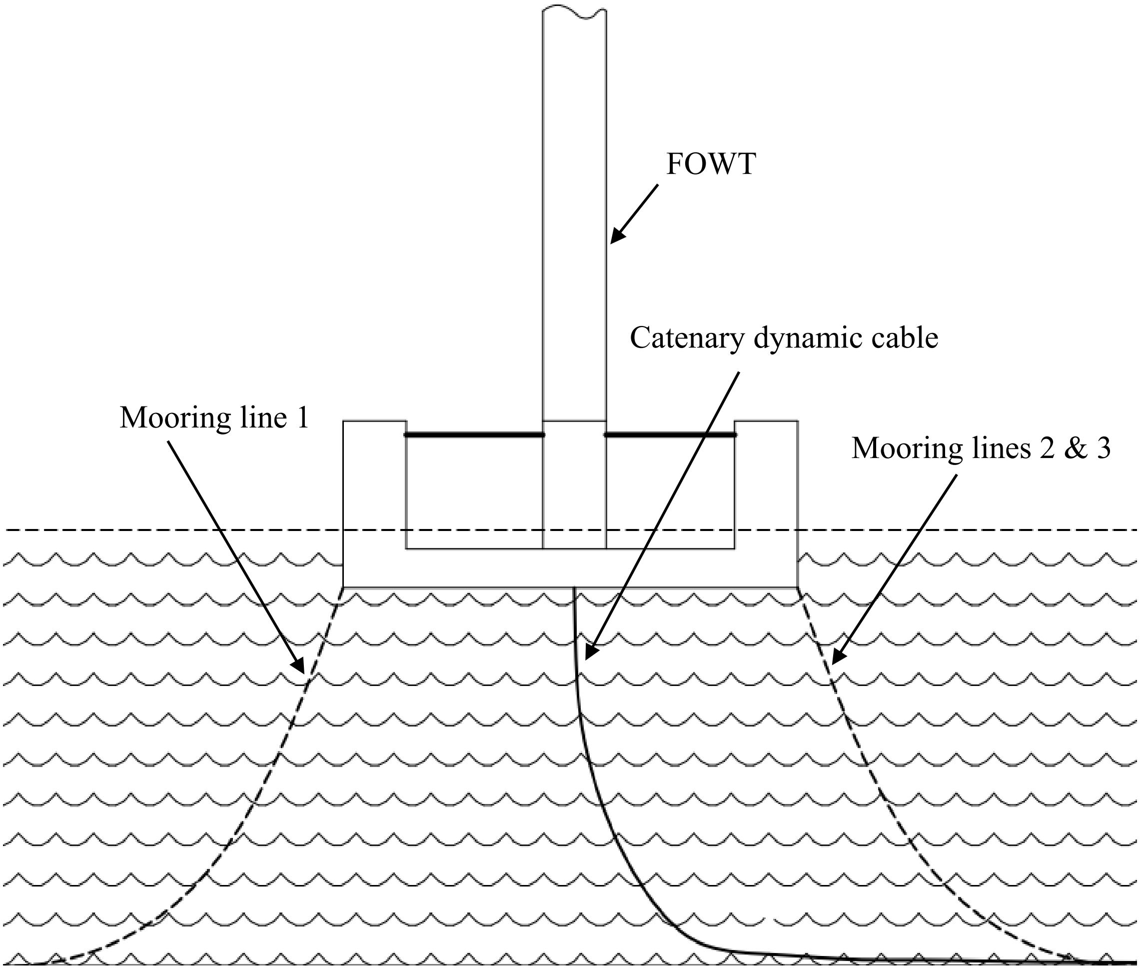


Figure 8.5: Catenary cable layout for simulation

The characteristics of the catenary and lazy wave configurations remain the same, with the only difference being the addition of buoyancy modules to achieve the lazy wave configuration. Although the simulation starts with the initial layout as previously mentioned, updates to the length and anchor point are made until both static and dynamic analyses for both configurations are successfully completed for a particular water depth.

This trial-and-error procedure is followed to ensure accuracy. The final input parameters for which the simulations were successfully run are mentioned in below Table 8.1. Refer the Annex A.1for simulation layouts.

Table 8.1: Input of cable layout for different depth

Water Depth [m]	Anchor point [m]	Cable Length [m]
50	78	100
75	100	150
100	100	200
150	85	225
200	165	285

8.3. Implicit Time Domain Analysis and Post Processing

Implicit time domain analysis was performed using OrcaFlex for dynamic simulation, following satisfactory static analysis. In implicit time domain analysis, the system's behaviour is simulated over time, with the equations of motion solved implicitly. This method accounts for nonlinearities and interactions within the system, offering predictions of dynamic response.

It captures the nonlinear behaviour and complex interactions of dynamic cables in floating offshore structures. It can handle various loading conditions, including irregular waves, wind, and currents, making it suitable for comprehensive dynamic analysis. These methods are computationally efficient, allowing for the simulation of long-duration events without sacrificing accuracy.

The time step chosen in the OrcaFlex simulation refers to the increment of time at which the simulation calculates the behaviour of the system. It is essentially of the simulation, determining how often the software updates the system's response. The duration of the simulation indicates the total time span over which the simulation runs, capturing the system's behaviour over a specified period. The time step chosen for the OrcaFlex simulation was set to 0.025 seconds. This means that the simulation calculates the system's response at intervals of 0.025 seconds.

The simulation spanned a comprehensive duration of 3600 seconds for study. The variation in the tension values is taken as the benchmark for ensuring that the simulation period is acceptable which means the multiple mean step behaviour of the tension value in the simulation period remains nearly constant, as advised from the industry advisor from Iberdrola. Despite its brevity in real-time terms, each simulation demanded approximately 20 hours to complete.

Initially, a static analysis phase was executed for each model, ensuring equilibrium and fine-tuning to mitigate software errors while upholding the study's integrity. Following this foundational step, dynamic analysis ensued, focusing sharply on a 500-second timeframe to pinpoint potential operational anomalies and refine system performance.

Central to the comparative assessment was the adoption of a fitness formula articulated in below mentioned Eq. (8.1) taken reference from *Manuel U. T. Rentschler, and Frank Adam, 2020.*

$$Fitness = \frac{MaximumTension}{MBL} + \frac{MinimumBendRadius}{MBR} \tag{8.1}$$

Here, the parameters Maximum Breaking Load (MBL) and Minimum Bend Radius (MBR) were derived from cable manufacturer specifications and critically informed the fitness evaluation. Throughout the simulations, these metrics - maximum tension and minimum bend radius - were extracted from analysis results, serving as pivotal inputs for estimating the layout's fitness value.

Notably, the fitness value serves as a crucial indicator of layout performance, where lower values signify superior configurations. This metric thus guides the determination of optimal layouts, underscoring the study's emphasis on achieving peak operational efficiency and reliability with reference to *Manuel U. T. Rentschler, and Frank Adam, 2020.*

Each simulation leveraged independent models. The value of model parameters across varying water depths, calibrated for 15MW scenarios, underscores meticulous adjustments made to mooring systems to withstand diverse environmental conditions.

In conclusion, the simulations conducted represent a meticulous approach to evaluating and optimizing system configurations, grounded in rigorous analysis and computation. This structured methodology, culminating in nuanced fitness evaluations, affirms the quest for excellence in offshore engineering design and operational planning.

A summary of the simulations carried out for the study is provided in Table 8.2.

Table 8.2: Outline of simulations – OrcaFlex

Simulation	Depth [m]	Cable layout	Direction
Simulation - 1	50	Catenary	0 °
Simulation - 2	75	Catenary	0 °
Simulation - 3	100	Catenary	0 °
Simulation - 4	150	Catenary	0 °
Simulation - 5	200	Catenary	0 °
Simulation - 6	50	Lazy wave	0 °
Simulation - 7	75	Lazy wave	0 °
Simulation - 8	100	Lazy wave	0 °
Simulation - 9	150	Lazy wave	0 °
Simulation - 10	200	Lazy wave	0 °
Simulation - 11	50	Catenary	180 °
Simulation - 12	75	Catenary	180 °
Simulation - 13	100	Catenary	180 °
Simulation - 14	150	Catenary	180 °
Simulation - 15	200	Catenary	180 °
Simulation - 16	50	Lazy wave	180 °
Simulation - 17	75	Lazy wave	180 °
Simulation - 18	100	Lazy wave	180 °
Simulation - 19	150	Lazy wave	180 °
Simulation - 20	200	Lazy wave	180 °

The mooring stiffness of the structure is also checked to finalize the model for each depth as advised by the industry advisor from Seaplace. The mooring stiffness was cross-referenced with the parent model mentioned previously. The closeness of the stiffness was verified to finalize the model. Additional suggestions from advisors and company experts were incorporated to ensure the practicality of the study was not compromised.

9. ANALYSIS EVALUATION

From each simulation, we extract motion and acceleration data derived from dynamic analyses of the structure to ensure compliance with project criteria. Throughout the entire simulation range for each depth, we closely monitor cable tension and minimum bend radius, crucial factors used to evaluate the layout's suitability detailed in Section 9.1 and Section 9.2. Detailed evaluations of the structure are meticulously documented in Annex A.3, Annex A.5 and Annex A.6for simulations at 0 degrees, and in Annex A.4, Annex A.7 and Annex A.8 for simulations at 180 degrees. Here, the cable radius is considered, with the minimum bend radius serving as a critical limit. The value obtained is then used to calculate the curvature, ensuring it does not exceed maximum curvature limits. This systematic approach simplifies evaluation and aligns with industry standards, where cable manufacturers prioritize curvature and tension values. This rigorous process guarantees that the structure meets rigorous operational and safety standards across diverse environmental conditions, enabling informed decisions regarding design and deployment strategies. The fitness metrics derived from each simulation are consolidated in Section 9.3, which synthesizes the findings of our study. These metrics represent average values calculated for specific water depths. Characteristics values for the cable are sourced from JDR, a leading manufacturer of dynamic cables in the offshore industry as mentioned in Table 9.1.

Table 9.1: JDR Cable Catalogue

Parameters	Value	Unit
Outside diameter	91	mm
Min. bend radius [MBR] for operation	3620	mm
Min. bend radius [MBR] for installation	3620	mm
Min. bend radius [MBR] for storage	910	mm
Dry weight	18	kg/m
Wet weight	12	kg/m
Min. breaking load [MBL]	720	kN
Bend stiffness	1	kN.m²
Axial stiffness	239	MN
Torsional stiffness	21	kN.m²

The criteria governing the structural response motion align with NORDFORSK standards, stipulating that nacelle acceleration under extreme environmental conditions should not exceed 0.4 * g, approximately 4 m/s^2, and motion should be limited to approximately 20°. While these values are referenced in plots to gauge proximity to limits, they are indicative rather than precise criteria. The criteria utilized here primarily reflect input from the reference project, a practical operational endeavour that underscores the importance of practical applicability in assessing design criteria.

This comprehensive approach ensures robust evaluation and validation of offshore wind structures, fostering confidence in their performance and reliability in challenging marine environments. In Section 9.3 and from the accompanying Figure 9.11 and Figure 9.12, it is evident that the fitness value of the catenary layout is notably lower compared to the lazy wave configuration for water depths ranging from 50 meters to 100 meters.

This trend continues until the depth of 100 meters, beyond which the lazy wave configuration emerges as the preferred choice over the catenary layout. This shift can be rationalized by the fact that the longer hang-off length in the catenary layout poses more impractical challenges, whereas the inclusion of buoyant sections in the lazy wave layout mitigates these issues with reference to *Manuel U. T. Rentschler, and Frank Adam, 2020*.

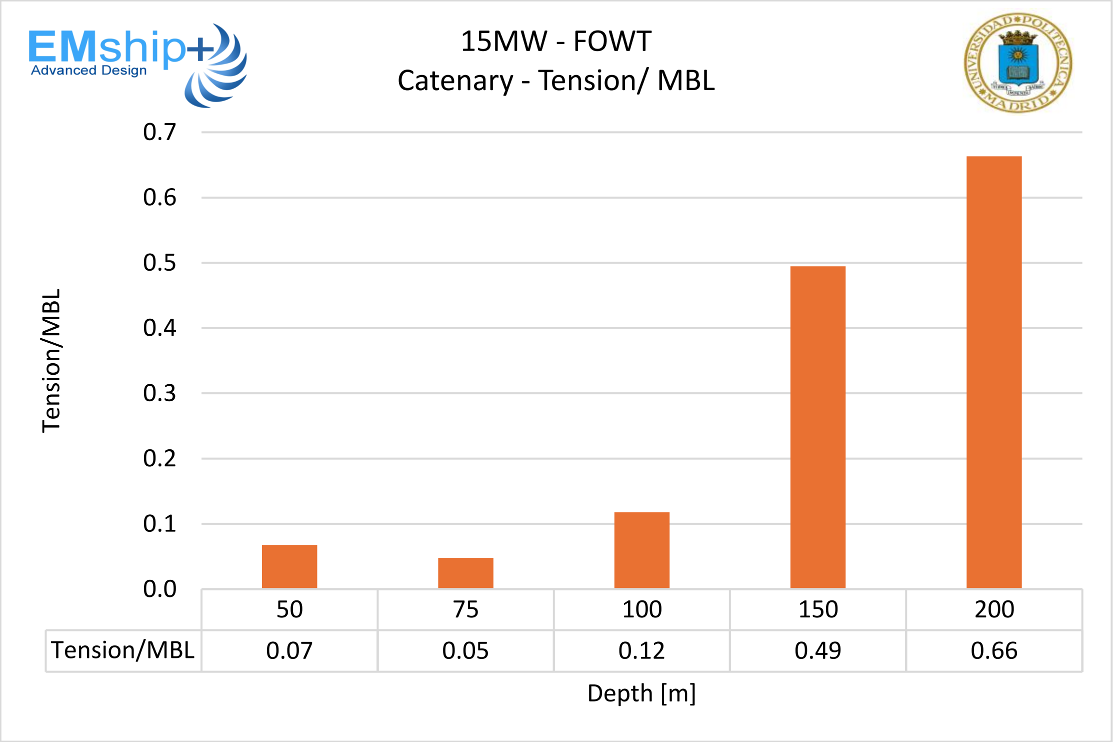
This comparative behaviour persists up to a depth of 200 meters. The transition from the catenary to the lazy wave layout occurs around the 100-meter water depth mark. This indicates that the catenary layout performs better at depths below 100 meters, while the lazy wave layout is more suitable for depths above 100 meters.

Furthermore, a detailed analysis of installation, capital expenditure (CAPEX), and operational expenditure (OPEX) for both layouts is conducted in sections 10 and section 11. These sections provide behaviour aspects of each configuration. By evaluating these factors, the study aims to determine the optimal layout for varying water depths.

This comprehensive study provides valuable insights into the structural performance and cost of different mooring layouts. The findings facilitate informed decision-making for stakeholders involved in offshore wind energy projects, ensuring that both performance and cost-effectiveness are considered in the design and deployment of floating offshore wind turbines.

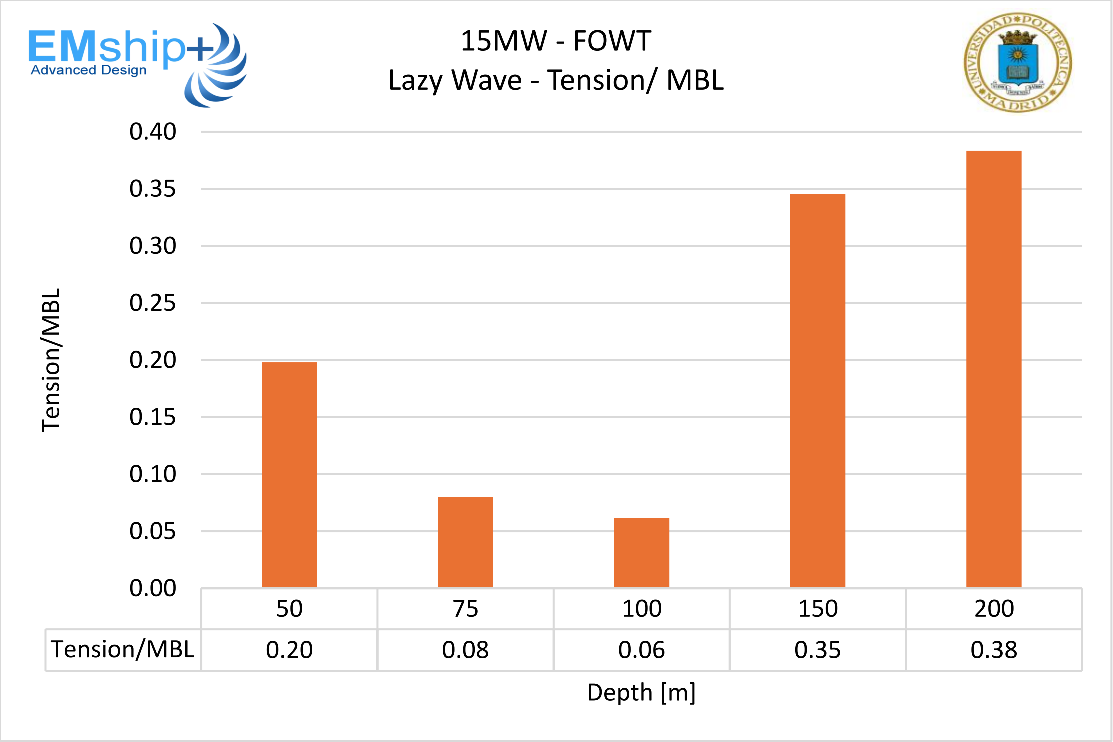
9.1. Simulation 1 – 10 [0 °]

9.1.1. *Bend Radius and Tension of the Cable*



	50	75	100	150	200
Tension/MBL	0.07	0.05	0.12	0.49	0.66

Figure 9.1: Tension/MBL for Catenary layout [0°]



	50	75	100	150	200
Tension/MBL	0.20	0.08	0.06	0.35	0.38

Figure 9.2: Tension/MBL for Lazy wave layout [0°]

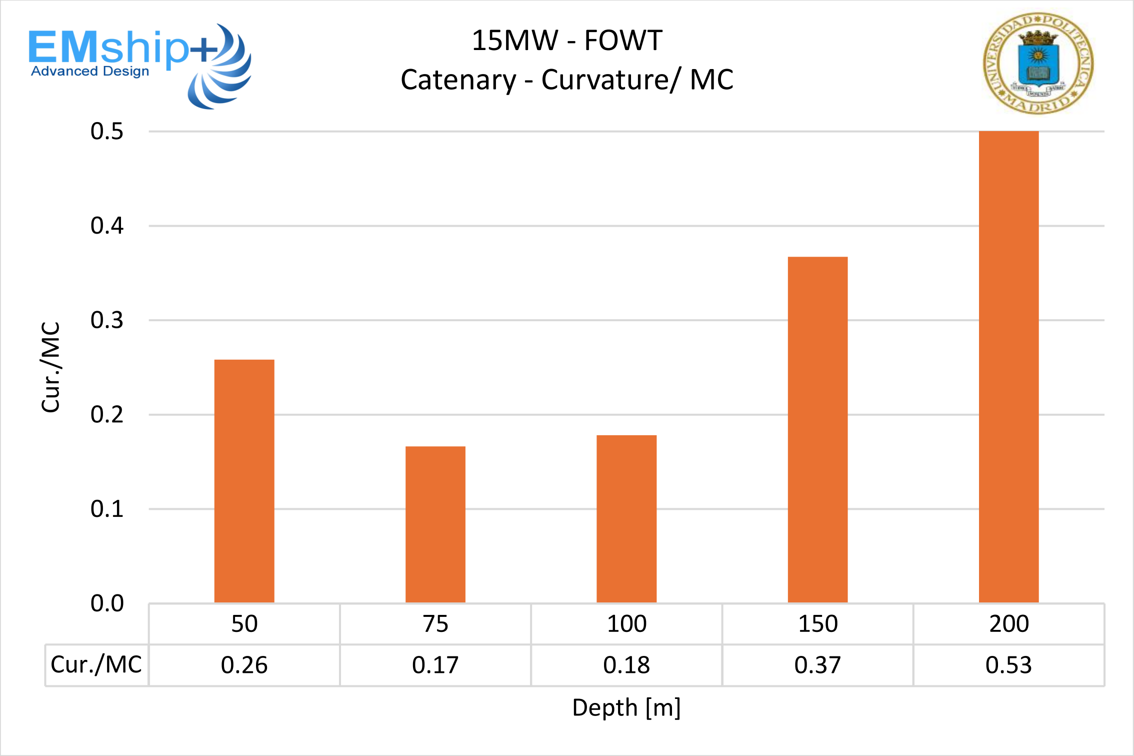


Figure 9.3: Curvature/MC for Catenary layout [0°]

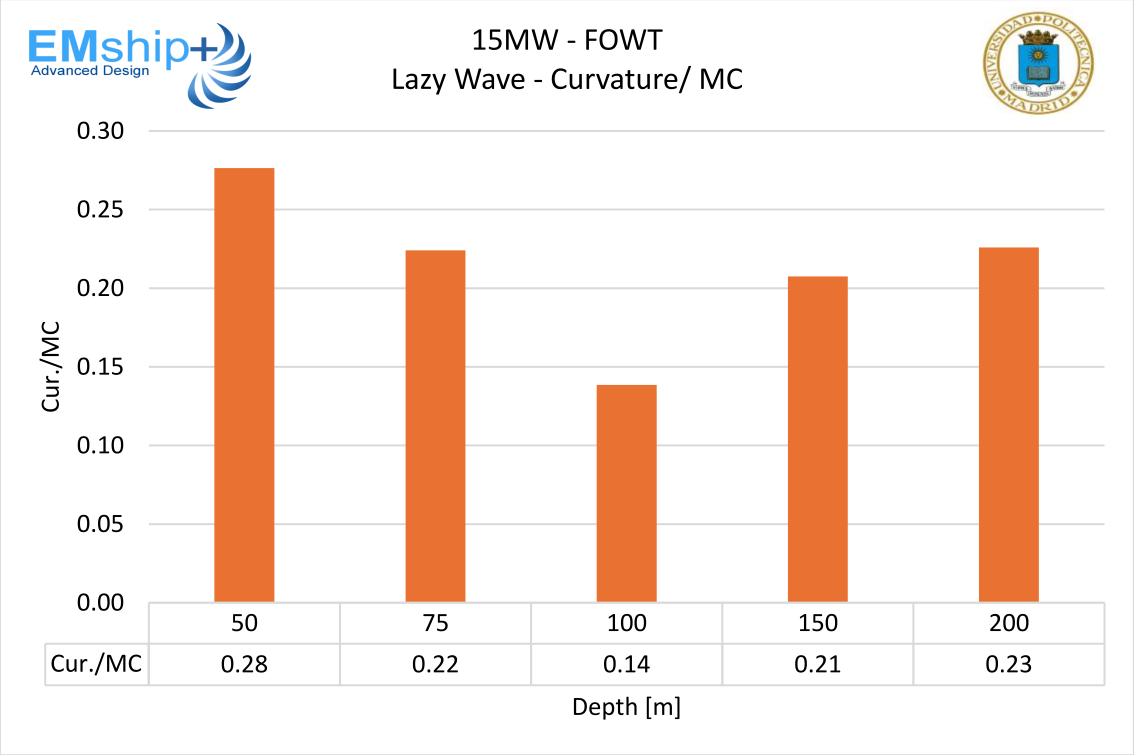


Figure 9.4: Curvature/MC for Lazy wave layout [0°]

9.1.2. *Fitness of the Cable*

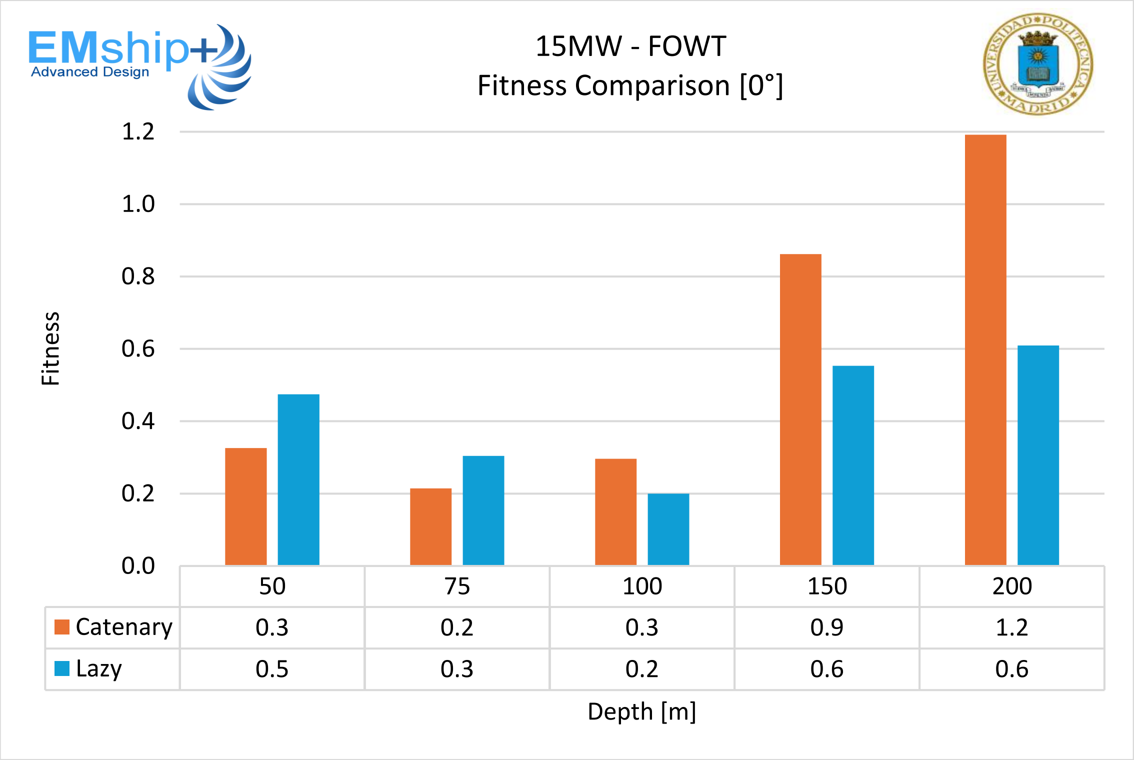


Figure 9.5: Fitness comparison of both layout for 0°

With reference to the fitness formula from *Manuel U. T. Rentschler, and Frank Adam, 2020*.

9.2. Simulation 11 – 20 [180 °]

9.2.1. *Bend Radius and Tension of the Cable*

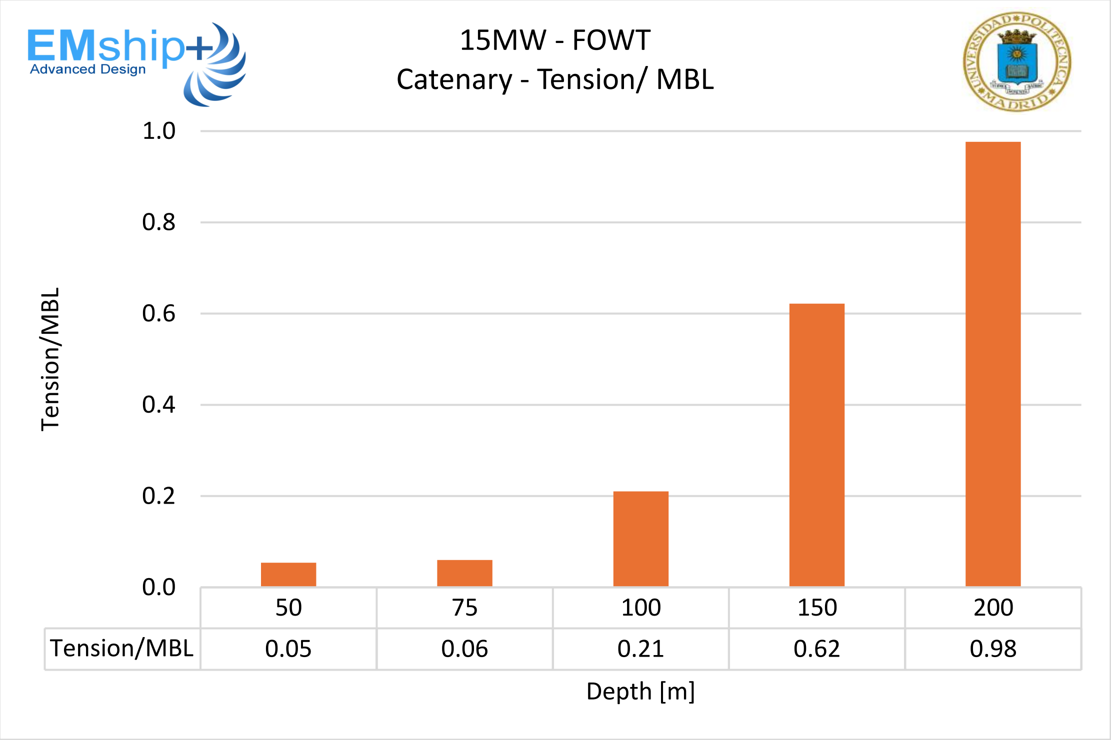


Figure 9.6: Tension/MBL for Catenary layout [180°]

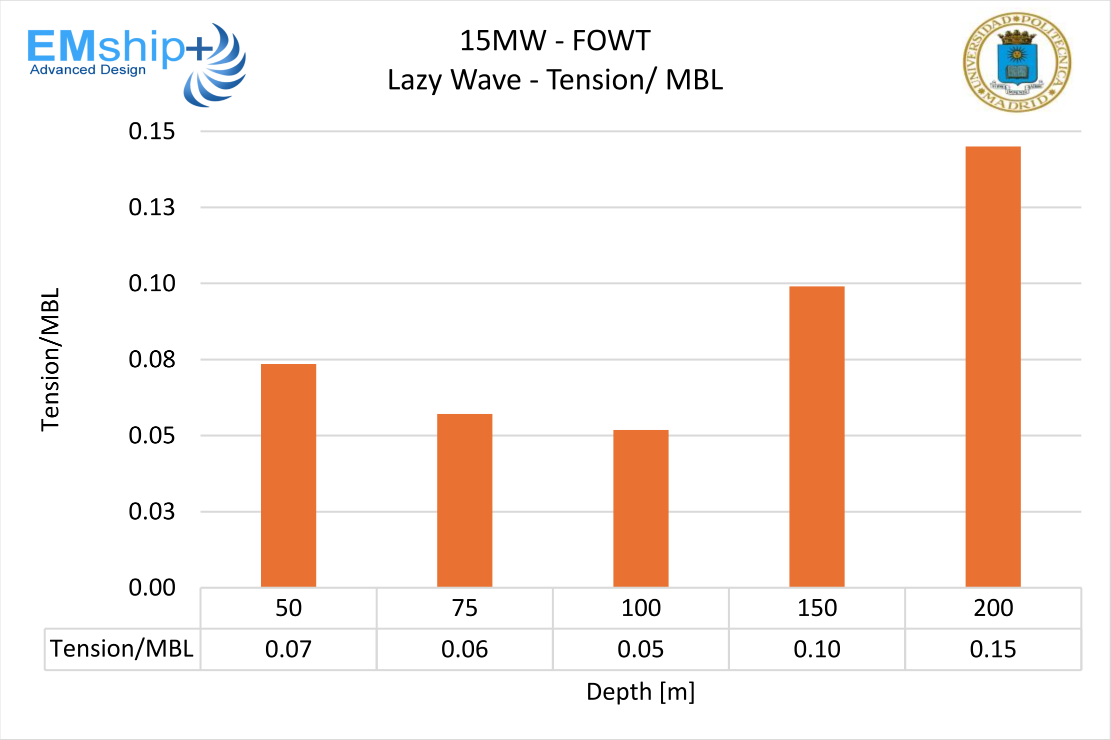
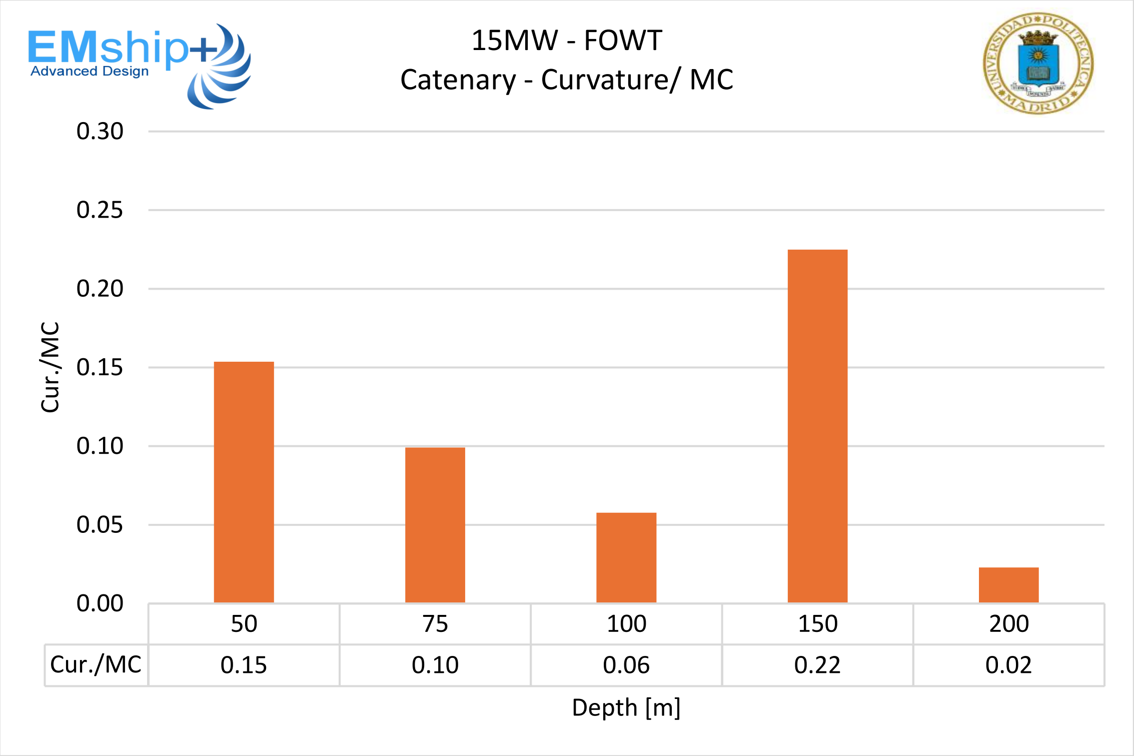
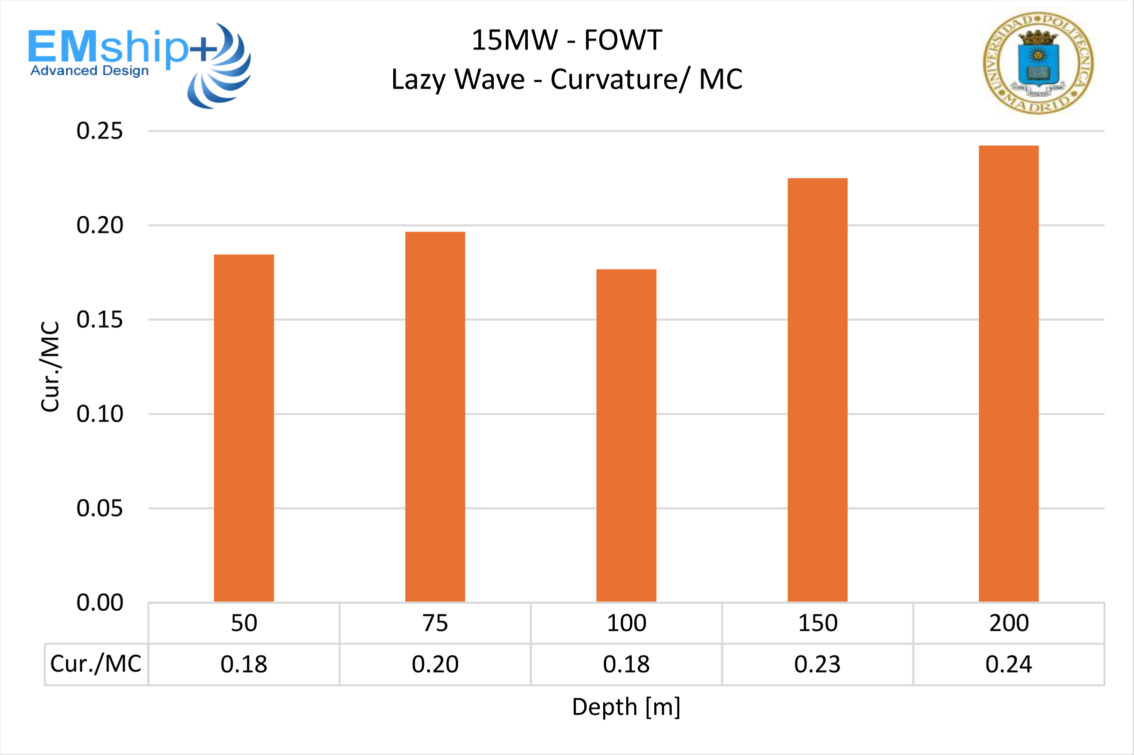


Figure 9.7: Tension/MBL for Lazy wave layout [180°]



	50	75	100	150	200
Cur./MC	0.15	0.10	0.06	0.22	0.02

Figure 9.8: Curvature/MC for Catenary layout [180°]



	50	75	100	150	200
Cur./MC	0.18	0.20	0.18	0.23	0.24

Figure 9.9: Curvature/MC for Lazy wave layout [180°]

9.2.2. *Fitness of the Cable*

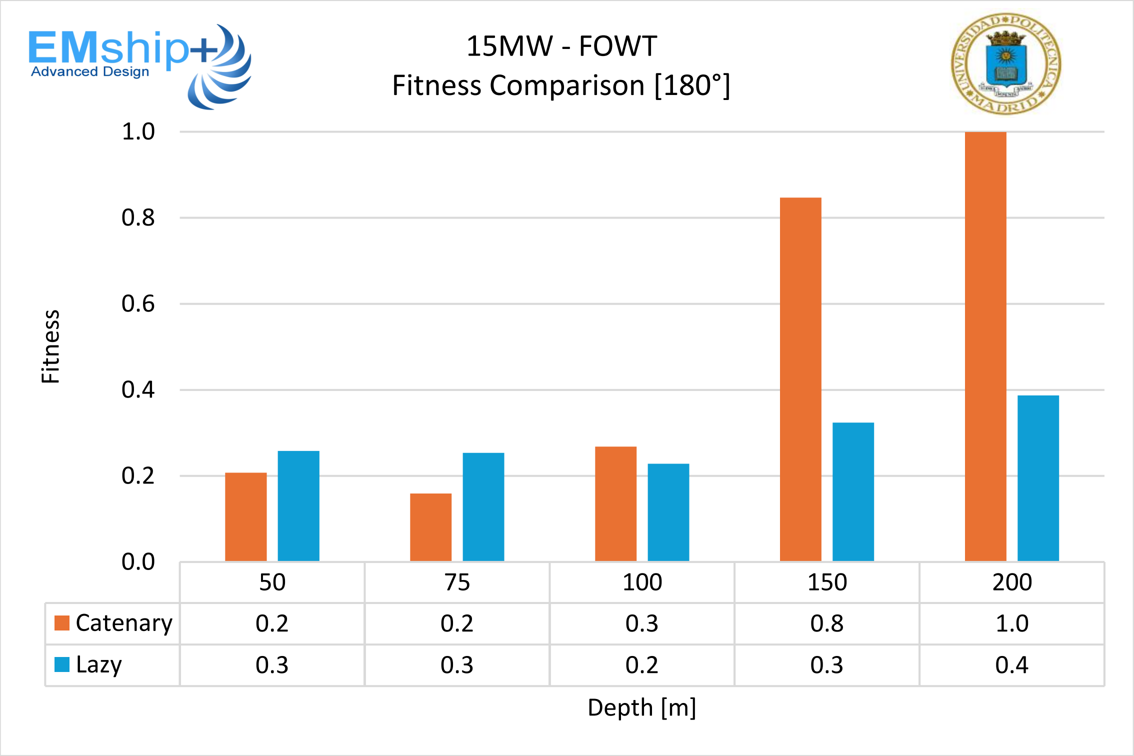


Figure 9.10: Fitness comparison of both layout for 180°

9.3. Final Fitness of the Cable

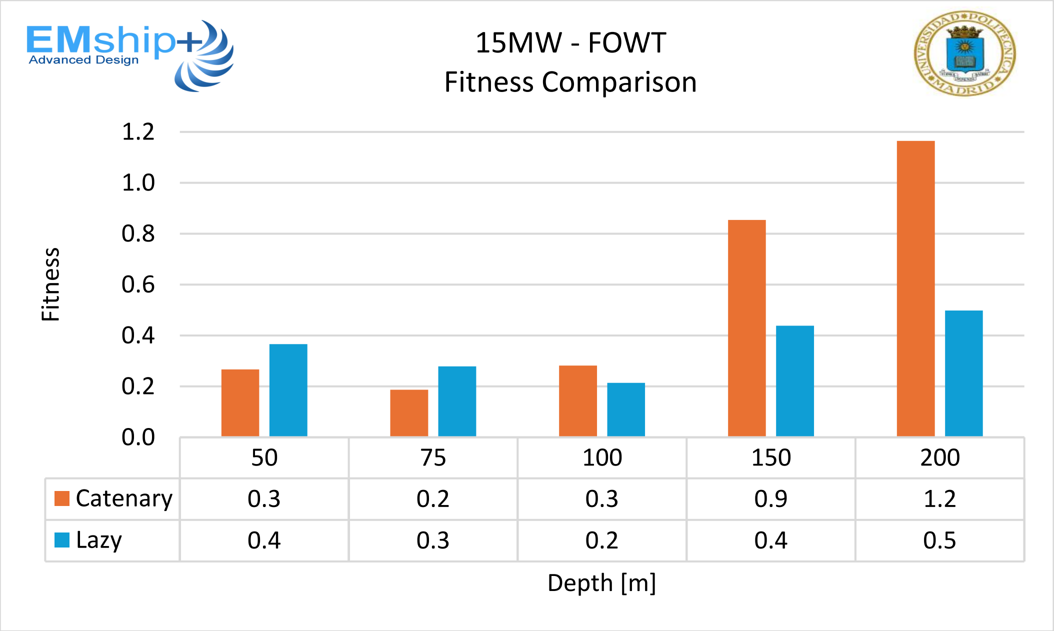


Figure 9.11: Fitness for Catenary and Lazy wave layout cable [Plot 1]

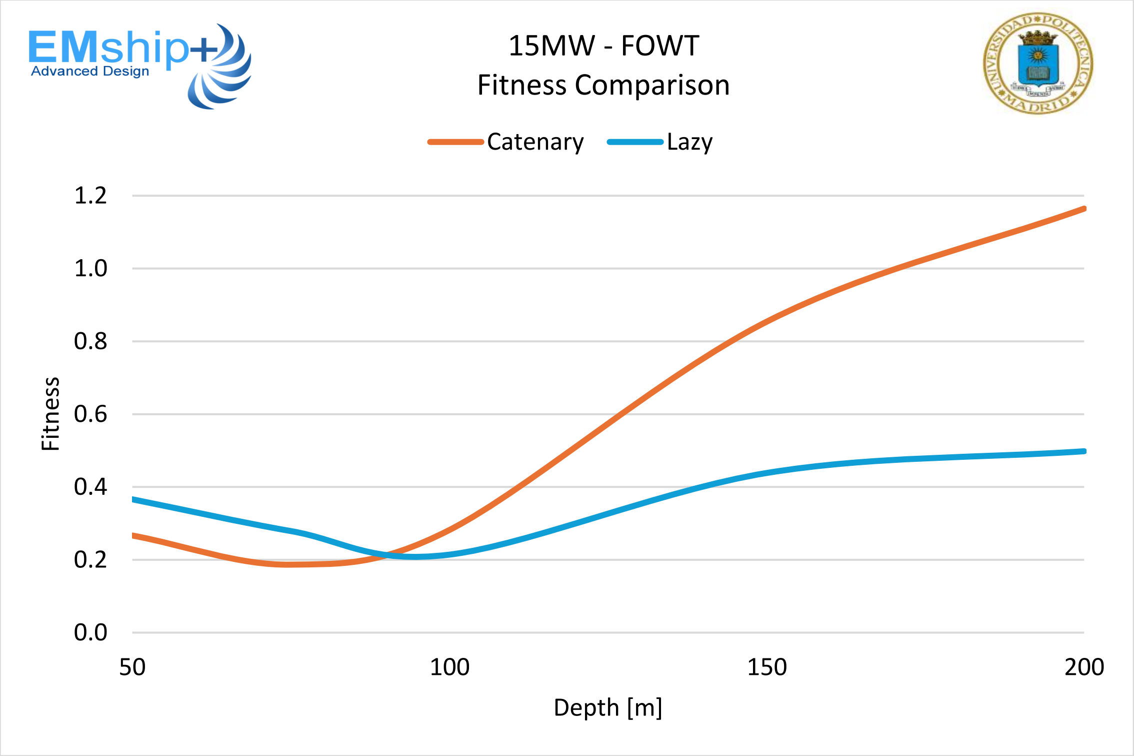


Figure 9.12: Fitness for Catenary and Lazy wave layout cable [Plot 2]

Based on the Figure 9.11 and Figure 9.12 depicting analysis under extreme environmental conditions of wind, wave, and current, the catenary configuration proves optimal for water depths below 100 meters, while the lazy wave configuration is more suitable for depths exceeding 100 meters. The capital expenditure (CAPEX) for the lazy wave configuration tends to be higher due to additional accessories compared to the catenary layout.

However, it is crucial to consider the overall project cost, which includes operational expenditure (OPEX). In this regard, OPEX for the lazy wave configuration is generally lower than for the catenary layout. This is primarily because the maintenance of a catenary layout involves addressing impacts and loads that can lead to regular repairs that affect power production. Conversely, the inclusion of buoyant sections in the lazy wave layout helps manage these load impacts, thereby reducing maintenance requirements, assuming regular inspections are conducted. This comprehensive analysis aims to provide a clearer understanding of the structural performance and economic implications associated with different mooring layouts in offshore wind projects. By considering both installation costs and operational efficiencies, stakeholders can make informed decisions that optimize both initial investment and long-term operational sustainability.

10. INSTALLATION

Dynamic cable installation for offshore wind structures involves several key steps and considerations to ensure safe and effective deployment:

10.1. Preparation and Planning

10.1.1. *Survey and Route Planning*

Preparation and planning for dynamic cable installation in offshore wind structures begin with comprehensive survey and route planning. Seabed surveys are conducted to assess the topography, soil conditions, and potential obstacles such as rocks or wrecks. This data is crucial for determining the optimal cable route that minimizes risks and ensures stability during installation. Environmental assessments follow, evaluating factors like currents, wave conditions, and marine life habitats to mitigate impacts on cable installation and operation. Based on survey findings and environmental considerations, engineers design detailed specifications for cable types, lengths, burial depths (if applicable), and installation methods.

This ensures alignment with project requirements and operational needs. Securing necessary permits and complying with local regulations are integral parts of the planning phase, addressing approvals for seabed disturbance, marine construction activities, and protection of marine ecosystems with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*. Risk assessments are also conducted to identify potential hazards during installation, including weather conditions, vessel operations, and interactions with existing infrastructure. Mitigation strategies are developed to minimize risks to personnel, equipment, and the environment throughout the installation process. Overall, thorough survey and route planning are essential for ensuring the successful deployment of dynamic cables in offshore wind farms, optimizing efficiency, and safeguarding the long-term reliability of the cable systems in challenging marine environments.

10.1.2. *Engineering Design*

Engineers meticulously specify the types of dynamic cables needed based on project specifications, considering factors such as voltage capacity, current requirements, and environmental conditions prevalent in offshore settings. They design the optimal route for cable deployment, leveraging survey data to determine the shortest and safest path from offshore wind turbines to substations or inter-array networks while minimizing impact on marine ecosystems and ensuring stability. The engineering design phase also encompasses selecting appropriate installation methods and equipment tailored to seabed conditions. This includes choosing specialized vessels equipped with cable-laying machinery, trenching tools, or ploughs to facilitate smooth deployment while maintaining cable integrity. Structural analysis is conducted to assess dynamic forces like wave-induced motions and currents, ensuring that cable supports, clamps, and connectors can withstand these forces over the cable's operational lifespan with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

Safety considerations are paramount throughout the design process, with engineers incorporating robust connectors, redundant systems, and fail-safe mechanisms to mitigate risks during installation, maintenance, and operation. They adhere closely to international standards and regulatory requirements to ensure compliance and enhance operational reliability. Cost-effectiveness and efficiency are also evaluated, optimizing cable lengths, selecting durable materials, and minimizing installation time to maximize project viability and minimize environmental impact. In essence, engineering design in the preparation and planning phase of dynamic cable installation plays a pivotal role in laying the groundwork for successful deployment and sustainable operation of offshore wind structures. It integrates technical expertise with environmental stewardship and safety protocols to deliver resilient cable systems capable of meeting the energy demands of offshore wind farms reliably and efficiently.

10.2. Cable manufacturing and testing

Regarding dynamic cable installation for offshore wind structures, cable manufacturing and testing are critical phases that ensure the cables meet stringent performance standards and reliability requirements.

10.2.1. *Manufacturing*

During the manufacturing phase, dynamic cables are produced according to precise engineering specifications and design requirements. This involves selecting high-quality materials such as copper or aluminium conductors, robust insulation materials like cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR), and protective outer sheaths resistant to environmental factors such as UV radiation, saltwater, and abrasion. Specialized manufacturing processes are employed to extrude, insulate, and armour the cables to withstand the harsh marine environment with reference to *IEC 60794, 2023*. Quality control measures are rigorously implemented throughout the manufacturing process to ensure consistency and adherence to industry standards.

10.2.2. *Testing*

Testing is conducted to verify the performance, durability, and reliability of dynamic cables before installation. Various tests are carried out to assess electrical conductivity, insulation resistance, mechanical strength, and resistance to environmental stresses. Electrical tests measure parameters such as voltage withstand insulation resistance, and conductor resistance to ensure efficient power transmission. Mechanical tests evaluate the cable's ability to withstand tensile strength, bending, and impact loads, simulating conditions encountered during installation and operation.

Environmental testing exposes cables to conditions such as temperature variations, moisture, and salt fog to evaluate their resilience and performance under real-world offshore conditions with reference to *IEC 60793,2022*. Additionally, tests for chemical resistance and abrasion resistance ensure the cables maintain integrity over their operational lifespan. All test results are meticulously documented and reviewed to confirm compliance with regulatory standards and project specifications. Cable manufacturing and testing are crucial stages in the dynamic cable installation process for offshore wind structures. They ensure that cables are robust, reliable, and capable of withstanding the demanding marine environment, thereby contributing to the long-term performance and efficiency of offshore wind farms.

10.3. Installation Techniques

Dynamic cable installation in offshore wind structures involves sophisticated techniques to ensure safe and efficient deployment, addressing the challenges posed by marine environments and varying seabed conditions.

10.3.1. *Cable Laying*

Cable laying in offshore wind projects relies on specialized vessels equipped with sophisticated machinery and tools designed for the demanding marine environment. These purpose-built vessels are crucial for deploying dynamic cables across diverse seabed conditions and depths. The vessels are equipped with advanced cable-laying machinery, including tensioners, carousels, and deployment systems, capable of handling large reels of cables. This equipment ensures controlled and precise laying of cables onto the seabed, managing tension and alignment to prevent damage and ensure optimal performance throughout the installation process.

Several techniques are employed depending on seabed characteristics. In softer seabed, ploughing or trenching techniques are utilized. A plough or trenching tool towed behind the vessel creates a trench where cables are laid and buried below the seabed surface. This method protects cables from external damage and minimizes interference from marine activities and fishing operations. Mechanical or hydraulic burial methods are employed to embed cables into the seabed, enhancing stability against environmental forces such as currents and waves. Burial reduces the risk of damage from anchors or fishing gear, contributing to the long-term reliability of the cable network and minimizing maintenance needs with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

For dynamic cables designed to accommodate movements and stresses, precise handling during laying is essential. Engineers and operators aboard the vessel ensure cables are deployed to avoid excessive tension, thereby maintaining their integrity. This approach is critical for cables connecting floating wind turbines or platforms, where movements can exert varying stresses on the cable system. Cable laying vessels are integral to offshore wind projects, facilitating the installation of dynamic cables with precision and efficiency. Their specialized equipment and techniques ensure cables are securely deployed and protected, supporting reliable electricity transmission from offshore wind farms to onshore substations. These vessels play a pivotal role in ensuring the success and longevity of offshore wind energy infrastructure.

10.3.2. *Dynamic Positioning Systems*

Dynamic positioning systems (DPS) play a critical role in offshore wind farms during cable laying operations, emphasizing precise vessel positioning without anchoring. Using GPS, thrusters, and sensors, DPS maintains vessel orientation relative to the seabed, minimizing environmental impact and seabed disturbance. This capability enhances manoeuvrability in challenging conditions like strong currents and variable winds, ensuring accurate cable deployment along designated routes while eliminating anchor-related risks.

By supporting efficient installation processes, DPS directly bolsters the reliability and performance of offshore wind structures with reference to *BVG, 2023*.In tandem with advanced cable laying techniques; DPS facilitates secure cable installation in dynamic marine environments, crucial for long-term operational success. Once cables are laid, additional protective measures such as rock dumping, concrete mattresses and durable casings safeguard against physical damage and stabilize cables on the seabed.

DPS remains integral here, ensuring precise placement of protective materials despite environmental factors like currents and seabed shifts. These combined efforts bolster the durability and reliability of dynamic cables, sustaining efficient operation in the rigorous offshore setting with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

10.4. Power connection

Power connection in the context of dynamic cable installation for offshore wind structures refers to the crucial process of establishing electrical connectivity between offshore wind turbines, substations, or inter-array networks and the onshore power grid. This phase is essential for transmitting electricity generated by offshore wind farms to consumers on land efficiently and reliably. Key Aspects of Power Connection are detailed,

10.4.1. *Subsea Connection Techniques*

In offshore wind structures, ensuring reliable subsea connection of dynamic cables is crucial for uninterrupted electrical continuity. Connector installation starts with meticulous selection based on cable specifications and environmental requirements, including voltage ratings and resistance to corrosion and mechanical strain. Connectors undergo thorough preparation, including cleaning, coating, and inspection before deployment. Specialized tools and equipment, often with the aid of divers or ROVs, are used for precise connector deployment in underwater environments. Connectors are securely affixed to cable terminations to maintain optimal alignment and engagement, critical for electrical continuity with reference to *Francisco Manzano-Agugliaro, and Alfredo Alcayde, 2020*.

Effective sealing mechanisms like resin or mechanical seals are applied to prevent water ingress and preserve insulation integrity. After installation, rigorous testing verifies connection reliability and performance. Electrical tests assess parameters such as continuity, insulation resistance, and dielectric strength to ensure connectors withstand operational voltages. Mechanical tests, including pull and load tests, confirm structural stability under installation and operational stresses. Environmental testing simulates offshore conditions to validate connectors' resilience over their lifespan. Functionality checks replicate operational scenarios to evaluate performance under electrical and mechanical stresses. Any issues prompt detailed evaluation and corrective actions to meet stringent safety and reliability standards in offshore wind installations.

10.4.2. *Onshore Connection Infrastructure:*

The onshore connection infrastructure for offshore wind farms ensures seamless integration and reliable transmission of electricity, starting with the termination and integration of dynamic cables and progressing through grid connection. At the cable landfall, offshore submarine cables connect to onshore cables within joint bays, facilitating secure power transfer. Transition jointing connects dynamic offshore cables to static onshore cables, accommodating their different properties. Onshore cables are routed to substations with consideration for environmental and infrastructure factors. Before operation, extensive testing ensures connection integrity and performance, covering electrical, mechanical, and thermal aspects.

At the onshore substation, electricity undergoes transformation to meet grid voltage and frequency requirements using transformers, switchgear, and control systems. Grid connection adheres to stringent standards for power quality, including voltage stability and frequency regulation. Protection and control systems manage power flow and safeguard infrastructure. High voltage transmission lines transport electricity to major substations in the broader grid network. This infrastructure links offshore wind turbines to onshore networks, enabling efficient electricity transmission while meeting operational and safety standards.

10.5. Functional and Operational Readiness

10.5.1. *Functional Testing*

Once the power connection is established in offshore wind farms, comprehensive electrical tests are crucial to validate the reliability of dynamic cables under various operational conditions. These tests are meticulously designed to ensure that the cables perform optimally and safely throughout their operational lifespan. Insulation Resistance Testing is conducted to assess the quality of the cable insulation, ensuring there are no faults or weaknesses that could lead to electrical leakage or failure. High Voltage Testing applies rigorous voltage levels to the cable to determine its ability to withstand operational voltages without breakdown or excessive leakage currents.

Continuity Testing verifies that the cable maintains uninterrupted electrical flow, crucial for consistent electricity transmission. Load Testing subjects the cable to different load conditions to evaluate its performance under varying operational scenarios, ensuring it can handle both peak loads and regular operational demands effectively with reference to *IEC 60793, 2022*. Additionally, Partial Discharge Testing is employed to detect any minor defects in the insulation that could potentially escalate into larger failures over time. These tests collectively ensure that all components of the cable system, including joints and connections, function correctly and meet stringent performance standards. By rigorously testing the cables before full operational deployment, engineers can confidently guarantee safe and efficient electricity transfer from offshore wind turbines to the onshore grid, minimizing risks of future failures and maintenance issues.

10.5.2. *Operational Monitoring:*

Following functional testing, continuous monitoring of cable performance is crucial post-installation to detect issues early and ensure reliable electricity transmission from offshore wind farms to the onshore grid. Operational monitoring involves real-time data collection using sensors for parameters like voltage, current, temperature, and mechanical stress. This data provides ongoing insights into cable status. Condition monitoring systems employ advanced algorithms to detect anomalies such as temperature rises or electrical load variations, alerting engineers remotely with reference to *Francisco Manzano-Agugliaro, and Alfredo Alcayde, 2020*.

Predictive maintenance analyses data trends to anticipate issues before they impact operations, optimizing maintenance scheduling. Alarm systems trigger alerts for immediate investigation and corrective actions when deviations occur. Performance reporting generates regular insights on cable health and operational efficiency, guiding maintenance and planning. These strategies uphold peak performance, extend cable lifespan, reduce downtime, and minimize maintenance costs, ensuring uninterrupted electricity transmission.

10.6. Post-Installation Monitoring and Maintenance

Post-installation monitoring and maintenance are essential aspects of ensuring the long-term reliability and performance of dynamic cable systems in offshore wind structures.

10.6.1. *Monitoring*

Adding to section 10.5.2, post-installation monitoring includes continuous surveillance and assessment of cable performance and environmental conditions to detect anomalies and potential issues with reference to *Francisco Manzano-Agugliaro, and Alfredo Alcayde, 2020*. Environmental monitoring assesses factors like seawater temperature, salinity, and currents, crucial for evaluating cable integrity and performance. Real-time data from sensors and logging systems supports ongoing analysis. Electrical monitoring ensures cables operate within safe parameters, tracking voltage levels, insulation resistance, and current flow for efficiency and safety. Deviations indicate possible faults or degradation requiring attention. Structural monitoring, using strain gauges or acoustic sensors, detects mechanical stresses or damage affecting cable performance, such as excessive bending or tension from marine activities. Remote monitoring systems enable operators to oversee cable performance remotely, integrating data analytics and predictive maintenance algorithms to anticipate issues and optimize maintenance schedules proactively.

10.6.2. *Maintenance*

Effective maintenance practices are essential to mitigate risks and ensure the longevity of dynamic cables in offshore wind structures. Scheduled inspections using remotely operated vehicles (ROVs), or divers assess cable conditions, checking for wear, corrosion, or marine growth along the entire cable length, including connections and terminations. Cleaning procedures are employed to remove marine growth or debris that can affect cable performance. Anti-fouling measures, such as coatings or materials resistant to biological attachment, help prevent excessive fouling and maintain cable efficiency. Prompt identification and repair of cable faults or damage are crucial to minimize downtime and ensure uninterrupted power transmission. Techniques like splicing, connector replacement, or localized repairs are implemented as needed. Lifecycle management plans ensure that maintenance activities are scheduled according to the cable manufacturer's recommendations and operational experience, optimizing performance and reliability over time. Post-installation monitoring and proactive maintenance practices are critical for enhancing the performance and reliability of dynamic cable systems in offshore wind structures. These measures mitigate risks, extend cable lifespan, and maximize energy production efficiency in challenging marine environments.

10.7. Safety and Environmental Compliance

Dynamic cable installation in offshore wind structures necessitates stringent adherence to safety protocols and environmental compliance to ensure the protection of personnel, equipment, and marine ecosystems.

10.7.1. *Safety Protocols*

Safety protocols are crucial throughout the cable installation process to protect personnel and equipment. Before installation begins, thorough risk assessments identify potential hazards like cable handling, lifting operations, vessel movements, and adverse weather conditions. Control measures are put in place to minimize these risks effectively. Personnel involved in installation, including vessel crews, engineers, and technicians, receive comprehensive training. This training covers safe handling practices, emergency procedures, proper use of personal protective equipment (PPE), and awareness of environmental hazards, ensuring safe operations throughout. Emergency response plans are developed to outline procedures for incidents such as cable damage, vessel collisions, or adverse weather. These plans include communication protocols, evacuation procedures, and emergency contacts for a coordinated response. All equipment used complies with safety standards and undergoes regular maintenance and inspection. Operators are trained and certified to operate machinery safely, maintaining safety as the top priority throughout the installation process.

10.7.2. *Environmental Compliance*

Environmental compliance measures are crucial for mitigating the impact of cable installation on marine ecosystems and meeting regulatory standards. This begins with conducting thorough Environmental Impact Assessments (EIAs) to assess potential risks to marine habitats, species, water quality, and cultural resources before installation. Mitigation measures are then implemented based on these assessments to minimize environmental impacts. Obtaining permits and approvals from regulatory authorities ensures that cable installation activities comply with local, national, and international environmental regulations. This process helps minimize disturbances to marine environments and ensures operations meet established standards. Engaging in marine spatial planning is essential for coordinating cable routes with other marine activities and stakeholders. This process identifies optimal routes that avoid conflicts with fishing areas, shipping lanes, and protected marine areas, thereby reducing disruption and enhancing environmental protection. Implementing environmental monitoring programs during and after installation allows for continuous assessment of marine ecosystem impacts. This includes monitoring water quality, observing marine mammals, and conducting seabed surveys to detect changes and ensure compliance with environmental commitments. By integrating safety protocols and environmental compliance into dynamic cable installation for offshore wind structures, operators can effectively manage risks, protect marine environments, and ensure sustainable deployment of offshore wind farms while promoting long-term environmental stewardship.

10.8. Installation Comparison of Lazy Wave and Catenary Configurations Cables

10.8.1. *Catenary Configuration*

The catenary configuration is ideal for water depths up to 100 meters due to its straightforward installation method. This approach involves laying the cable in a natural curve, leveraging its weight and tension to form a descending and ascending path between the floating structure and the seabed. The installation process typically begins with a pre-lay survey to ensure the seabed is clear. Anchors or clump weights are then strategically placed to secure the cable at specified intervals. Subsequently, the dynamic cable is deployed from the floating structure towards the seabed, adjusting tension as needed to maintain the desired curvature without overstraining the cable. Finally, connections are made to integrate the cable with the power system on the floating structure and the seabed infrastructure. This configuration is valued for its simplicity and cost-effectiveness in shallow waters, where it eliminates the need for buoyancy modules or complex installation techniques.

10.8.2. *Lazy Wave Configuration*

The lazy wave configuration is designed for depths exceeding 100 meters and employs buoyancy modules to impart a wave-like shape to the cable. This method addresses the challenges posed by deeper waters by reducing tension and accommodating movements of the floating structure, including heave, pitch, and yaw. The installation process begins with meticulous pre-lay surveys and route planning. Buoyancy modules are strategically attached along the cable to create the desired wave form, enhancing its stability. Anchors or weights are positioned to secure the cable, followed by controlled deployment to ensure precise placement of the modules. Tension adjustments are made to maintain the wave shape and minimize bending stresses. Finally, connections are established to integrate the cable with both the floating structure and seabed infrastructure. The lazy wave configuration offers distinct advantages in deep waters by effectively managing dynamic forces and distributing the cable's weight more evenly, thereby enhancing overall system reliability and performance.

10.8.3. *Comparison*

The summary of the comparison of configurations regarding the installations is detailed below,

- Water Depth Suitability: Catenary configuration is optimal for depths up to 100 meters due to its simpler installation and cost-effectiveness. Lazy wave configuration is preferred for depths greater than 100 meters, where its ability to handle the floating structure's movements becomes critical.
- Handling Floating Structure Movements: Catenary configuration is less effective in accommodating significant movements, which can lead to higher stresses and potential fatigue in deeper waters. Lazy wave configuration has its superiority in managing the excursions and sea-keeping motions of floating structures.
- Installation Complexity: Catenary configuration is simpler and quicker to install, with fewer components and straightforward deployment. Lazy wave configuration is more complex due to the additional buoyancy modules and precise placement required to achieve the wave shape.

When choosing dynamic cables for offshore floating wind structures, water depth and movement management are key factors. For depths up to 100 meters, the catenary configuration is ideal due to its simplicity and cost-effectiveness, featuring cables that hang naturally from the platform to the seabed. For depths over 100 meters, the lazy wave configuration is preferred. This design includes buoyant sections that create a wave-like shape, effectively handling floating structure movements and distributing stress more evenly. It enhances cable longevity and reduces maintenance costs, as the buoyant sections better withstand wear and tear compared to the longer catenary cables in deep waters. Thus, the lazy wave configuration is more durable and economical for installations in deeper waters.

11. COST EVALUATION

The cost evaluation of dynamic cables for offshore wind structures involves a comprehensive analysis of both CAPEX and OPEX. Dynamic cables, essential for transmitting electricity from floating wind turbines to onshore grids, face unique challenges due to their exposure to harsh marine environments and dynamic operational conditions. Here, we delve into the various cost components and considerations involved in evaluating the financial implications of using dynamic cables in offshore wind installations.

11.1. Capital Expenditure

11.1.1. *Cable Manufacturing and Materials*

Dynamic cables for offshore wind structures are engineered with high-grade materials and advanced techniques to withstand harsh marine conditions. They feature copper or aluminium conductors for excellent conductivity and mechanical strength, insulated with materials like XLPE or EPR for superior electrical insulation and thermal stability.

Armoured with steel wires, these cables resist abrasion and impact damage from marine environments. Integrated fibre optic elements allow for real-time monitoring of critical parameters. Despite higher manufacturing costs, these design elements ensure reliability and durability in offshore wind installations.

11.1.2. *Design and Engineering*

Designing dynamic cables for offshore wind structures involves rigorous engineering to meet marine environment demands and operational requirements. These cables are tailored to withstand dynamic loads from waves, currents, and turbine movements, using advanced modelling for durability. Each project requires custom solutions based on factors like water depth and seabed conditions. Deeper waters may require complex designs like lazy wave or catenary systems to manage increased stresses effectively.

Materials such as cross-linked polyethylene (XLPE) or ethylene propylene rubber (EPR) provide insulation against electrical and environmental stressors. Steel wire armouring protects against physical damage. Adhering to strict standards and regulations ensures safety and performance, with thorough testing and certification verifying compliance. Overall, designing dynamic cables for offshore wind involves significant engineering effort to ensure robustness, reliability, and efficiency in challenging marine environments.

11.1.3. *Ancillaries*

Ancillaries and accessories play a crucial role in the cost of dynamic cables for offshore wind structures, impacting their installation, operation, and maintenance. Buoyancy modules, essential for configurations like lazy wave setups, elevate costs due to materials, manufacturing, and strategic deployment in deeper waters. Cable protection systems such as bend restrictors and outer sheaths mitigate environmental risks, enhancing durability and reducing maintenance expenses.

Specialized termination hardware ensures secure connections at turbine and subsea interfaces, warranting reliability in challenging conditions. Installation tools like cable-laying vessels and ROVs, along with monitoring systems for real-time data collection and analysis, add to expenditures but are vital for efficient deployment and early issue detection. Repair and maintenance kits, comprising spare parts and sealing materials, support ongoing upkeep to minimize downtime and extend cable lifespan, emphasizing long-term cost-effectiveness and operational success in offshore wind projects.

11.1.4. *Installation*

The installation of dynamic cables for offshore wind structures is a critical phase crucial to project success and long-term operational reliability. Comprehensive planning and pre-installation surveys, including seabed mapping and environmental assessments, are essential to identify hazards and optimize cable routes. Specialized cable-laying vessels equipped with dynamic positioning systems ensure accurate deployment without damage, using equipment like tensioners and turntables. ROVs play a vital role in guiding cables, inspecting seabed, and installing protective systems. Techniques such as cable burial and the use of protective materials safeguard against external threats.

Configurations like catenary or lazy wave are tailored for mechanical stress reduction, with buoyancy modules in lazy wave setups enhancing durability. Precise termination and connection methods are crucial for secure, watertight junctions, monitored in real-time for early issue detection. Post-installation inspections verify cable integrity, setting the stage for ongoing maintenance and operational efficiency enhancements. This meticulous approach, though resource-intensive, is pivotal in ensuring the longevity and cost-effectiveness of offshore wind projects. Refer to the relevant section 10 for further details and consult the annex A.9 for a breakdown of installation expenses.

11.2. Operational Expenditure

Maintenance and inspections are pivotal for ensuring the long-term reliability of dynamic cables in offshore wind structures. Condition-based monitoring, utilizing technologies like Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS), plays a crucial role in detecting potential issues early. Regular inspections enable timely preventive maintenance, minimizing downtime and extending the cables' operational lifespan. Repairs and replacements are inevitable for dynamic cables due to factors such as wear, environmental stress, and accidental damage. These interventions can incur substantial costs, particularly in deep water or challenging marine environments.

Proper planning and proactive maintenance strategies are essential to manage these costs effectively. Operational monitoring systems, often integrated with the Internet of Things (IoT), provide continuous tracking of dynamic cable conditions. While these systems involve initial setup costs and ongoing operational expenses, they offer substantial benefits by preventing catastrophic failures and optimizing maintenance schedules. Investing in advanced monitoring technology ensures the reliability and cost-effectiveness of offshore wind projects over the cable's lifecycle.

11.3. Cost Comparison - Catenary vs. Lazy Wave Configurations

11.3.1. *Catenary Configuration*

- CAPEX: Generally lower due to the simpler design and fewer ancillaries required.
- OPEX: The cable's long hanging sections is a challenge

11.3.2. *Lazy Wave Configuration*

- CAPEX: Higher initial costs due to the inclusion of buoyancy modules and additional components.

- OPEX: Lower in the long term for deep water installations. The buoyancy modules reduce excessive bending and tension, decreasing wear and tear and extending the cable's lifespan.

From the industry advisors, for offshore wind installations in water depths exceeding 100 meters, the lazy wave configuration emerges as a more cost-effective choice over the lifecycle of dynamic cables. Despite its higher initial investment (CAPEX), this configuration minimizes operational and maintenance costs (OPEX) through improved durability and reduced wear and tear. By effectively mitigating dynamic loads and environmental impacts, which can substantially affect catenary systems in deep waters, the lazy wave configuration optimizes the overall cost structure of dynamic cable deployment in offshore wind projects with reference to *Manuel U. T. Rentschler, and Frank Adam, 2020*.

11.4. Cost Estimate

A cost evaluation and estimate of a site is detailed in this section. The site characteristics are as mentioned in Table 11.1. The cost breakdown is mentioned in Annex A.9. The reference is made to the with reference to *BVG, 2023*.

Table 11.1: Site characteristics for estimating cost

Parameter	Value	Unit
First operation year	2028	
Wind farm rating	450	MW
Turbine rating	15	MW
Water depth	100	m
Distance from offshore substation to export cable landing point on the shore	60	km
Distance from export cable landing point to the onshore substation	10	km

The day rate cost for a cable laying vessel is € 180,000 with reference to *BVG, 2023*. The main suppliers for these vessels are Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Jan de Nul [shown in Figure 11.1], Oceanteam, Seaway 7 and Van Oord. Proper planning is essential before chartering cable-laying vessels to avoid significant increases in project installation costs. It's also beneficial to explore alternative vessel options equipped with auxiliary equipment that can perform installations that project demands, potentially saving the cost associated with dedicated Cable Laying Vessels (CLVs).

Figure 11.1. Cable laying vessel – Issac Newton [*Source: Jan De Nul*]

The estimation with reference to *BVG, 2023* reveals that the construction and installation costs amount to € 2.4 million per MW for the aforementioned floating offshore wind farm. Conducted on a 450 MW scale, the comprehensive study calculated a total CAPEX of € 1.1 billion. This underscores the critical importance of detailed, project-specific analyses across all facets of the endeavour to achieve substantial cost savings without compromising operational requirements. It highlights the significance of comprehensive planning and assessment, paving the way for informed decision-making throughout the project lifecycle. In essence, this study exemplifies how attention to detail and a methodical evaluation of project components can yield significant cost benefits, reinforcing the value of precision in project management and execution. Reference to the Figure 11.2, 15% of the total cost is spent on cables, which is double the mooring expense. Therefore, adequate cost reduction is possible if an appropriate study is carried out prior to project construction regarding cables. The configuration and cable selection depend on the project, site, environmental conditions, and operational lifespan. Thus, it should be done independently for each project.

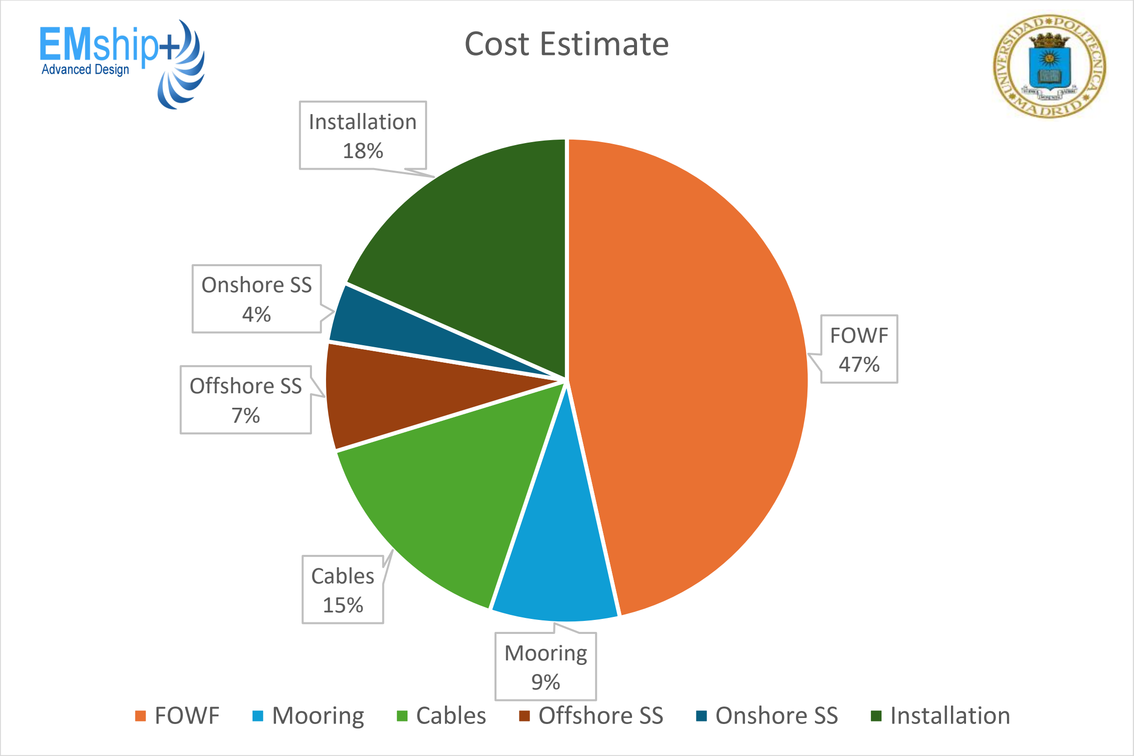


Figure 11.2: CAPEX Summary reference to *BVG, 2023*

11.5. Cost Reduction Measures

A thorough cost evaluation of dynamic cables for offshore wind structures involves balancing initial capital expenditures (CAPEX) with long-term operational expenditures (OPEX). By considering specific environmental conditions and project requirements, stakeholders can make informed decisions that ensure the financial viability and operational reliability of their offshore wind installations. Standardizing cable and ancillary components across different projects can lead to economies of scale, thereby reducing manufacturing and installation costs. Optimizing installation techniques and utilizing advanced, efficient vessels can lower installation costs and reduce the risk of damage during deployment. Investing in advanced real-time monitoring and predictive maintenance technologies can further minimize unexpected failures and optimize maintenance schedules, leading to significant cost savings over time. Adopting collaborative design approaches that integrate cable design with the overall wind farm infrastructure can result in more efficient and cost-effective solutions, reducing both CAPEX and OPEX. The CAPEX for floating offshore wind turbines is most favourable at water depths of 100 to 200 meters. At depths shallower than 100 meters, additional accessories are needed to protect the cables from bending and load due to the structure's motion, which increases costs. Significant cost reductions can be achieved by controlling OPEX. Maintenance of the catenary layout at depths over 100 meters is very expensive due to the impact of the long hanging length. In contrast, the lazy wave configuration mitigates this impact with a buoyant section, reducing maintenance costs. The accessories required for the lazy wave configuration also ensure lower maintenance costs compared to the catenary layout. A detailed cost breakdown in Annex A.9 shows that reducing annual operations and maintenance costs can lead to substantial overall cost reductions. The Figure 11.2 illustrates the significant contribution of cables to the overall cost of an offshore wind project. Given the substantial budgets associated with these projects, this contribution is far from negligible. To optimize project expenses without compromising safety and operational efficiency, it is crucial to explore potential cost reductions in cable design and installation.

One key strategy for cost reduction is ensuring that the design of the cables does not compromise safety or operational efficiency. This involves selecting materials and configurations that are both cost-effective and reliable. Additionally, the proper installation of the cables, with a focus on long-term maintenance, is essential. Implementing best practices during the installation phase can prevent future issues and reduce maintenance costs over the project's lifespan. Referencing operational projects and existing wind farms is invaluable during the initial phases of a new project. Learning from the experiences and challenges faced by these projects can help avoid undesirable costs and inefficiencies. This knowledge allows for the identification of best practices and potential pitfalls, enabling more informed decision-making and more accurate budgeting.

In conclusion, by carefully considering cable design, installation techniques, and leveraging insights from existing projects, stakeholders can achieve significant cost reductions while maintaining the integrity and efficiency of their offshore wind installations. This holistic approach ensures that the project remains financially viable and operationally robust over its lifetime.

12. INSPECTION AND MONITORING

In the context of offshore wind structures, particularly those utilizing dynamic cables, the inspection and monitoring protocols are critical to ensuring operational safety, reliability, and longevity of the power transmission systems. These cables, essential for transmitting electricity from floating wind turbines to onshore grids, face unique challenges due to their exposure to harsh marine environments and dynamic operational conditions. After the initial installation of dynamic cables in Floating Offshore Wind Platform (FOWP), comprehensive inspections are conducted to assess their as-laid condition. This initial inspection serves as a baseline to document any potential damage incurred during the laying process, which can significantly impact the cable's performance and lifespan over time. The primary objective here is to identify any immediate concerns and ensure that the cable meets operational standards from the outset with reference to *Maria Ikhennicheu, and Mattias Lynch, 2020*.

12.1. Long-Term Monitoring Strategies

Long-term monitoring is essential for ensuring the reliability and longevity of dynamic cables in Floating Offshore Wind Platform (FOWP). These cables face harsh marine conditions, including temperature fluctuations, seawater corrosion, and mechanical stresses, making early detection of degradation crucial. Monitoring enables operators to identify issues like insulation deterioration and mechanical damage early, preventing costly repairs and minimizing downtime. Effective long-term monitoring involves initial as-laid inspections and condition-based maintenance (CBM). As-laid inspections establish baseline data upon installation, ensuring cables meet operational standards. CBM utilizes advanced technologies such as optical fibre sensors for real-time monitoring of temperature, strain, and vibration, providing insights into cable health and facilitating proactive maintenance.

Technologies like Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS) enhance monitoring capabilities further, same detailed later in the section. These tools enable early anomaly detection and proactive maintenance planning. Long-term monitoring not only enhances reliability but also optimizes costs by minimizing downtime and extending cable lifespan through proactive maintenance. It ensures compliance with safety and environmental regulations, demonstrating operational excellence and sustainability in offshore wind installations.

12.2. Advanced Monitoring Technologies

Several advanced technologies are deployed to enhance the monitoring capabilities of dynamic cables:

12.2.1. *Distributed Temperature Sensing*

Distributed Temperature Sensing (DTS) is crucial in offshore wind energy for monitoring temperature along dynamic cables in Floating Offshore Wind Platform (FOWP). Using optical fibres and laser pulses, DTS detects temperature changes, crucial for identifying overheating or insulation degradation. It offers high spatial resolution to pinpoint anomalies and operates reliably in harsh offshore conditions. Integrated with alarms, DTS alerts to temperature thresholds, aiding proactive maintenance.

12.2.2. *Distributed Acoustic Sensing*

Distributed Acoustic Sensing (DAS) is vital for monitoring submarine cables in Floating Offshore Wind Platform (FOWP). By utilizing coherent Rayleigh scattering, DAS converts optical fibres into distributed sensors that detect vibrations and acoustic disturbances along the cable with high spatial resolution, down to meters. This continuous monitoring capability without additional sensors allows real-time detection of environmental impacts, operational activities, and structural integrity issues. DAS operates reliably in harsh offshore conditions, enduring saltwater exposure and mechanical stresses, ensuring data accuracy over extended periods. Integrated with alarm systems, it promptly alerts when acoustic thresholds are exceeded, enabling swift responses to potential issues and enhancing operational safety. Future advancements aim to integrate DAS with other technologies for comprehensive asset management and predictive maintenance in offshore wind farms, supporting sustainable energy production and efficient operations.

12.2.3. *Partial Discharge Measurement*

Partial Discharge (PD) Measurement is crucial for assessing insulation integrity in dynamic cables at Floating Offshore Wind Platform (FOWP). It detects minor insulation defects early, not visible during routine inspections, ensuring operational reliability through continuous monitoring. Engineers use PD data to diagnose defects, plan proactive maintenance, and extend cable lifespan offshore. Despite requiring specialized equipment and expertise, PD

Measurement improves reliability by predicting failures and optimizing maintenance strategies. Future advancements aim to enhance sensitivity and integration with IoT for remote monitoring, supporting sustainable offshore wind energy development.

12.2.4. *Distributed Strain Sensing*

Distributed Strain Sensing (DSS) is vital for monitoring strain variations in dynamic cables at Floating Offshore Wind Platform (FOWP). Operating on Optical Time Domain Reflectometry (OTDR), DSS uses embedded optical fibres as sensors to detect mechanical loading, bending, and environmental stresses affecting cable integrity. It provides continuous, high-resolution strain monitoring, enabling early detection of stress-induced issues like fatigue or deformation. DSS systems withstand offshore conditions, integrating with broader structural health monitoring to enhance operational safety and lifespan of offshore wind installations. Future advancements aim to improve accuracy, reliability, and integration with IoT for real-time data analytics and predictive maintenance, supporting sustainable offshore energy development.

12.3. Integration with IoT

Integration with the Internet of Things (IoT) revolutionizes the monitoring of dynamic cables in Floating Offshore Wind Platform (FOWP). IoT connects sensors like Distributed Temperature Sensing (DTS), Distributed Acoustic Sensing (DAS), and more across cable infrastructure. These sensors capture real-time data on temperature, strain, vibration, and insulation. Data is transmitted via networks to centralized systems for continuous monitoring and analysis using advanced analytics and predictive algorithms. This enables early fault detection, predictive maintenance scheduling, and optimized operational decisions to enhance reliability and reduce costs. IoT benefits include real-time monitoring for early problem detection, predictive maintenance for efficient resource allocation, and remote capabilities for swift response to incidents. Challenges like data security and scalability require robust solutions. Future IoT advancements may include edge computing for real-time data processing, AI for autonomous decision-making, and smart grid integration.

13. CONCLUSION

In conclusion, this report presents a investigation into the catenary and lazy wave configurations for catenary-moored floating offshore wind structures, focusing on their suitability across varying water depths. The study aims to pinpoint the optimal configuration for different depth ranges, considering both operational efficiency and cost-effectiveness. The analysis underscores that the catenary configuration performs admirably in shallow water depths up to 100 meters. It demonstrates lower initial costs and simpler installation procedures, making it a favourable choice where depth-related challenges are less pronounced. However, as water depths exceed 100 meters, the advantages of the lazy wave configuration become increasingly apparent. The incorporation of buoyancy elements and specialized accessories such as bend stiffeners and modules significantly reduces motion-induced wear and maintenance requirements. This shift is crucial for mitigating the substantial hanging load and operational complexities associated with deeper installations as detailed in the fitness summary Table 13.1.

Table 13.1: Fitness of Catenary and Lazy wave layout

Fitness					
Depth [m]	50	75	100	150	200
Catenary 0°	0.3	0.2	0.3	0.9	1.2
Lazy 0°	0.5	0.3	0.2	0.6	0.6
Catenary 180°	0.2	0.2	0.3	0.8	1.1
Lazy 180°	0.3	0.3	0.2	0.3	0.4
Average Fitness					
Catenary	0.3	0.2	0.3	0.9	1.2
Lazy	0.4	0.3	0.2	0.4	0.5

Moreover, the study emphasizes the critical role of installation practices tailored to each configuration. While the catenary offers straightforward deployment in shallower waters, both layouts require meticulous planning and execution to ensure long-term operational reliability. Beyond 100 meters, the lazy wave configuration emerges as more operationally efficient, leveraging advanced technologies and design integration to minimize lifecycle costs and maximize uptime.

The economic analysis presented in Figure 9.12, Figure 11.2 and Table 13.1, highlights the clear cost advantages of the lazy wave configuration for depths exceeding 100 meters. Despite potentially higher initial CAPEX, the reduced OPEX and enhanced durability over the project's lifespan make it a more cost-effective choice in the long run. Conversely, while the catenary layout may offer lower upfront investment, its higher maintenance and operational costs in deeper waters diminish its overall economic viability.

Furthermore, the report addresses the significant maintenance challenges associated with the catenary configuration due to its susceptibility to motion and wear. This necessitates frequent and often unscheduled repairs, which incur additional expenses and logistical challenges. Moreover, the critical nature of cable systems in delivering power means that neglecting repairs is not an option, as interruptions could lead to significant operational disruptions.

In contrast, the lazy wave configuration offers distinct advantages, particularly in deep waters. These layouts includes accessories such as bend stiffeners, modules, and bend restrictors, which play crucial roles in reducing wear and minimizing the need for repairs during severe and extreme sea states. By effectively managing cable movement and stress, these accessories enhance the configuration's durability and reliability, ultimately lowering maintenance costs and operational risks. Unlike the catenary layout, which is more susceptible to environmental stresses, the incorporation of specialized accessories in the lazy wave design ensures robust performance and longevity. This strategic approach not only enhances operational efficiency but also reinforces the economic viability of offshore wind projects in challenging offshore conditions.

In summary, the findings from this study provide valuable insights for stakeholders involved in the design, deployment, and management of 15 MW catenary-moored semi-submersible floating offshore wind turbines. By identifying the optimal water depth range of 50 to 200 meters for effective deployment and highlighting the superior performance of the lazy wave configuration in deeper waters, this research contributes to economically viable offshore wind energy solutions. These insights are pivotal for shaping future strategies that enhance the efficiency, reliability, and cost-effectiveness of offshore wind projects worldwide.

14. FUTURE WORKS

This study focused on the behaviour of dynamic cables in Floating Offshore Wind Turbines (FOWTs) under extreme environmental conditions, primarily analysing the catenary mooring configuration due to its critical motions. Future research could explore other mooring configurations to understand their behaviour under different conditions, considering factors like site characteristics and environmental conditions.

The load case examined extreme environmental conditions, crucial for understanding the structure's resilience. Future studies could extend this to normal and severe sea states to provide a broader perspective on performance under various scenarios.

Initially targeting semi-submersible structures, the study's insights can apply to other structures like Tension Leg Platforms (TLP), Spars, and Barges, reflecting the evolving offshore wind industry. Each structure type merits detailed study based on its specific operational criteria and industry demands.

The study compared catenary and lazy wave mooring configurations, focusing on the latter's benefits in deeper waters despite the initial cost advantages of the former. Further research could delve deeper into mooring system design and cable specifics, enhancing understanding and optimization of floating offshore wind structures.

Simulation duration of 3600 seconds was chosen to capture extreme environmental events, typical in a 50-year period. Longer simulations and diverse load cases could provide more comprehensive data for design and operational planning.

Future research could also include detailed cost estimation and installation analysis over the project lifespan, identifying cost-intensive periods and optimizing cost management strategies accordingly.

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17. ANNEXURE

A.1 Simulation layout

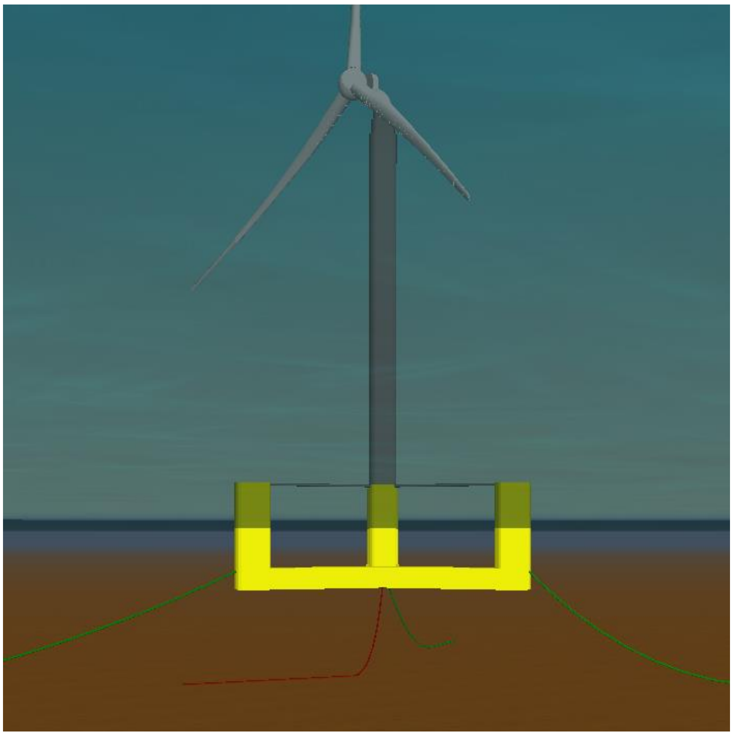


Figure 17.1: Catenary configuration for 50 metre water depth (Simulation 1 & 11)

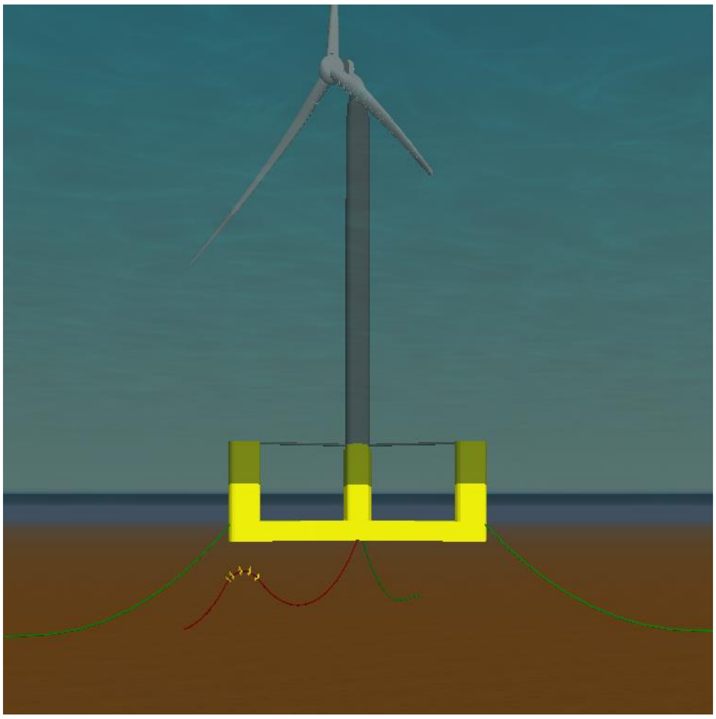


Figure 17.2: Lazy wave configuration for 50 metre water depth (Simulation 2 & 12)

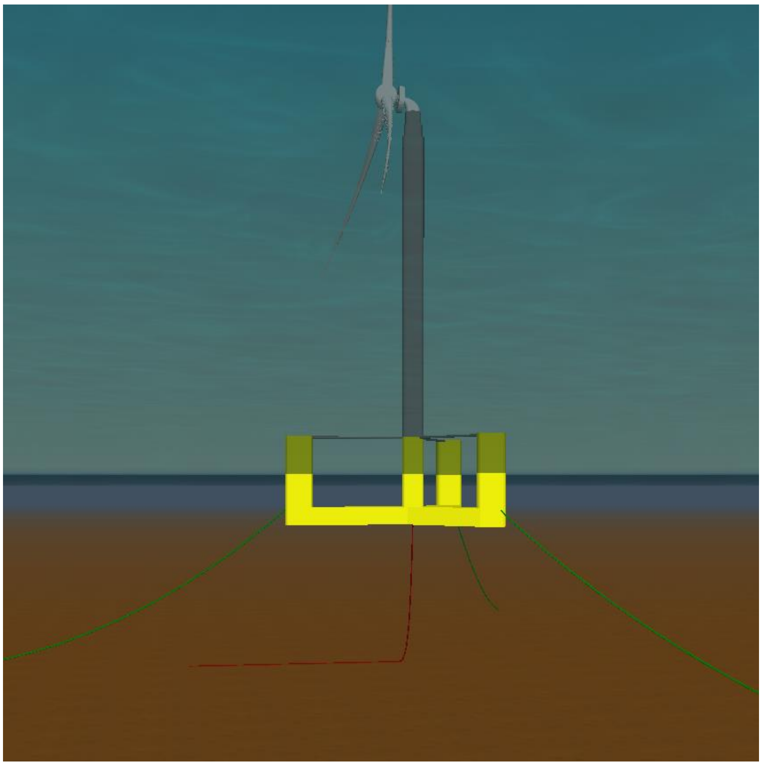


Figure 17.3: Catenary configuration for 75 metre water depth (Simulation 3 & 13)

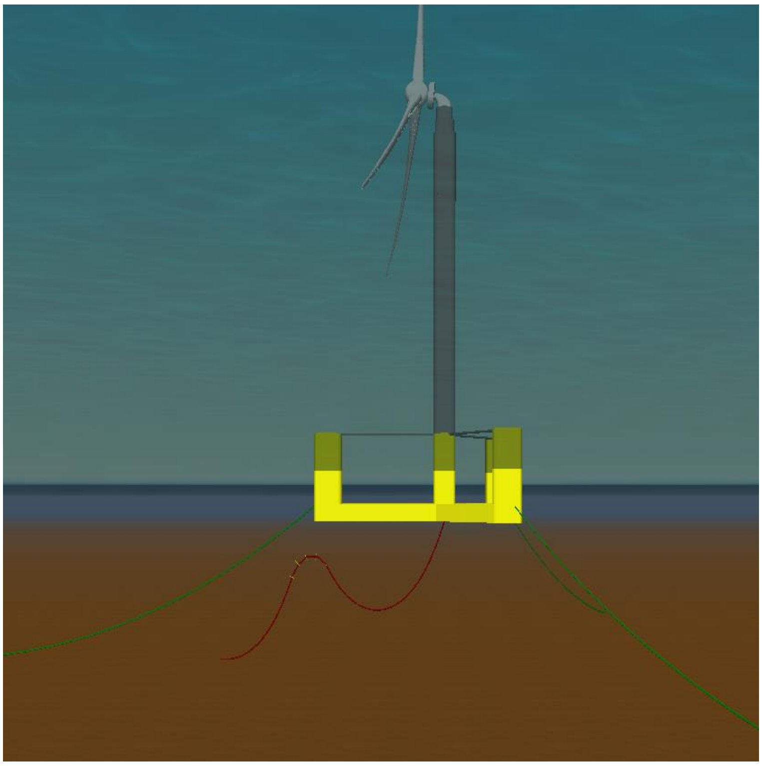


Figure 17.4: Lazy wave configuration for 75 metre water depth (Simulation 4 & 14)

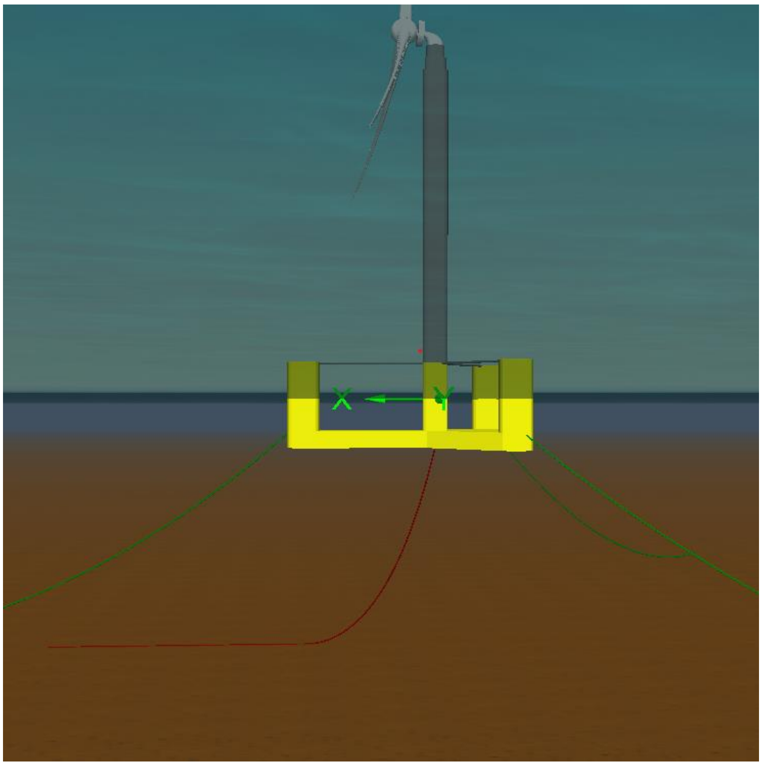


Figure 17.5: Catenary configuration for 100 metre water depth (Simulation 5 & 15)

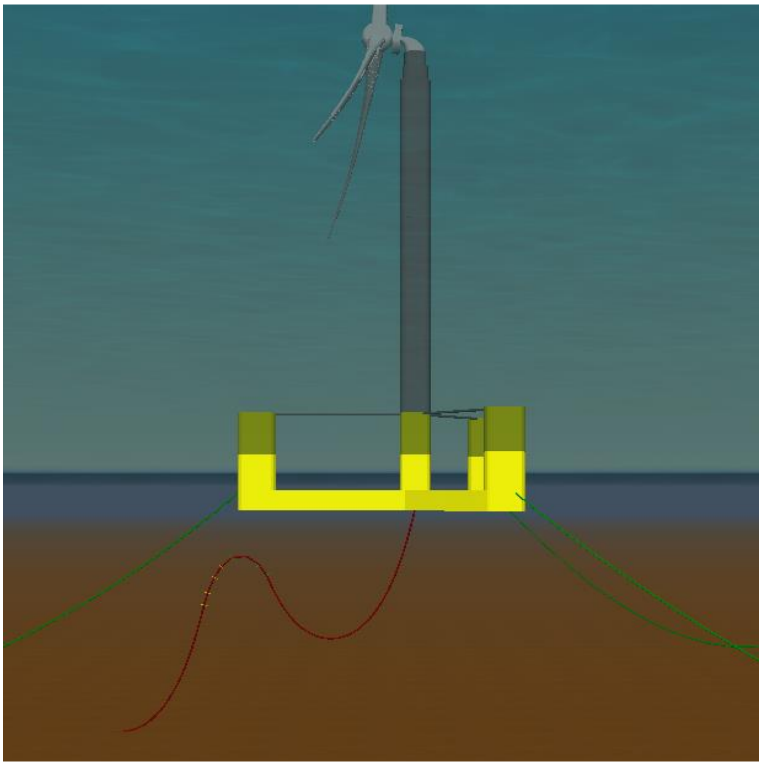


Figure 17.6:Lazy wave configuration for 100 metre water depth (Simulation 6 & 16)

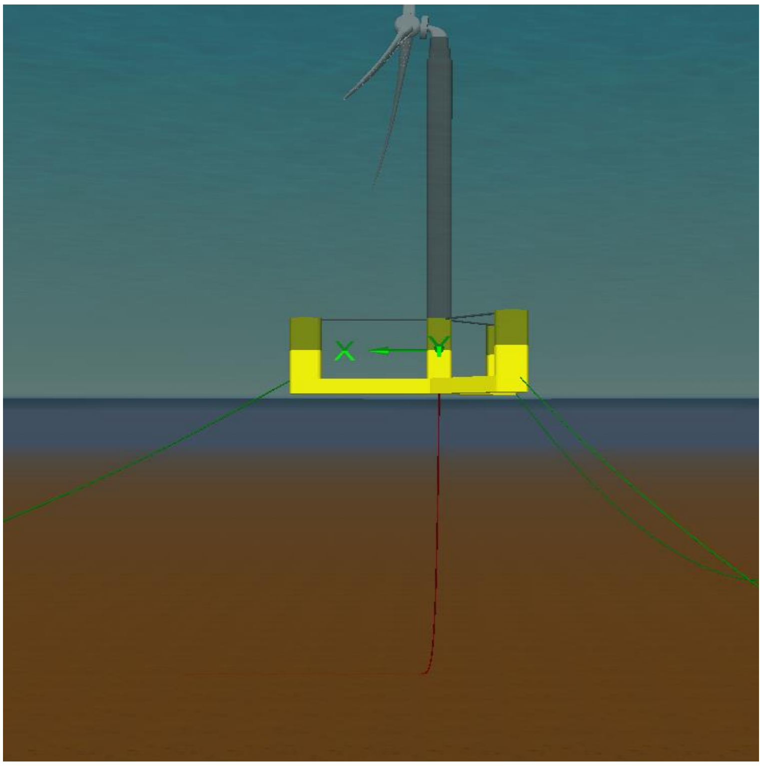


Figure 17.7: Catenary configuration for 150 metre water depth (Simulation 7 & 17)

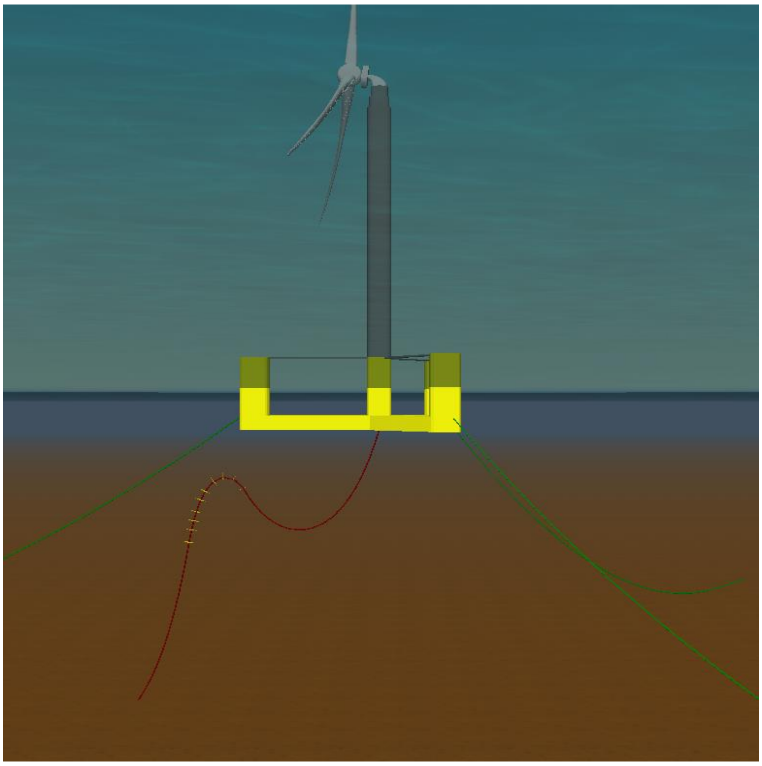


Figure 17.8: Lazy wave configuration for 150 metre water depth (Simulation 8 & 18)

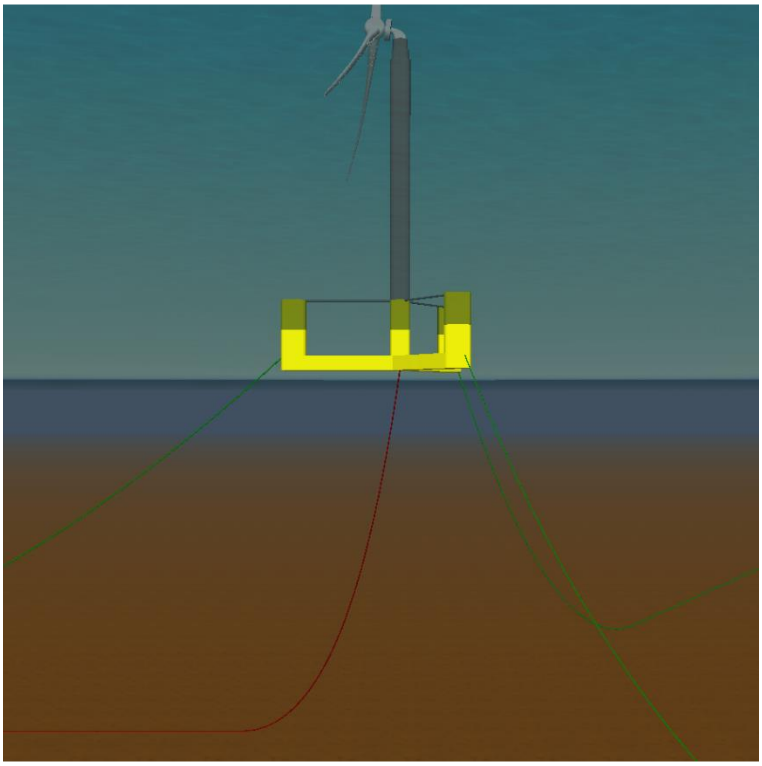


Figure 17.9: Catenary configuration for 200 metre water depth (Simulation 9 & 19)

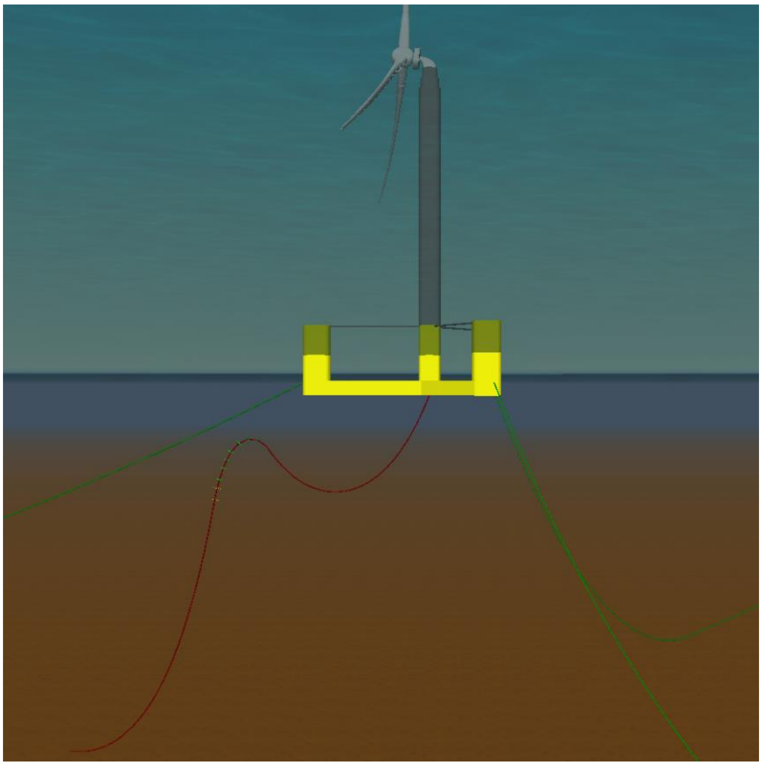


Figure 17.10: Lazy wave configuration for 200 metre water depth (Simulation 10 & 20)

A.2 Ancillary market data

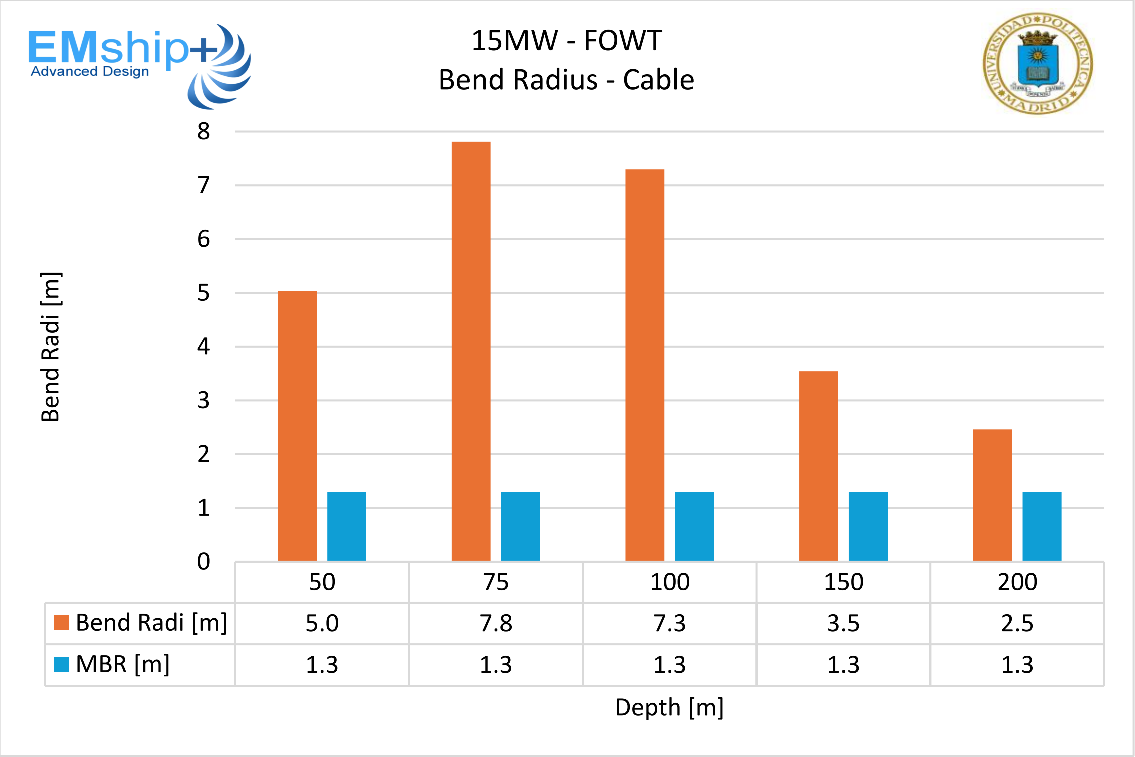
Table 17.1: Bend stiffener market details

Manufacturer	Type	Line diameter [mm]	Length [m]	Weight [kg]	External diameter [mm]	Source
EXSTO	Static & Dynamic	30 - 400	1.2 - 8	15 - 3500	300 - 2000	*EXSTO*
Trelleborg	Static & Dynamic	Project spec.	Project spec.	Project spec.	Project spec.	*Trelleborg*
Bardot	Static, Dynamic & Split	Project spec.	Project spec.	Project spec.	Project spec.	-
BMP	Static, Dynamic & Split	Project spec.	Project spec.	Project spec.	Project spec.	*BMP*
Balmoral	Static, Dynamic & Split	Project spec.	Up to 14 m	Project spec.	Project spec.	*Balmoral*
Plastiprene	Static & Dynamic	Project spec.	Up to 12 m	Project spec.	Project spec.	-

Table 17.2: Bend restrictor market details

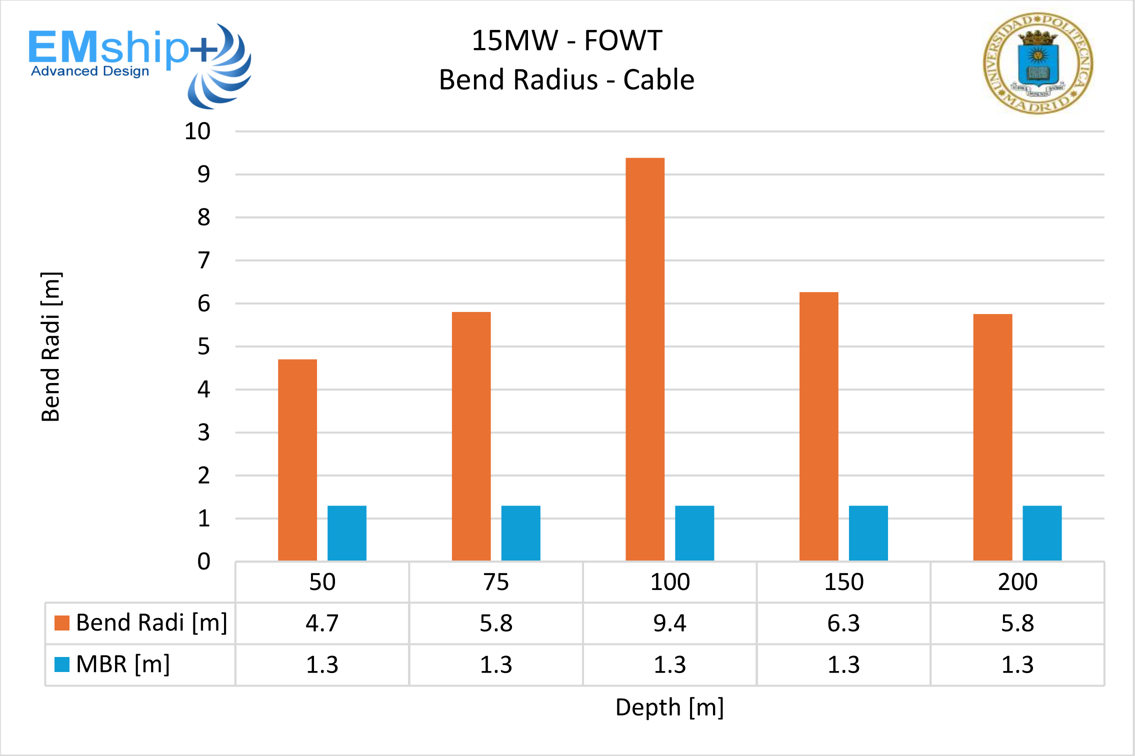
Manufacturer	Type	External diameter [mm]	MBR [m]	Weight [kg]	Source
EXSTO	Polyurethane or steel	30 - 400	0.5 - 15	0.5 - 100	*EXSTO*
ABCO subsea	Steel	100 - 400	-	-	*ABCO*
Trelleborg	Subsea and renewable	-	-	-	*Trelleborg*

A.3 Cable results [0°]



	50	75	100	150	200
🟧 Bend Radi [m]	5.0	7.8	7.3	3.5	2.5
🟦 MBR [m]	1.3	1.3	1.3	1.3	1.3

Figure 17.11: Bend radius for Catenary layout [0°]



	50	75	100	150	200
🟧 Bend Radi [m]	4.7	5.8	9.4	6.3	5.8
🟦 MBR [m]	1.3	1.3	1.3	1.3	1.3

Figure 17.12: Bend radius for Lazy wave layout [0°]

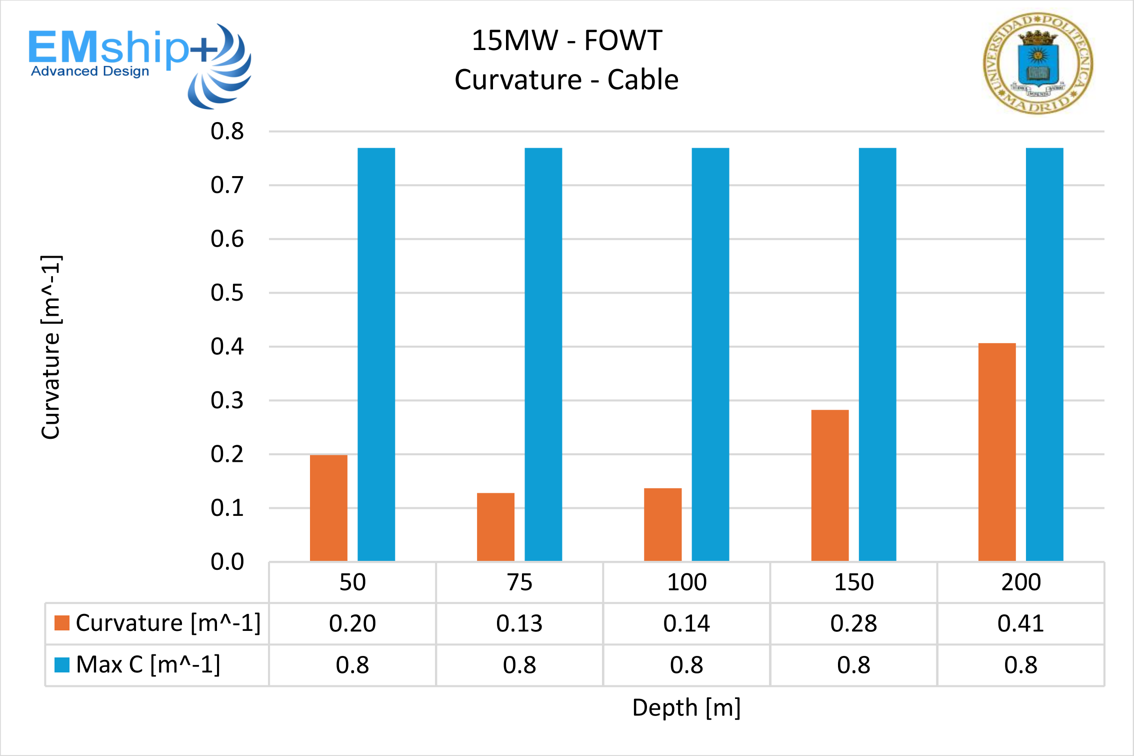


Figure 17.13: Curvature for Catenary layout [0°]

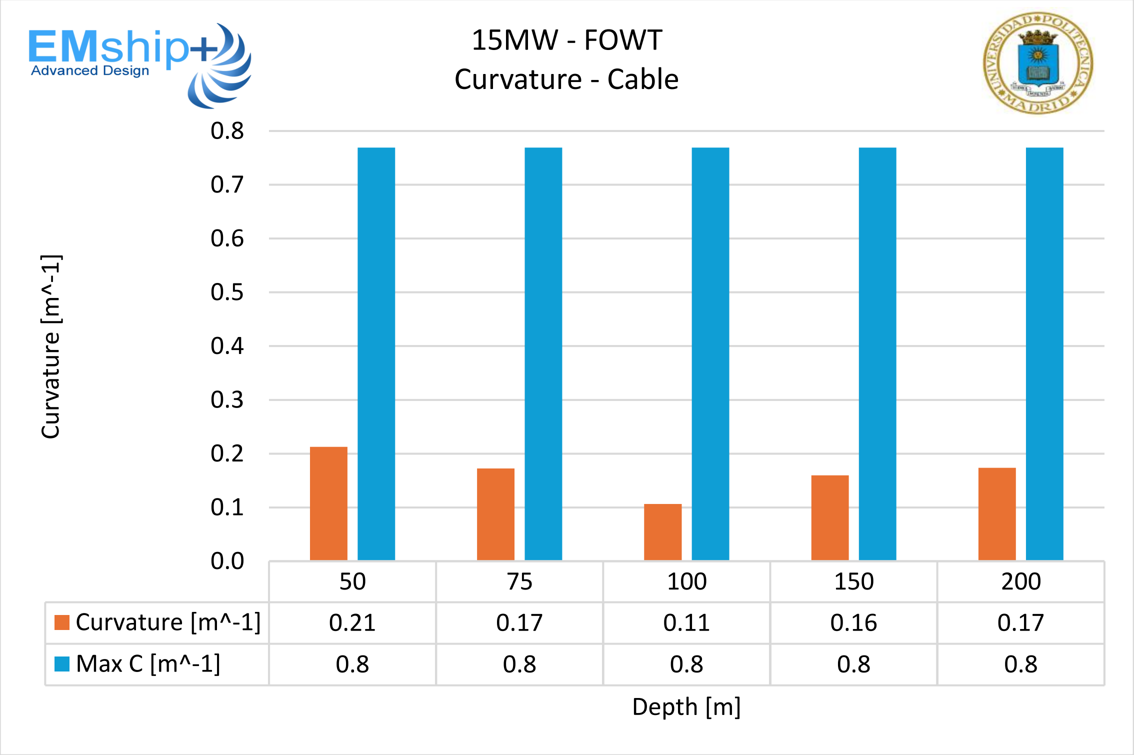


Figure 17.14: Curvature for Lazy wave layout [0°]

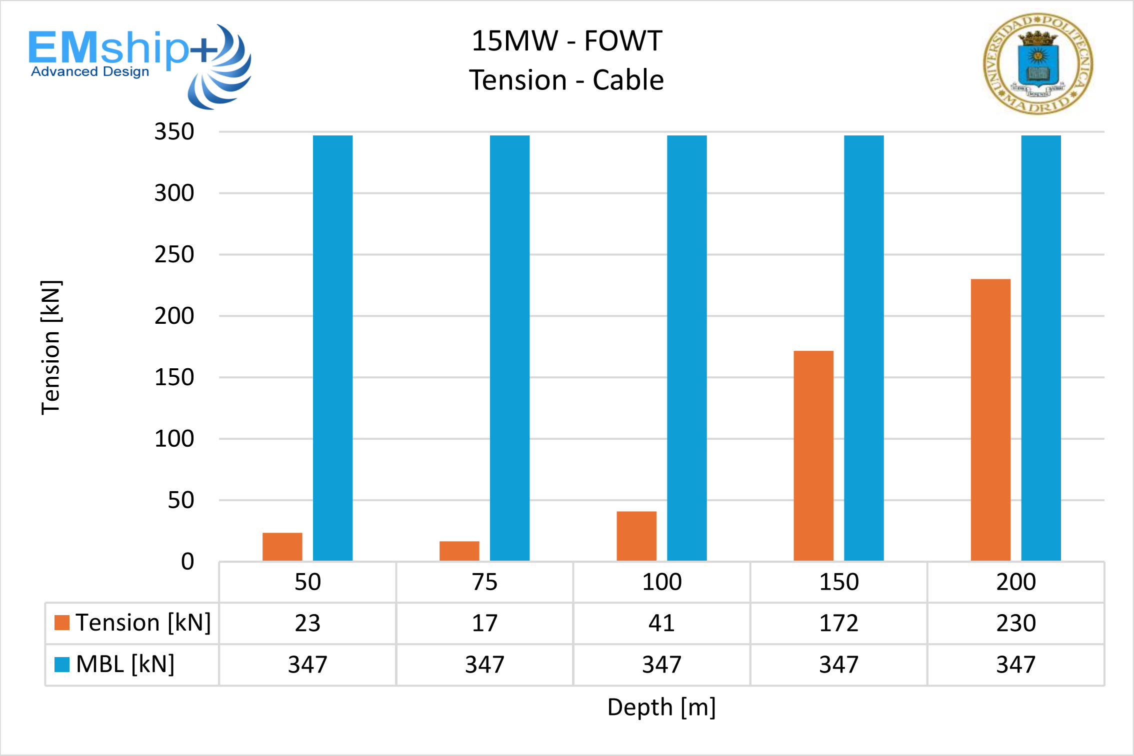


Figure 17.15: Tension for Catenary layout [0°]

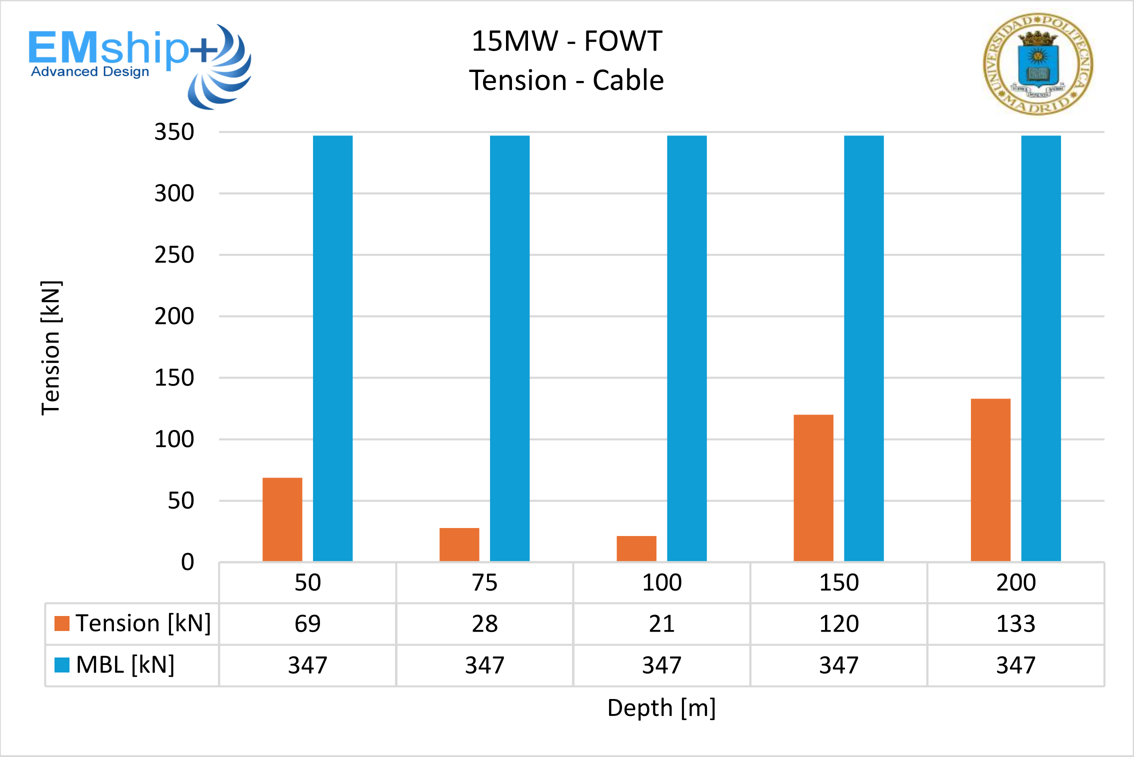


Figure 17.16: Tension for Lazy wave layout [0°]

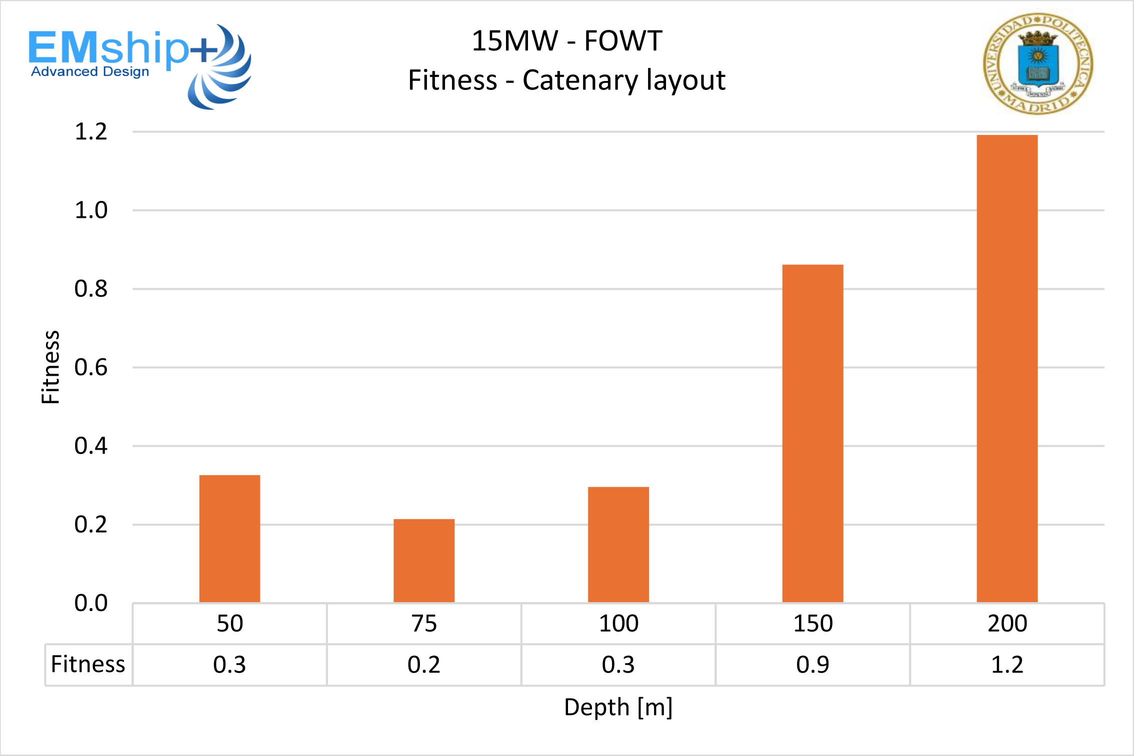


Figure 17.17: Fitness for Catenary layout [0°]

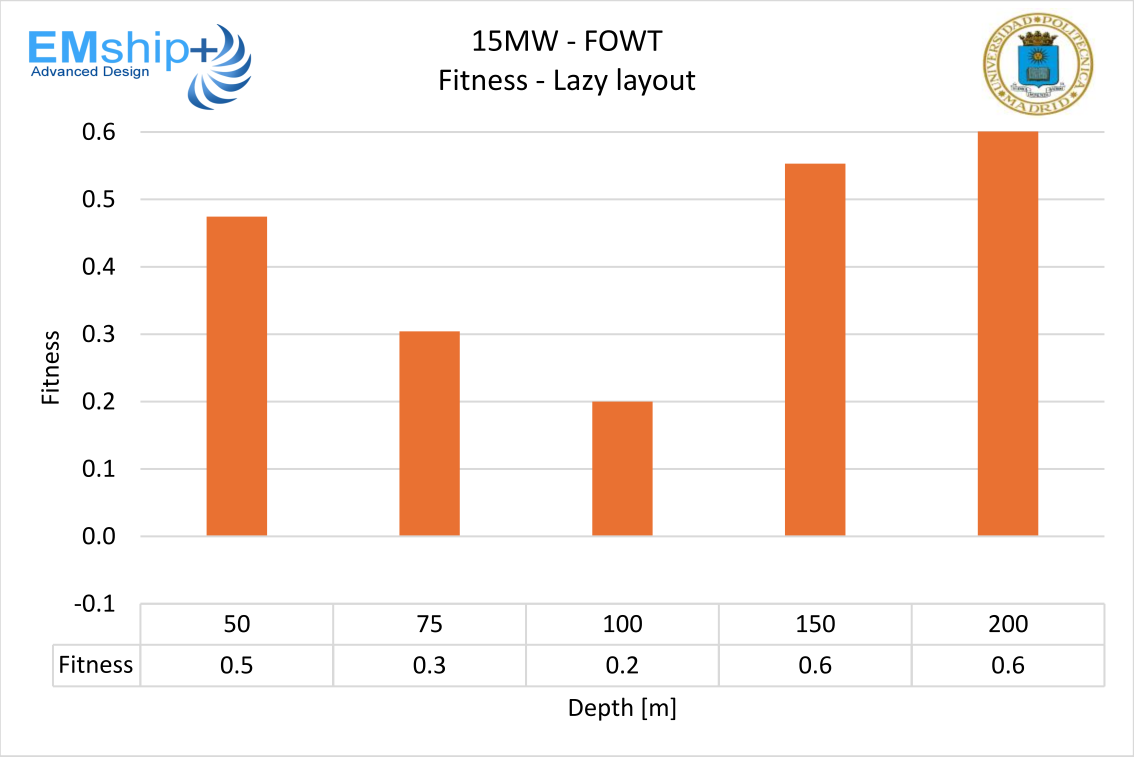
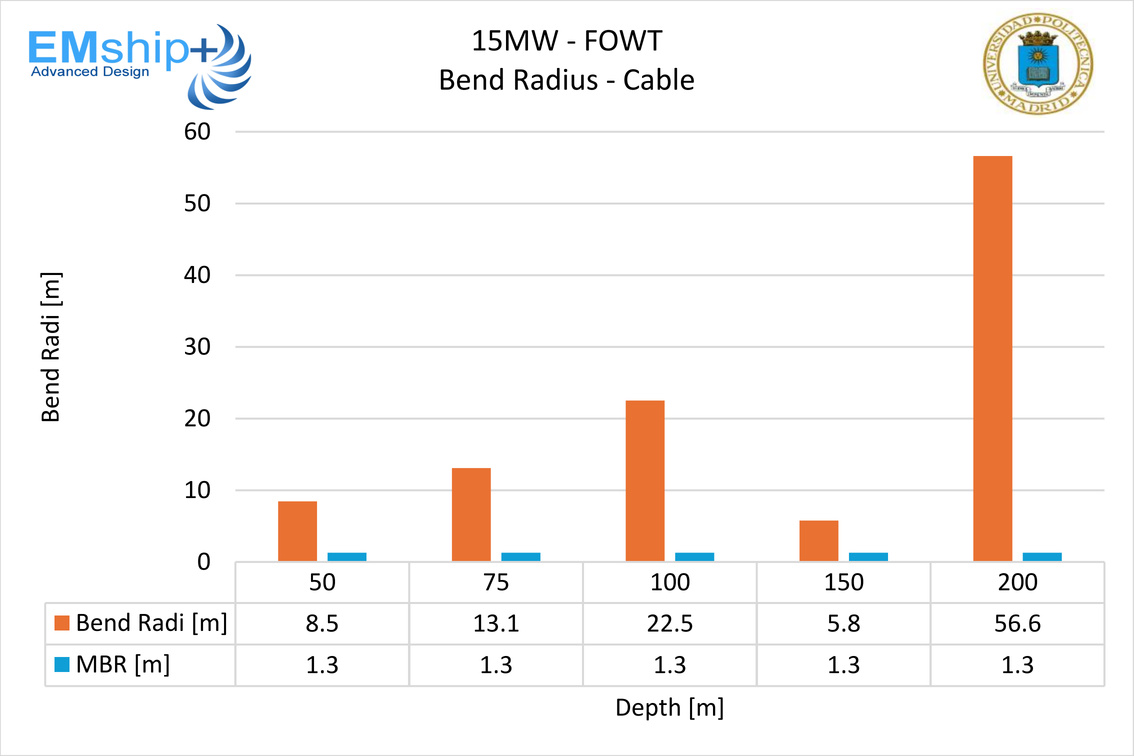


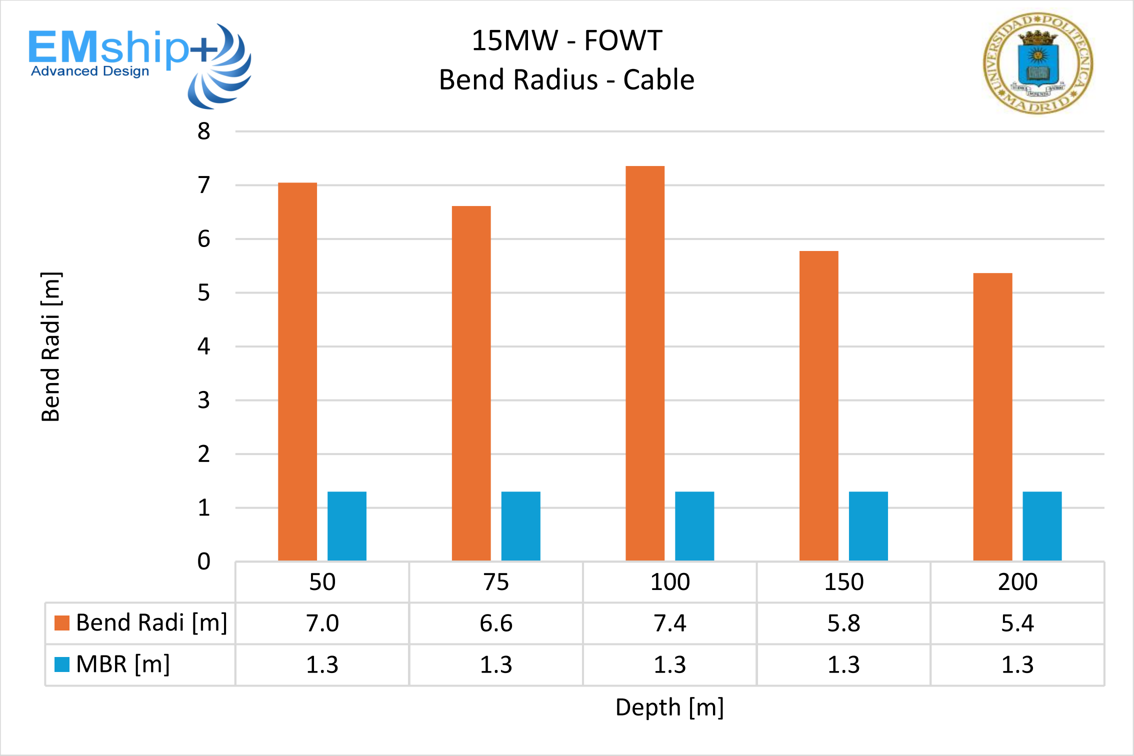
Figure 17.18: Fitness for Lazy wave layout [0°]

A.4 Cable results [180°]



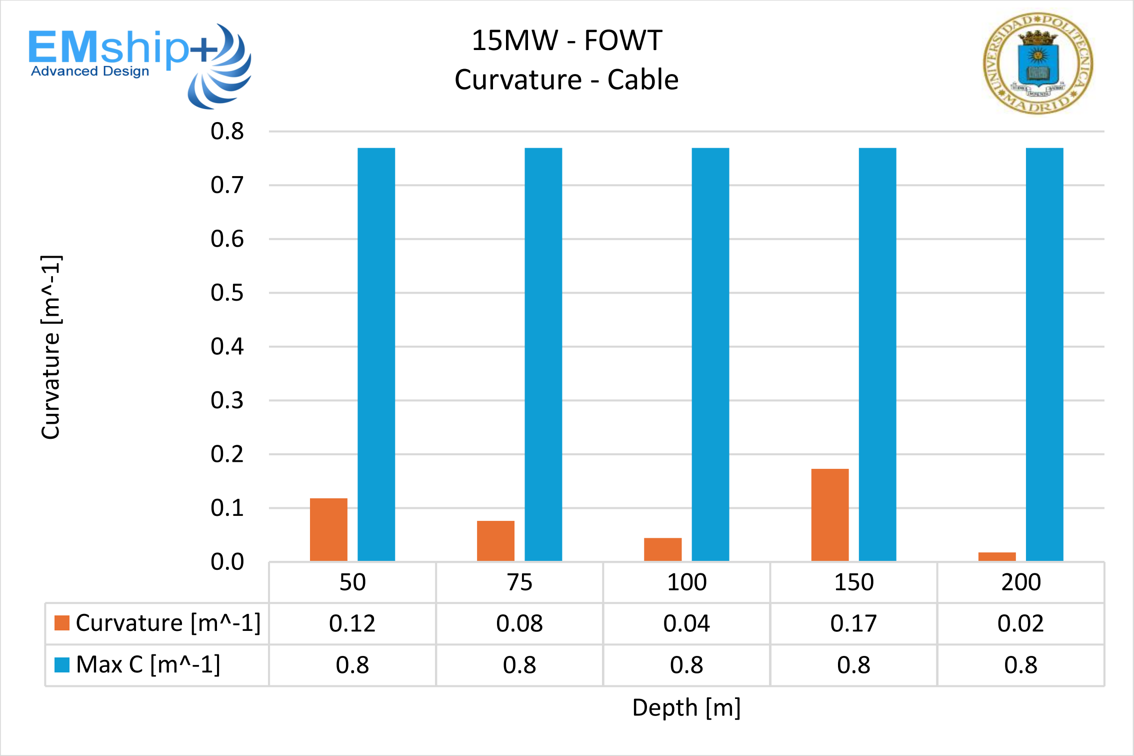
	50	75	100	150	200
🟧 Bend Radi [m]	8.5	13.1	22.5	5.8	56.6
🟦 MBR [m]	1.3	1.3	1.3	1.3	1.3

Figure 17.19: Bend radius for Catenary layout [180°]



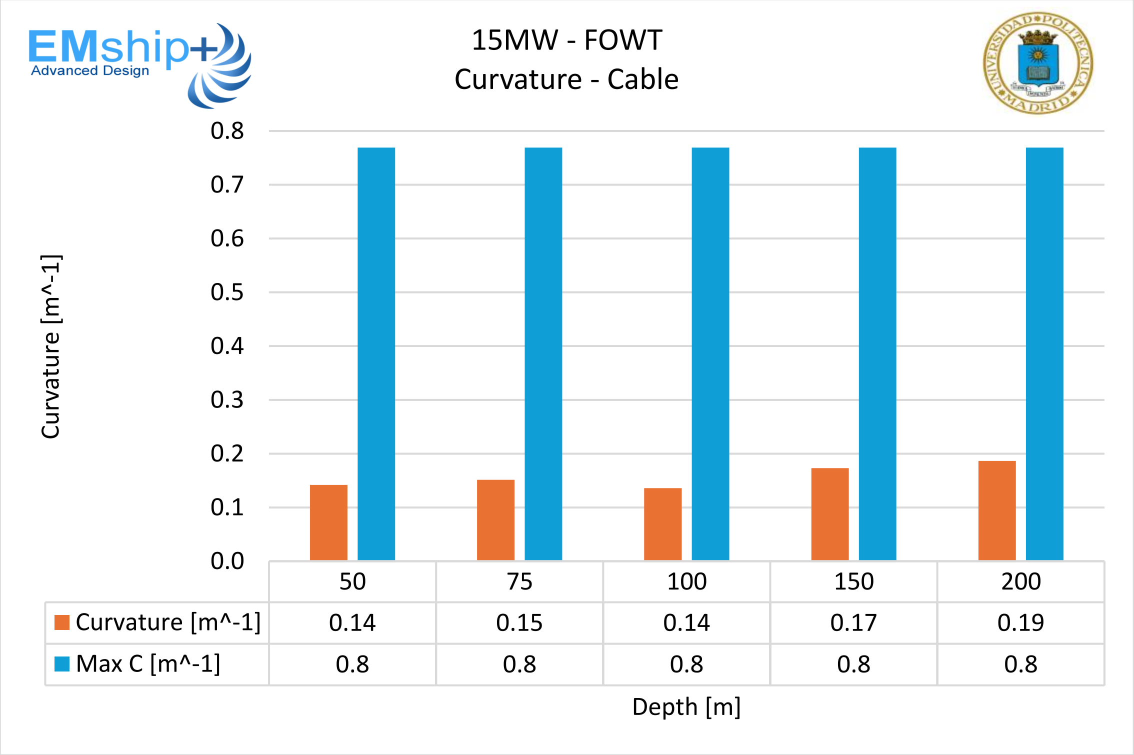
	50	75	100	150	200
🟧 Bend Radi [m]	7.0	6.6	7.4	5.8	5.4
🟦 MBR [m]	1.3	1.3	1.3	1.3	1.3

Figure 17.20: Bend radius for Lazy wave layout [180°]



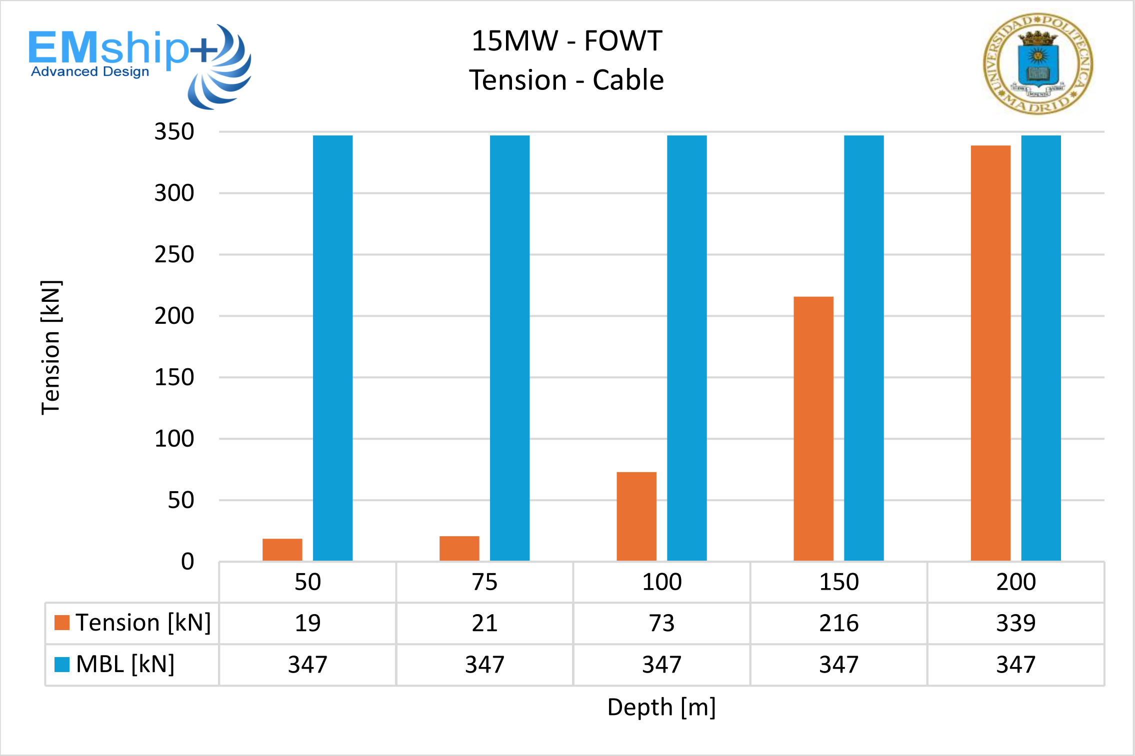
	50	75	100	150	200
🟧 Curvature [m^-1]	0.12	0.08	0.04	0.17	0.02
🟦 Max C [m^-1]	0.8	0.8	0.8	0.8	0.8

Figure 17.21: Curvature for Catenary layout [180°]



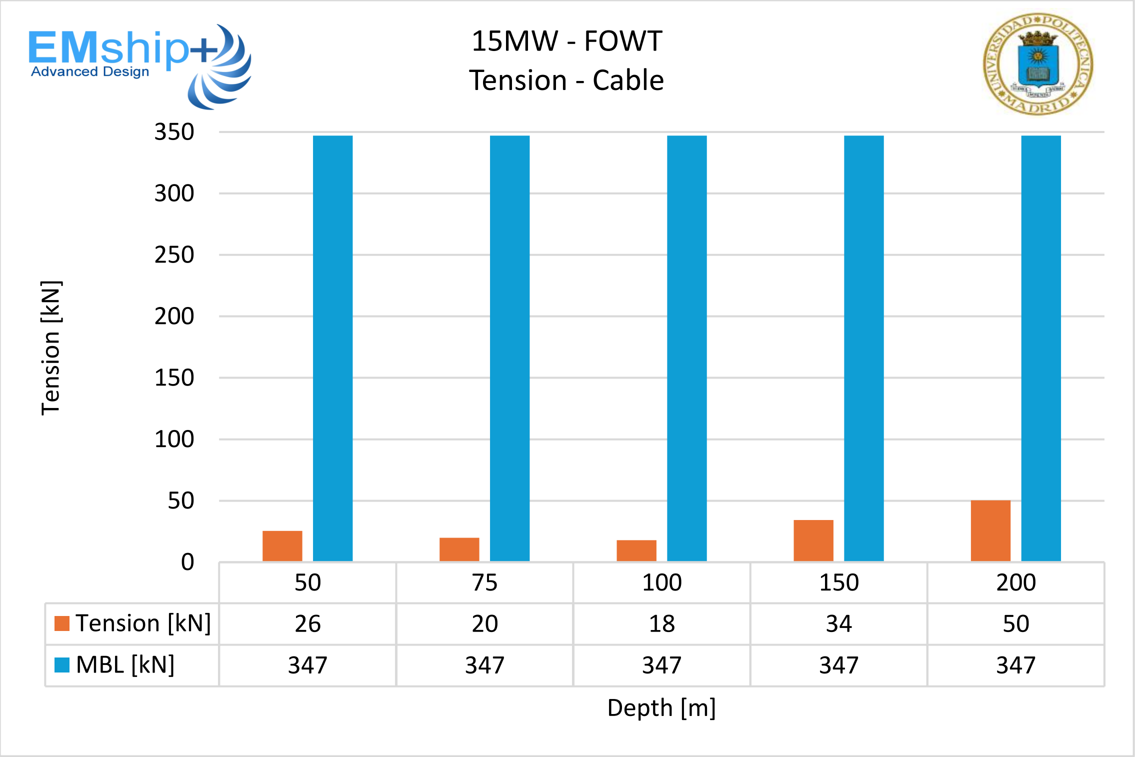
	50	75	100	150	200
🟧 Curvature [m^-1]	0.14	0.15	0.14	0.17	0.19
🟦 Max C [m^-1]	0.8	0.8	0.8	0.8	0.8

Figure 17.22: Curvature for Lazy wave layout [180°]



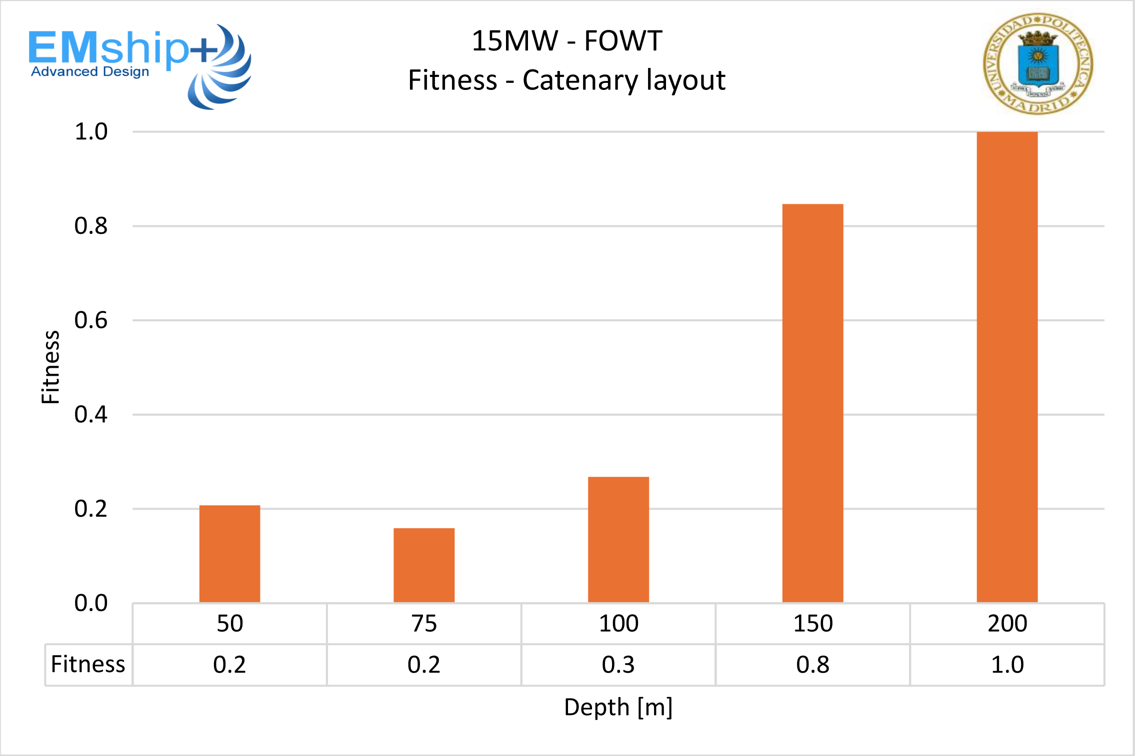
Depth [m]	50	75	100	150	200
🟧 Tension [kN]	19	21	73	216	339
🟦 MBL [kN]	347	347	347	347	347

Figure 17.23: Tension for Catenary layout [180°]



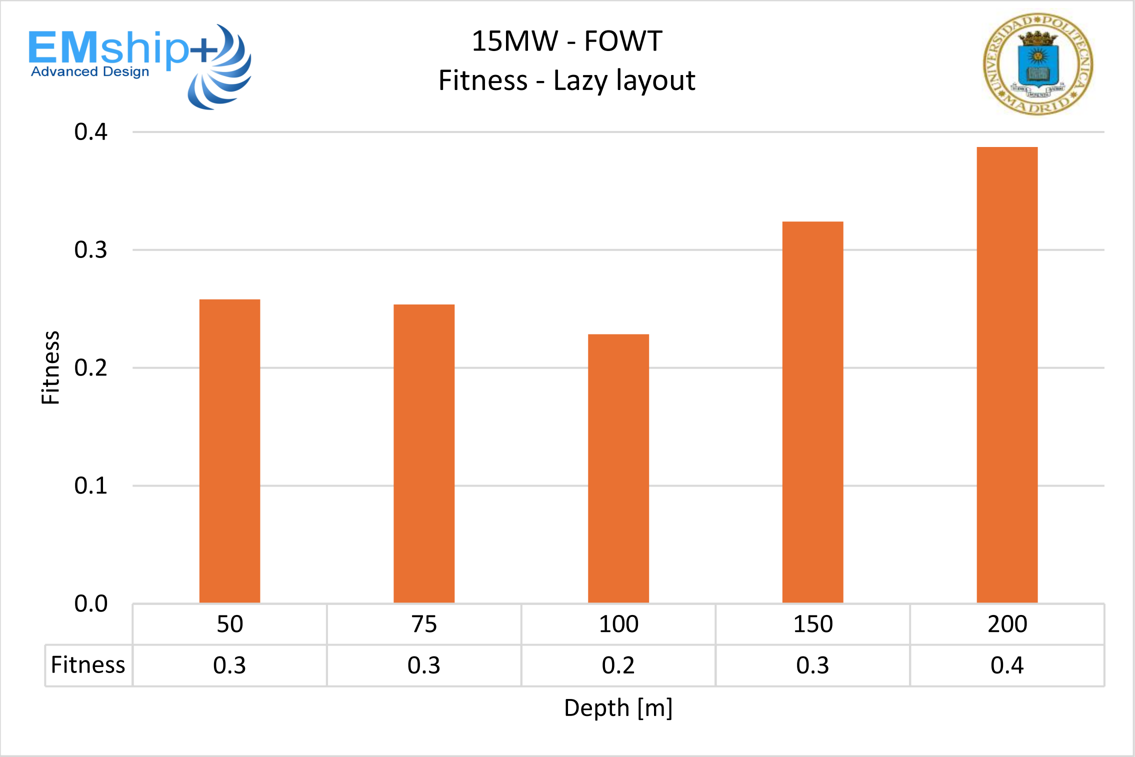
Depth [m]	50	75	100	150	200
🟧 Tension [kN]	26	20	18	34	50
🟦 MBL [kN]	347	347	347	347	347

Figure 17.24: Tension for Lazy wave layout [180°]



	50	75	100	150	200
Fitness	0.2	0.2	0.3	0.8	1.0

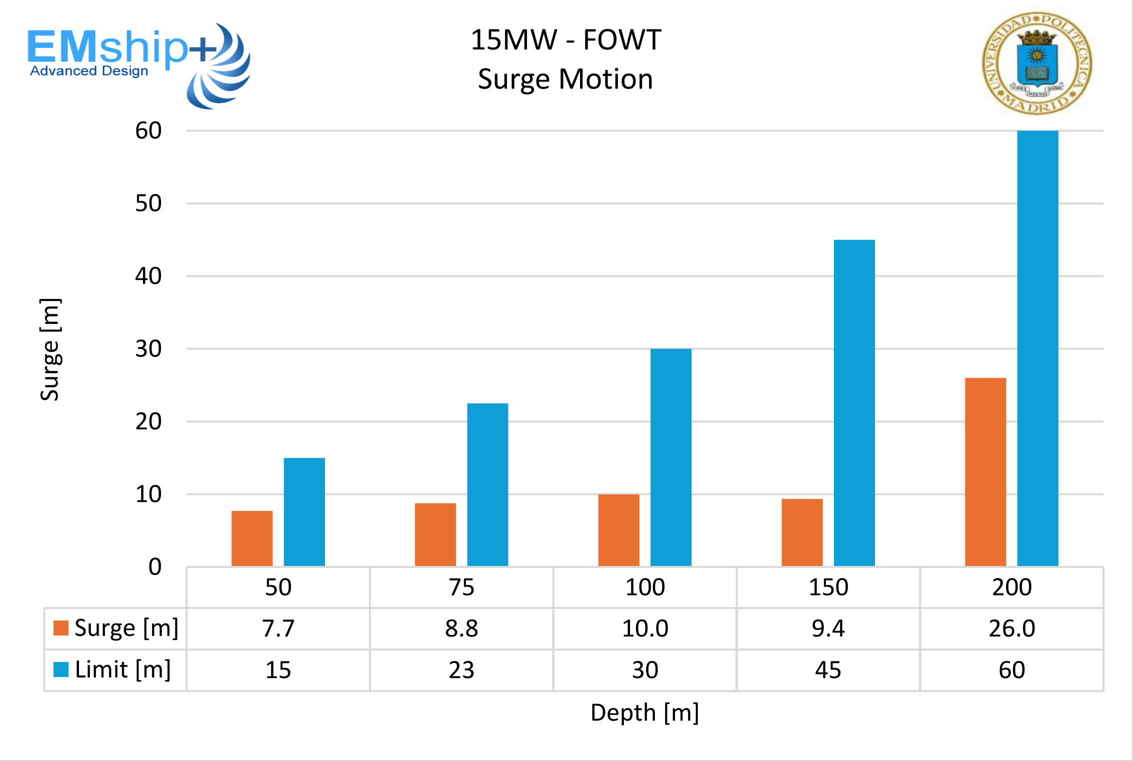
Figure 17.25: Fitness for Catenary layout [180°]



	50	75	100	150	200
Fitness	0.3	0.3	0.2	0.3	0.4

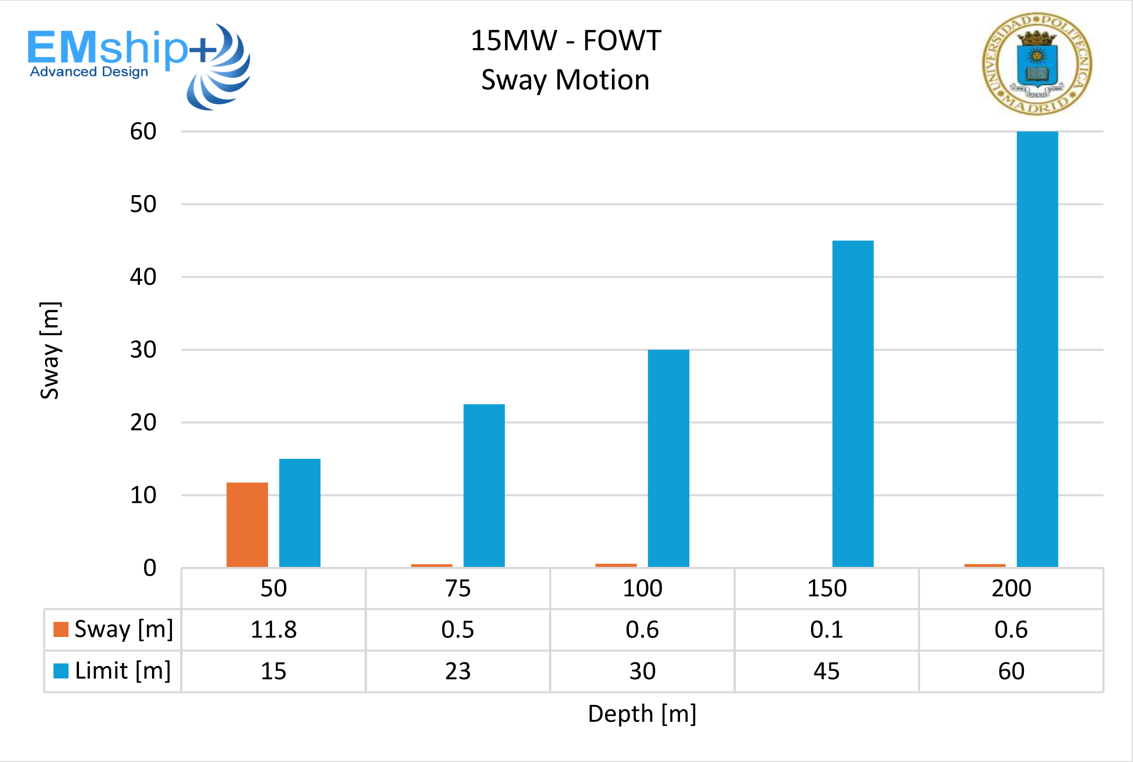
Figure 17.26: Fitness for Lazy wave layout [180°]

A.5 Motion of the Structure[0 °]



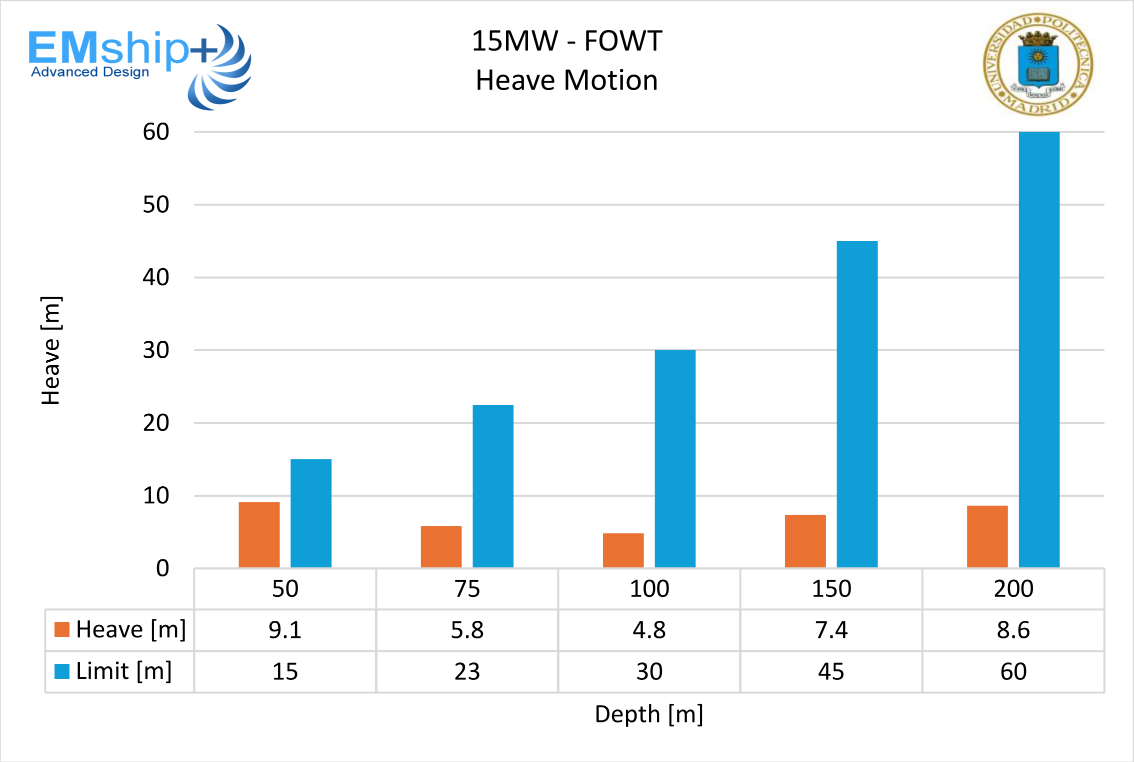
	50	75	100	150	200
🟧 Surge [m]	7.7	8.8	10.0	9.4	26.0
🟦 Limit [m]	15	23	30	45	60

Figure 17.27: Surge motion for Catenary layout [0°]



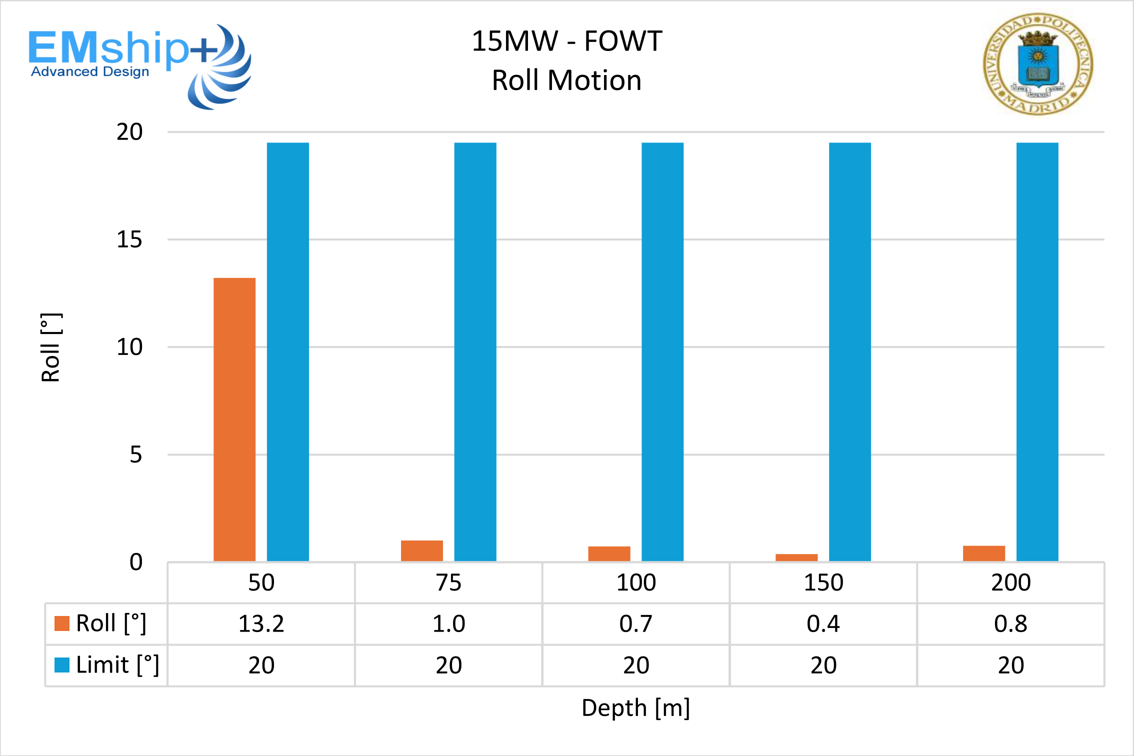
	50	75	100	150	200
🟧 Sway [m]	11.8	0.5	0.6	0.1	0.6
🟦 Limit [m]	15	23	30	45	60

Figure 17.28: Sway motion for Catenary layout [0°]



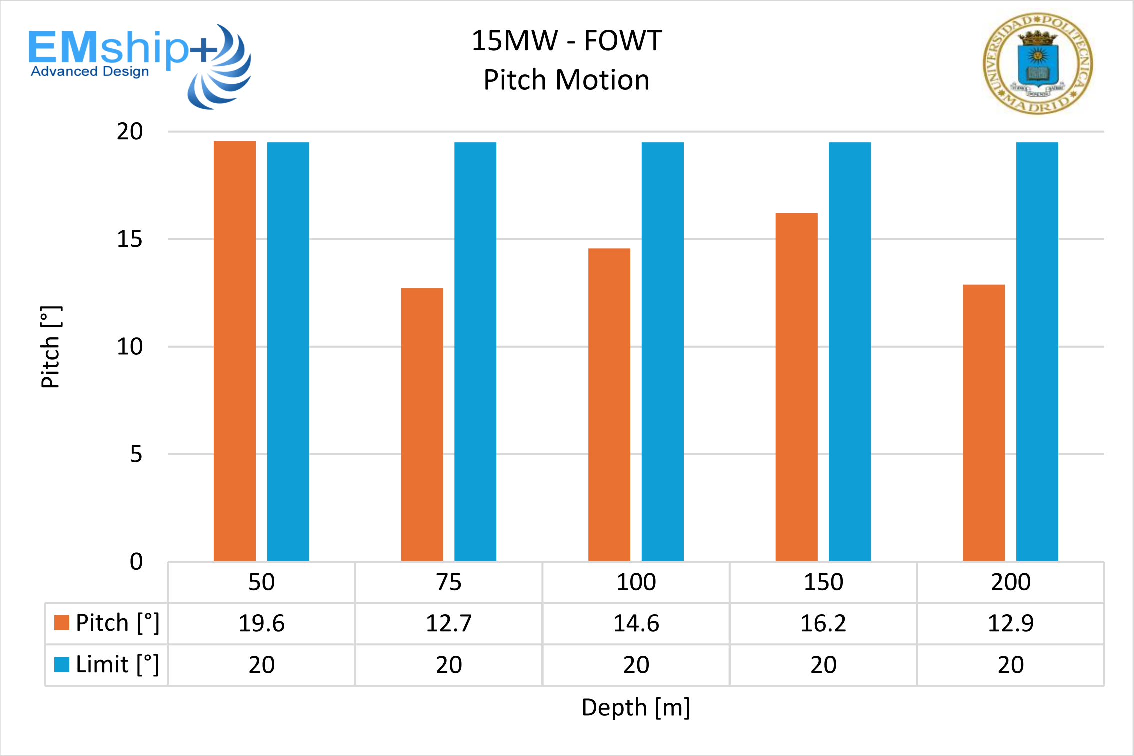
	50	75	100	150	200
🟧 Heave [m]	9.1	5.8	4.8	7.4	8.6
🟦 Limit [m]	15	23	30	45	60

Figure 17.29: Heave motion for Catenary layout [0°]



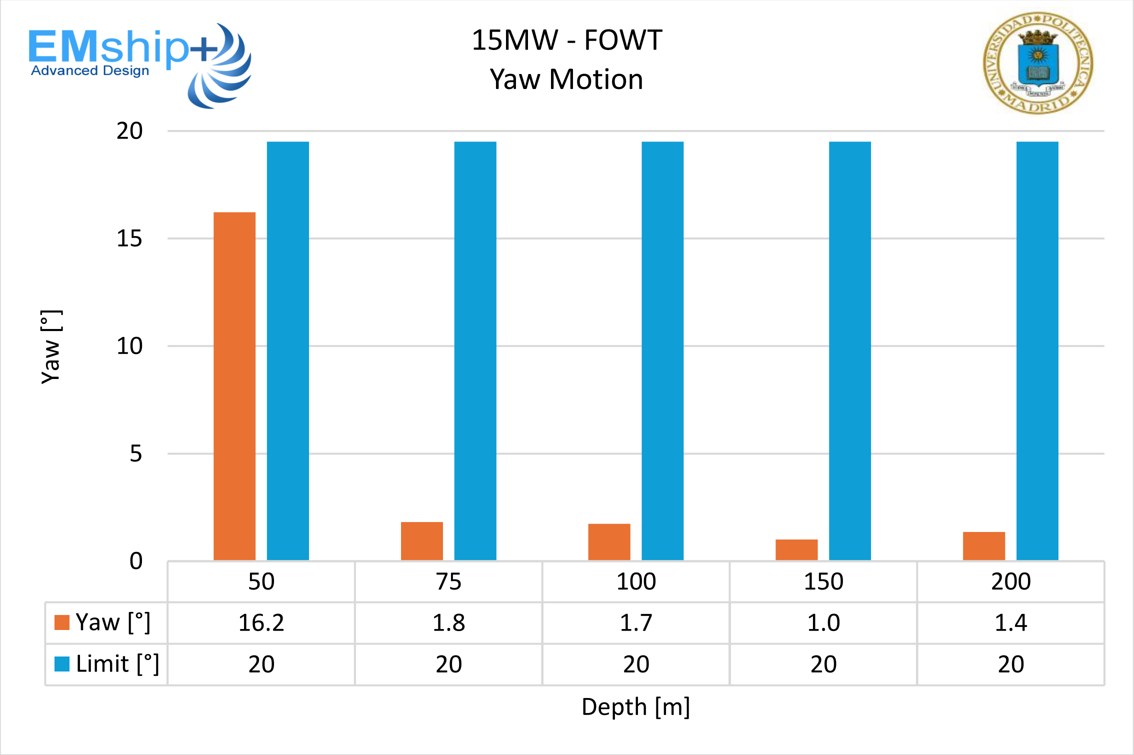
	50	75	100	150	200
🟧 Roll [°]	13.2	1.0	0.7	0.4	0.8
🟦 Limit [°]	20	20	20	20	20

Figure 17.30: Roll motion for Catenary layout [0°]



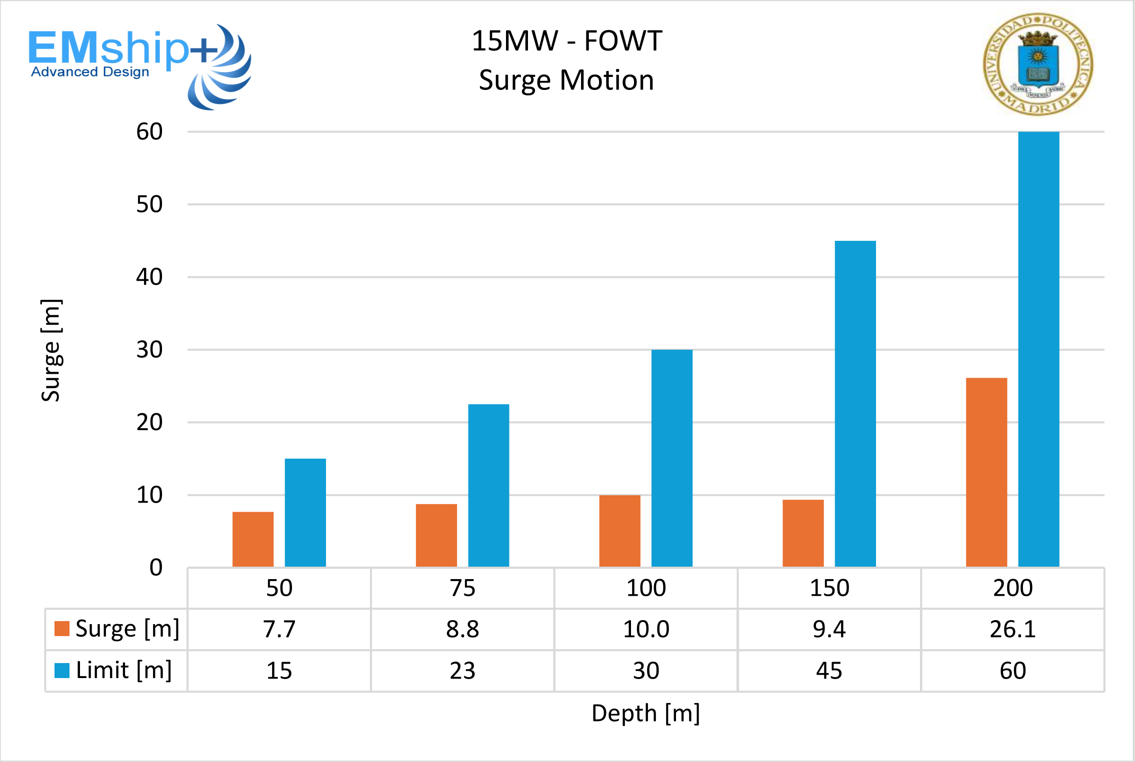
	50	75	100	150	200
🟧 Pitch [°]	19.6	12.7	14.6	16.2	12.9
🟦 Limit [°]	20	20	20	20	20

Figure 17.31: Pitch motion for Catenary layout [0°]



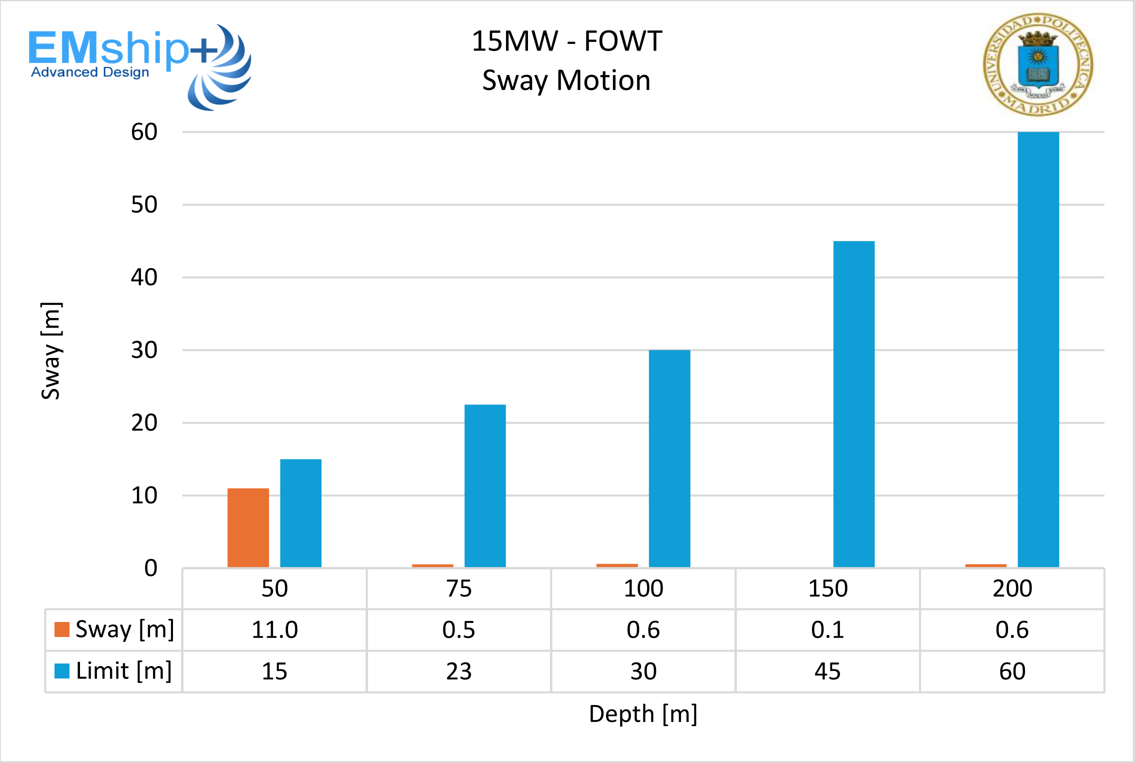
	50	75	100	150	200
🟧 Yaw [°]	16.2	1.8	1.7	1.0	1.4
🟦 Limit [°]	20	20	20	20	20

Figure 17.32: Yaw motion for Catenary layout [0°]



	50	75	100	150	200
🟧 Surge [m]	7.7	8.8	10.0	9.4	26.1
🟦 Limit [m]	15	23	30	45	60

Figure 17.33: Surge motion for Lazy wave layout [0°]



	50	75	100	150	200
🟧 Sway [m]	11.0	0.5	0.6	0.1	0.6
🟦 Limit [m]	15	23	30	45	60

Figure 17.34: Sway motion for Lazy wave layout [0°]

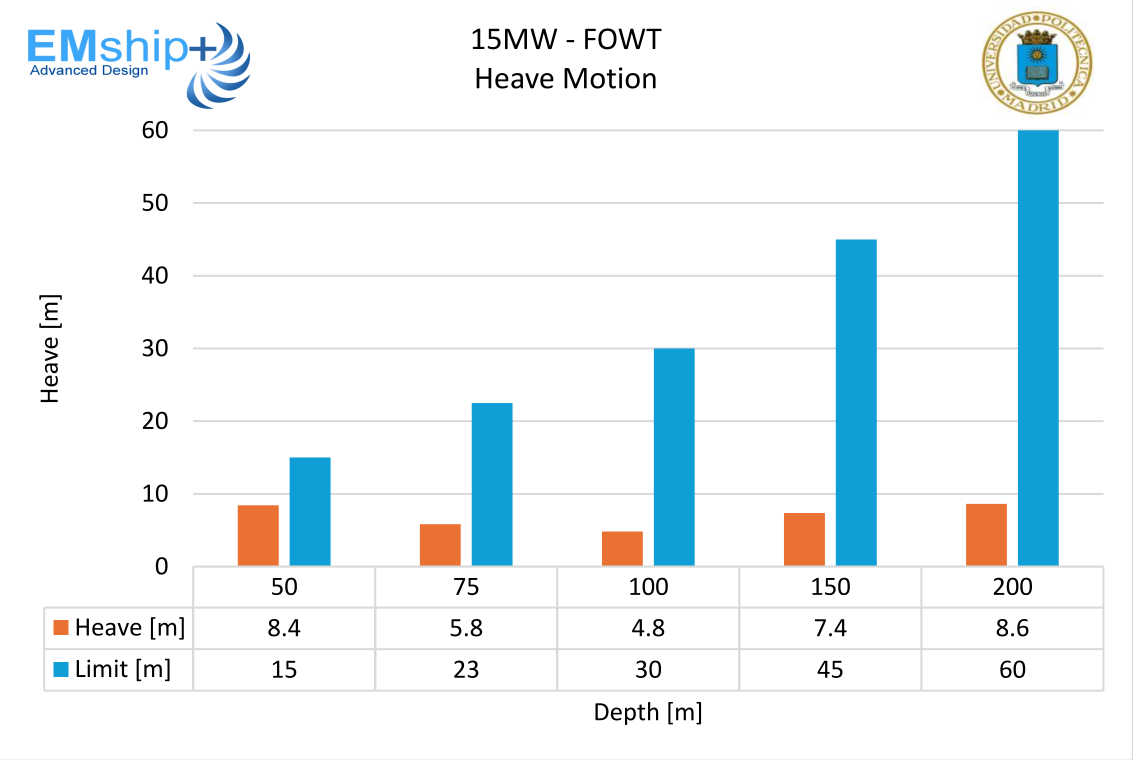


Figure 17.35: Heave motion for Lazy wave layout [0°]

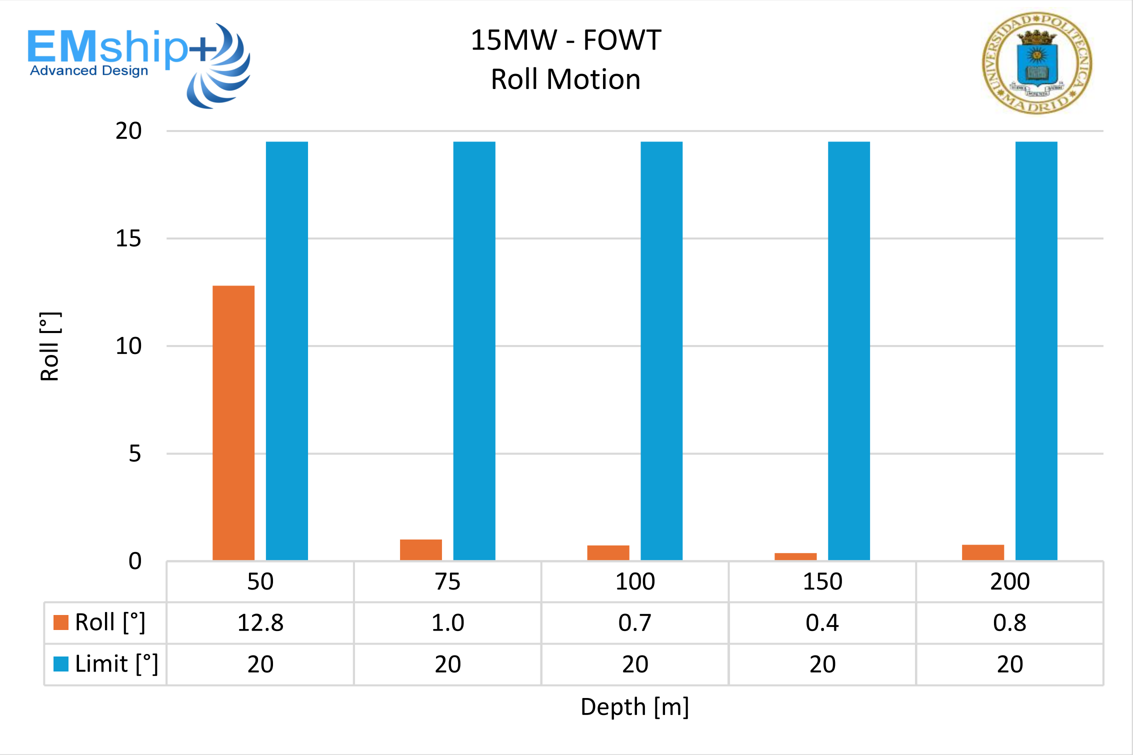
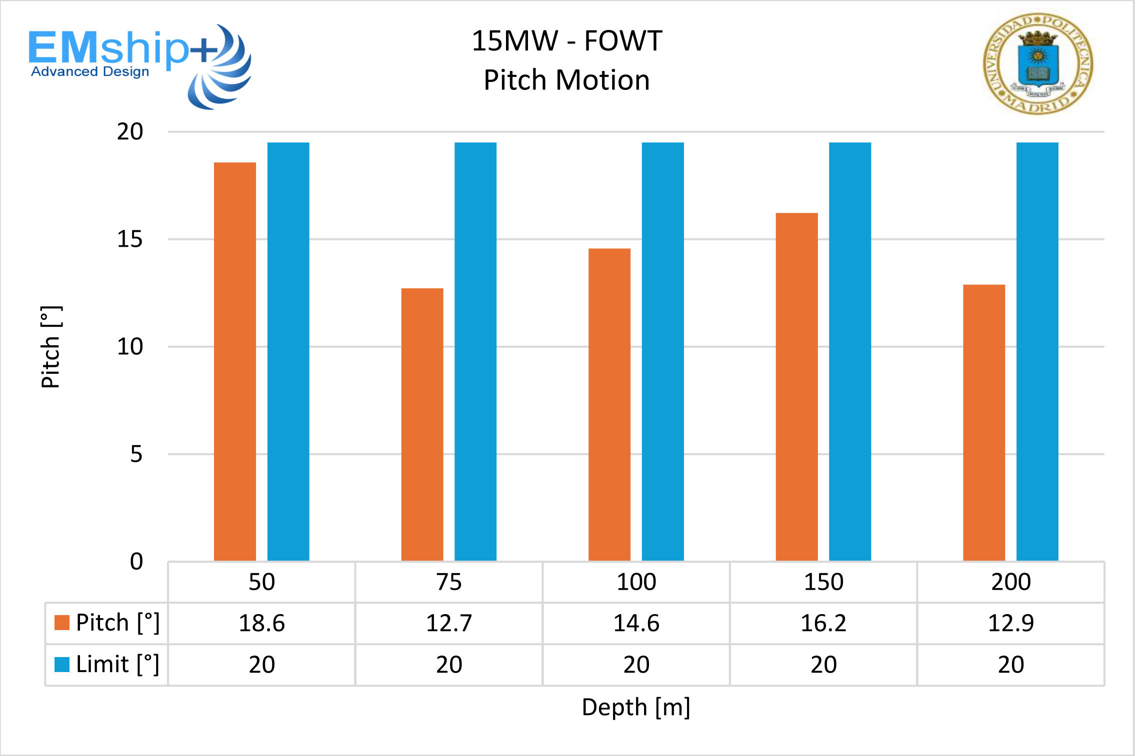
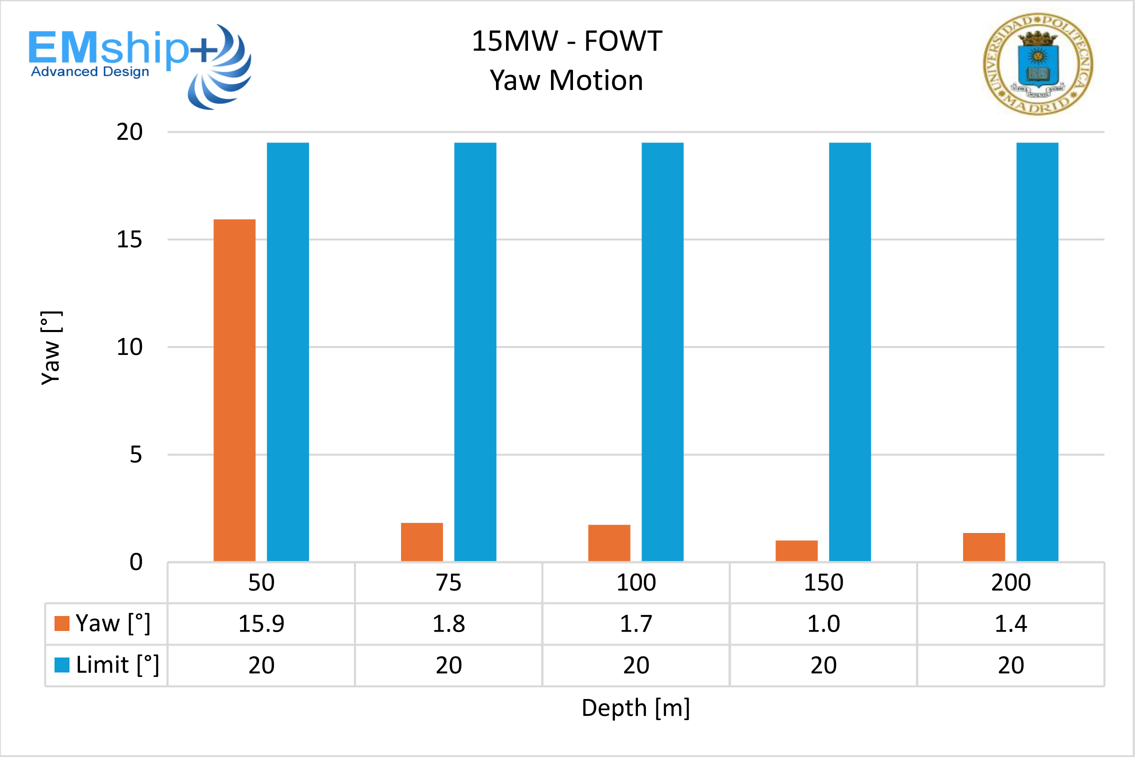


Figure 17.36: Roll motion for Lazy wave layout [0°]



	50	75	100	150	200
🟧 Pitch [°]	18.6	12.7	14.6	16.2	12.9
🟦 Limit [°]	20	20	20	20	20

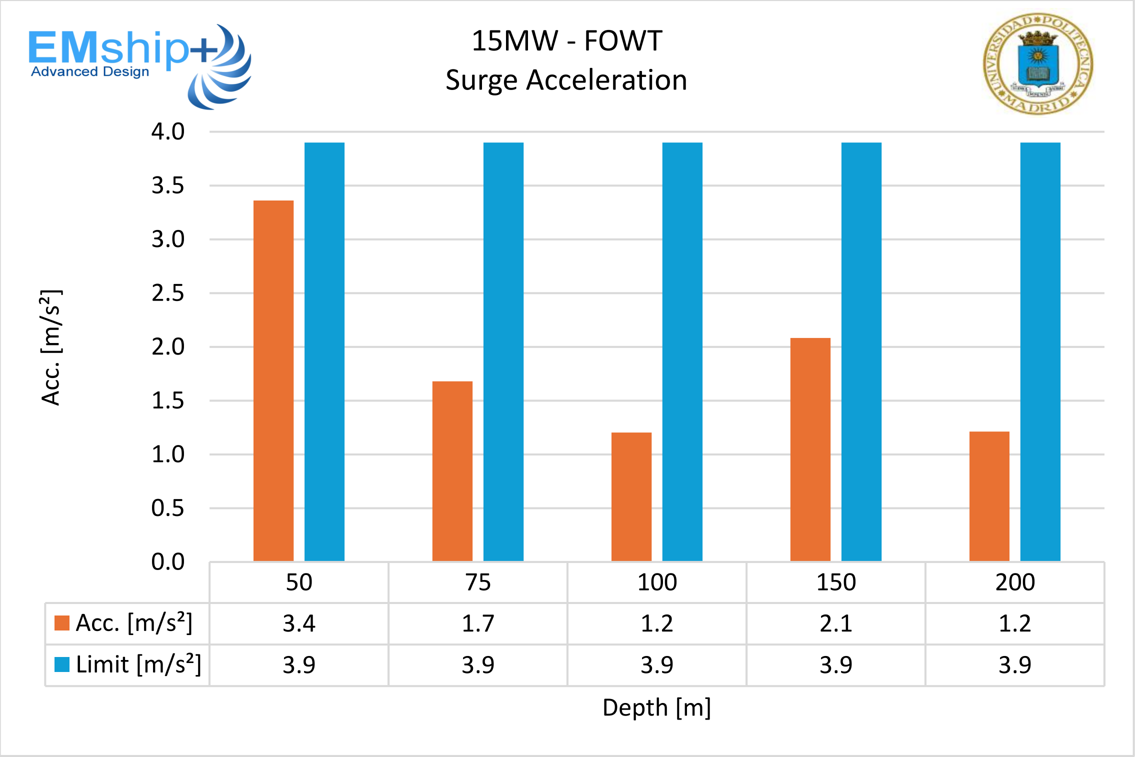
Figure 17.37: Pitch motion for Lazy wave layout [0°]



	50	75	100	150	200
🟧 Yaw [°]	15.9	1.8	1.7	1.0	1.4
🟦 Limit [°]	20	20	20	20	20

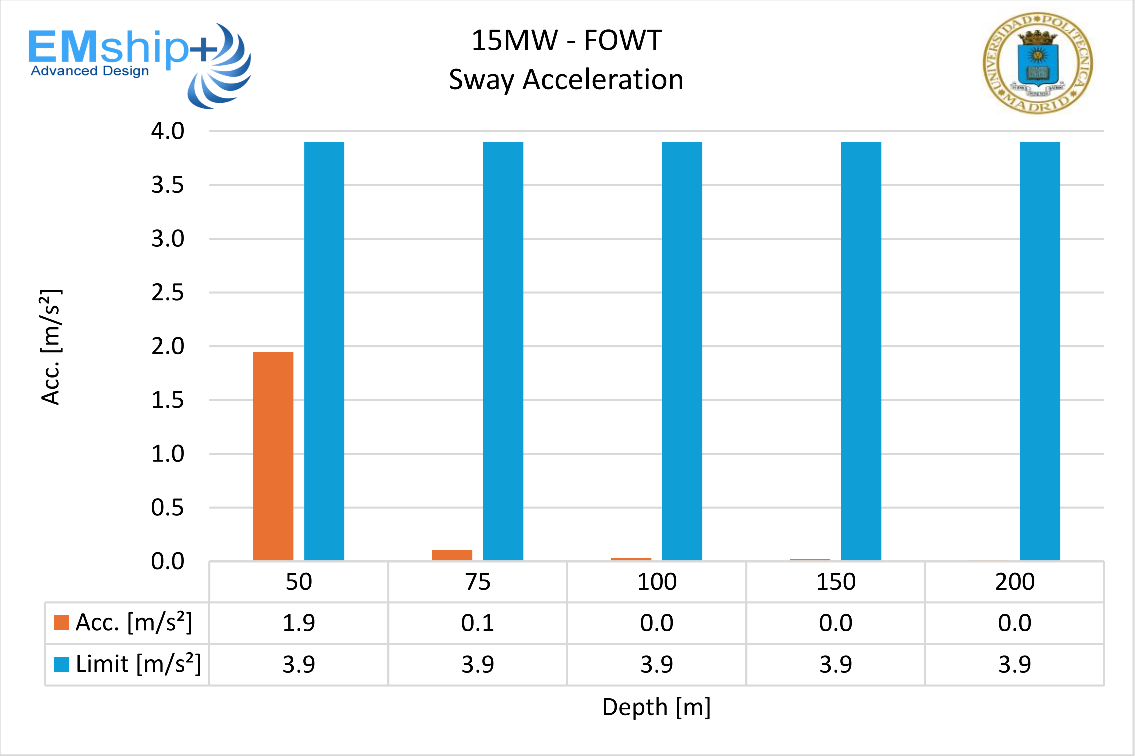
Figure 17.38: Yaw motion for Lazy wave layout [0°]

A.6 Acceleration of the Structure [0 °]



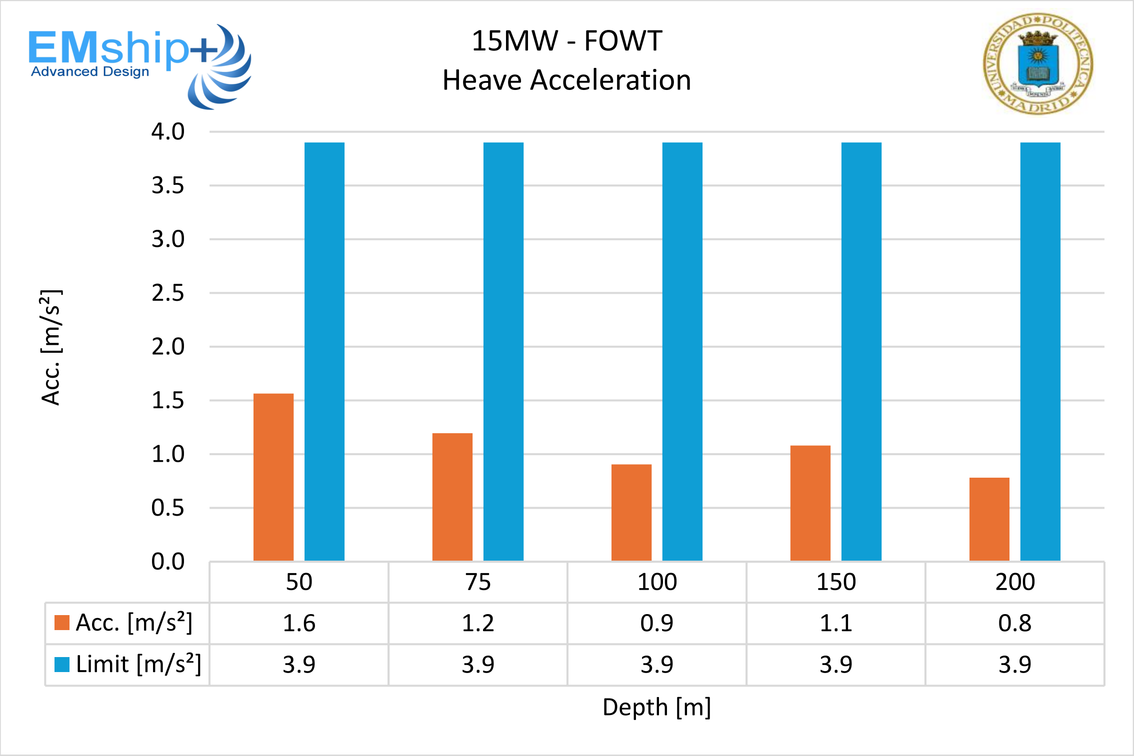
	50	75	100	150	200
🟧 Acc. [m/s²]	3.4	1.7	1.2	2.1	1.2
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.39: Surge acceleration for Catenary layout [0°]



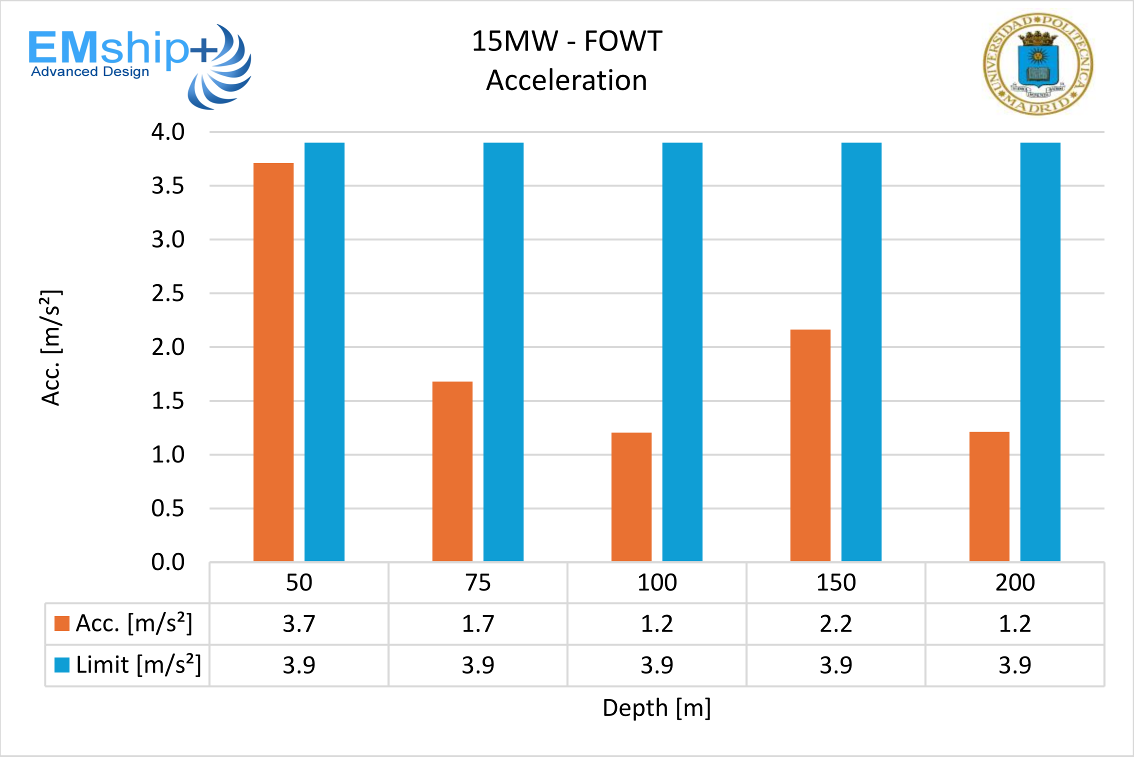
	50	75	100	150	200
🟧 Acc. [m/s²]	1.9	0.1	0.0	0.0	0.0
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.40: Sway acceleration for Catenary layout [0°]



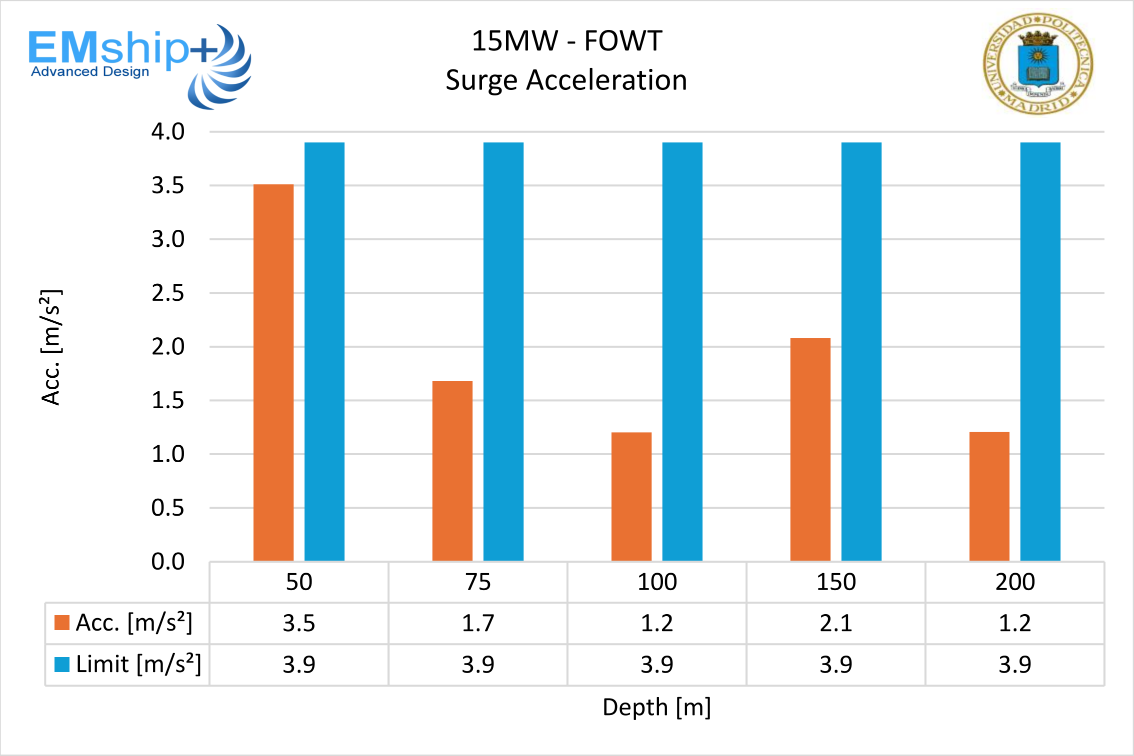
	50	75	100	150	200
🟧 Acc. [m/s²]	1.6	1.2	0.9	1.1	0.8
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.41: Heave acceleration for Catenary layout [0°]



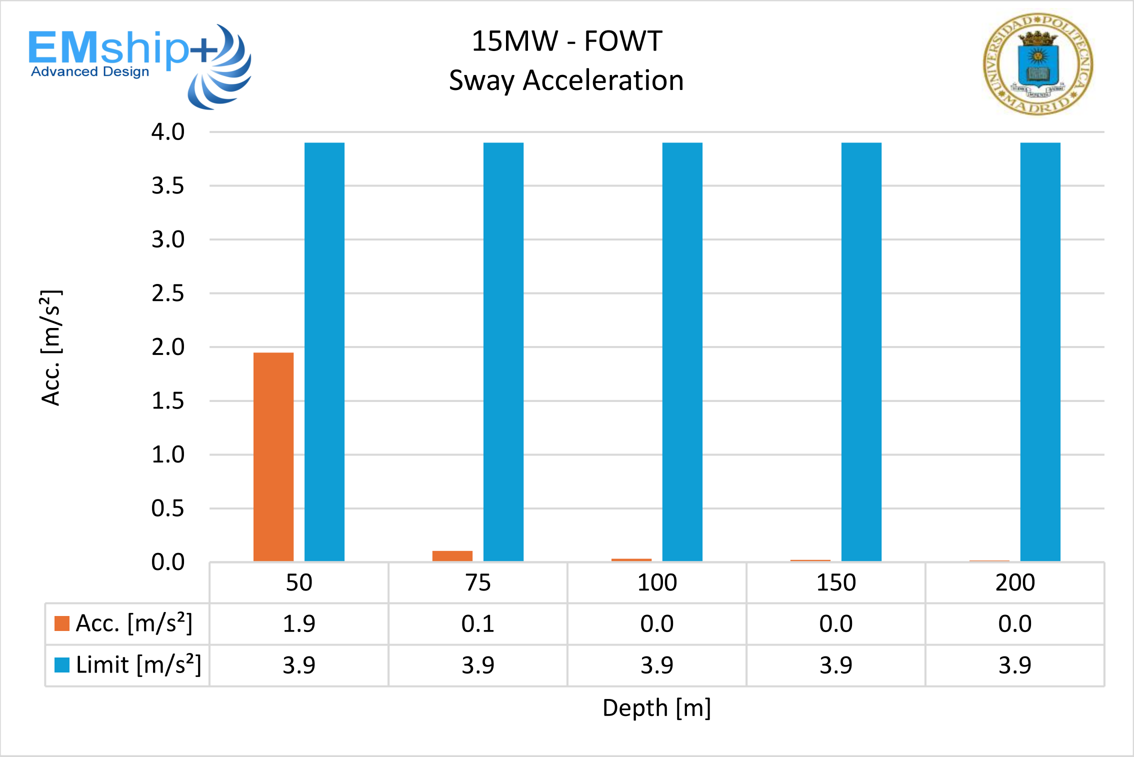
	50	75	100	150	200
🟧 Acc. [m/s²]	3.7	1.7	1.2	2.2	1.2
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.42: Acceleration (extreme) for Catenary layout [0°]



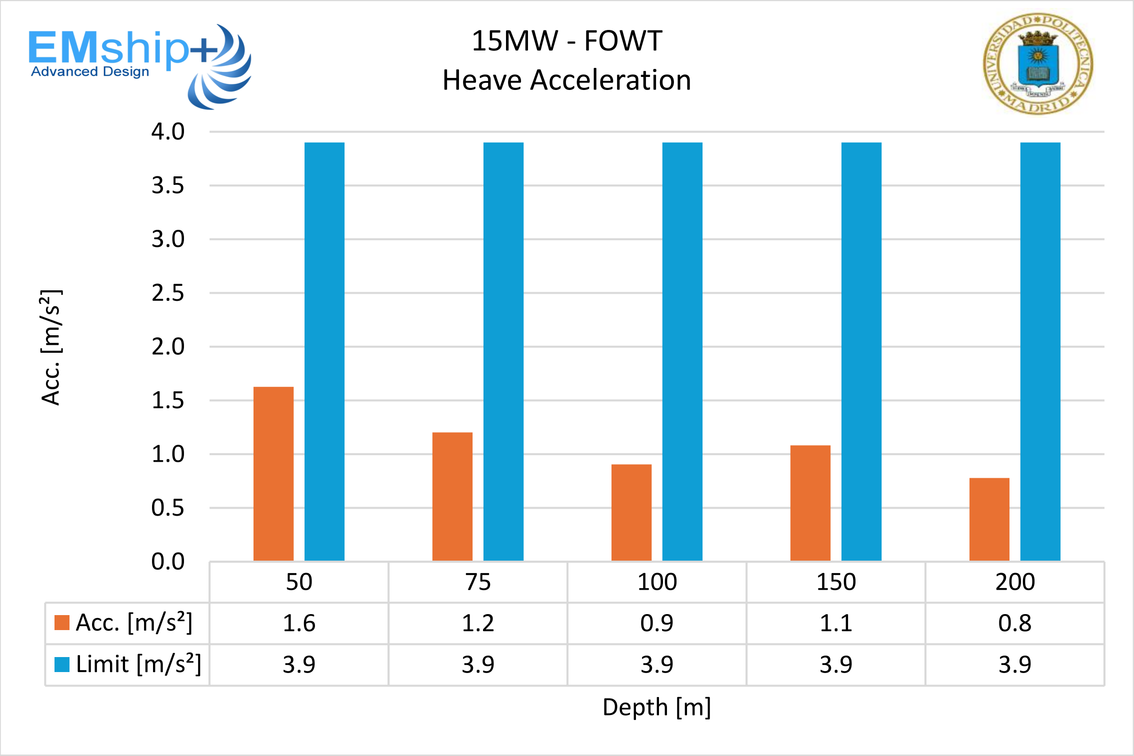
	50	75	100	150	200
🟧 Acc. [m/s^2]	3.5	1.7	1.2	2.1	1.2
🟦 Limit [m/s^2]	3.9	3.9	3.9	3.9	3.9

Figure 17.43: Surge acceleration for Lazy wave layout [0°]



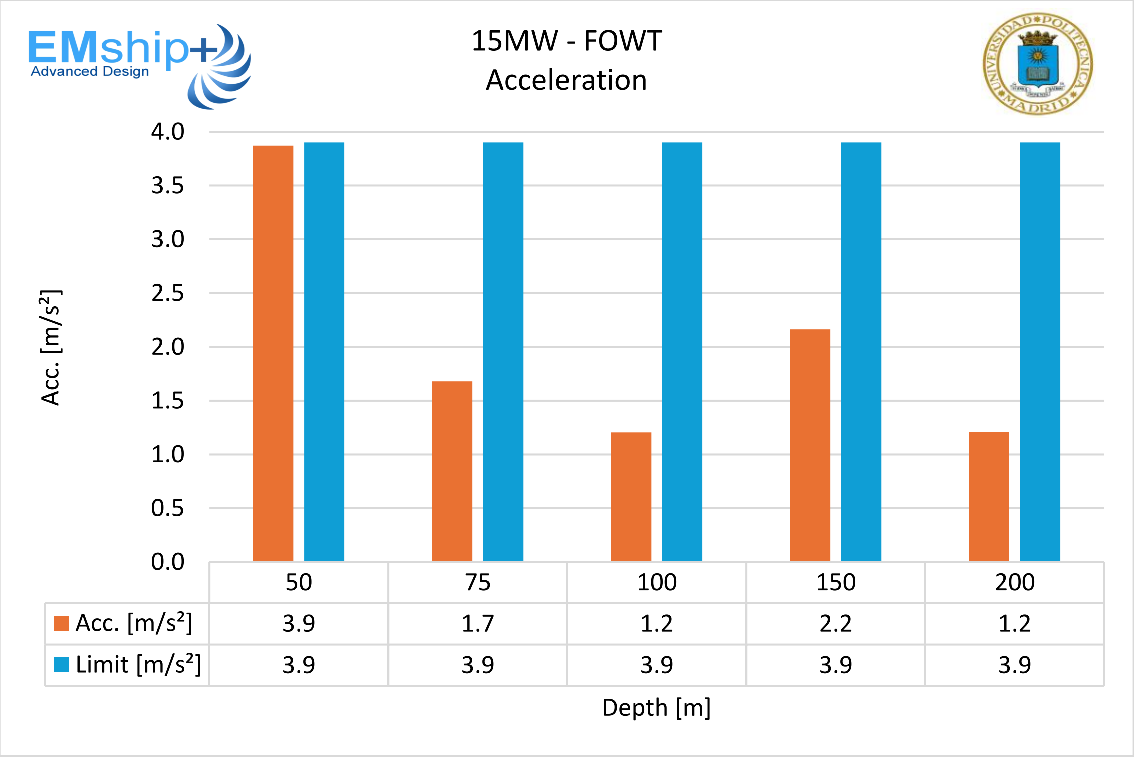
	50	75	100	150	200
🟧 Acc. [m/s^2]	1.9	0.1	0.0	0.0	0.0
🟦 Limit [m/s^2]	3.9	3.9	3.9	3.9	3.9

Figure 17.44: Sway acceleration for Lazy wave layout [0°]



Depth [m]	50	75	100	150	200
🟧 Acc. [m/s²]	1.6	1.2	0.9	1.1	0.8
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

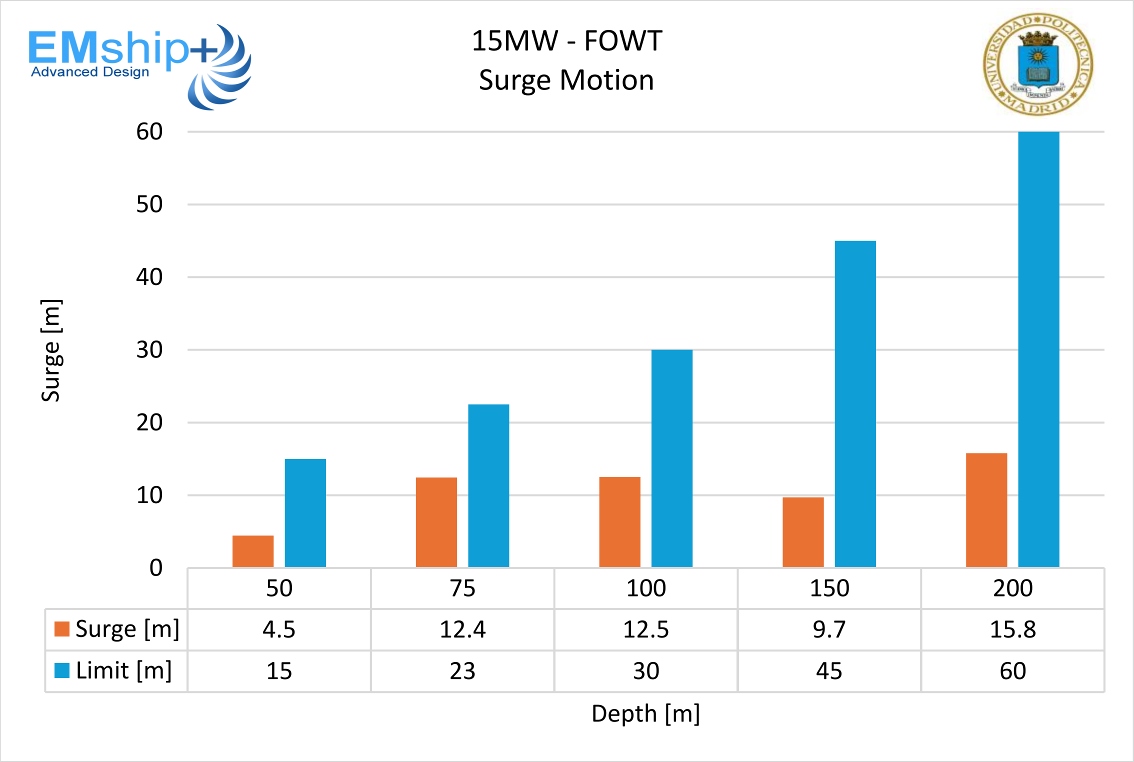
Figure 17.45: Heave acceleration for Lazy wave layout [0°]



Depth [m]	50	75	100	150	200
🟧 Acc. [m/s²]	3.9	1.7	1.2	2.2	1.2
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

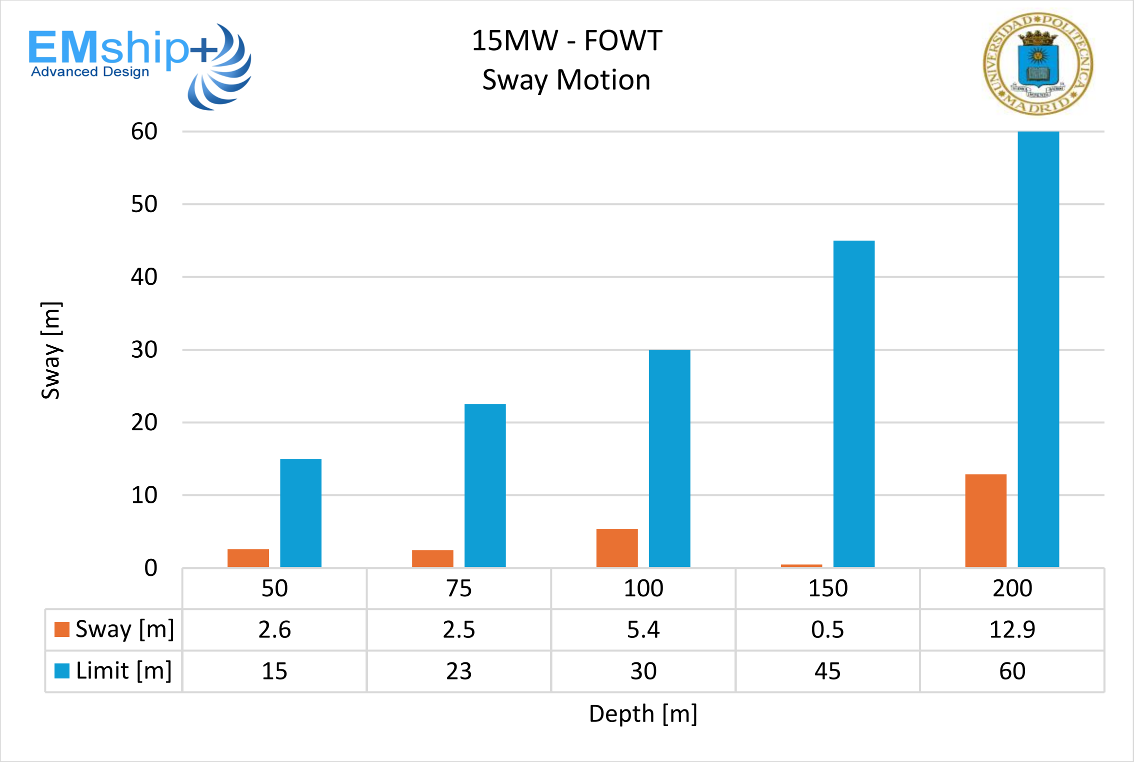
Figure 17.46: Acceleration (extreme) for Lazy wave layout [0°]

A.7 Motion of the Structure [180 °]



	50	75	100	150	200
🟧 Surge [m]	4.5	12.4	12.5	9.7	15.8
🟦 Limit [m]	15	23	30	45	60

Figure 17.47: Surge motion for Catenary layout [180°]



	50	75	100	150	200
🟧 Sway [m]	2.6	2.5	5.4	0.5	12.9
🟦 Limit [m]	15	23	30	45	60

Figure 17.48: Sway motion for Catenary layout [180°]

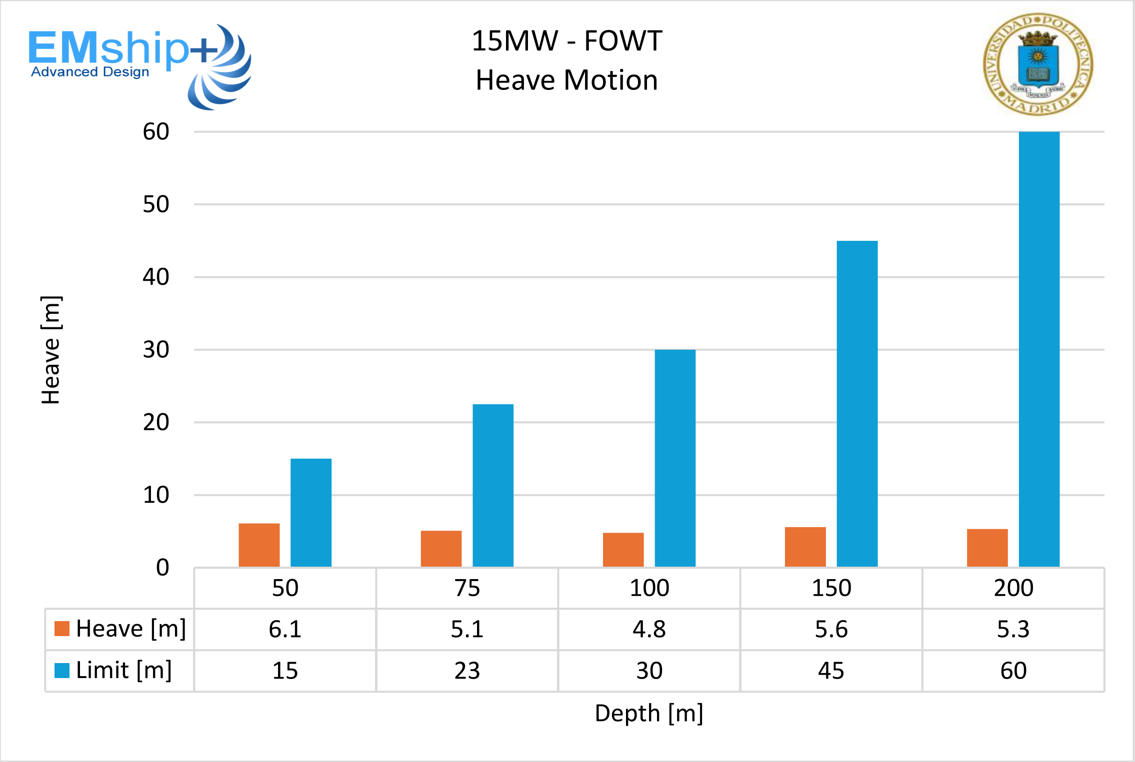


Figure 17.49: Heave motion for Catenary layout [180°]

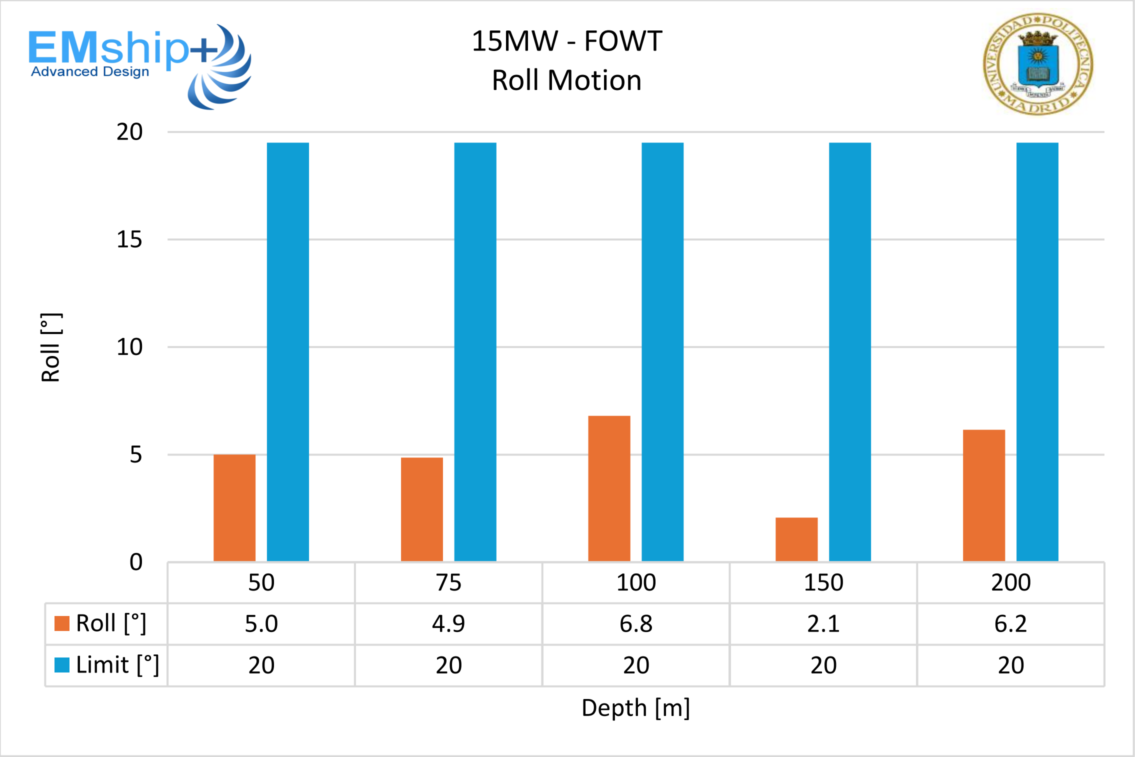


Figure 17.50: Roll motion for Catenary layout [180°]

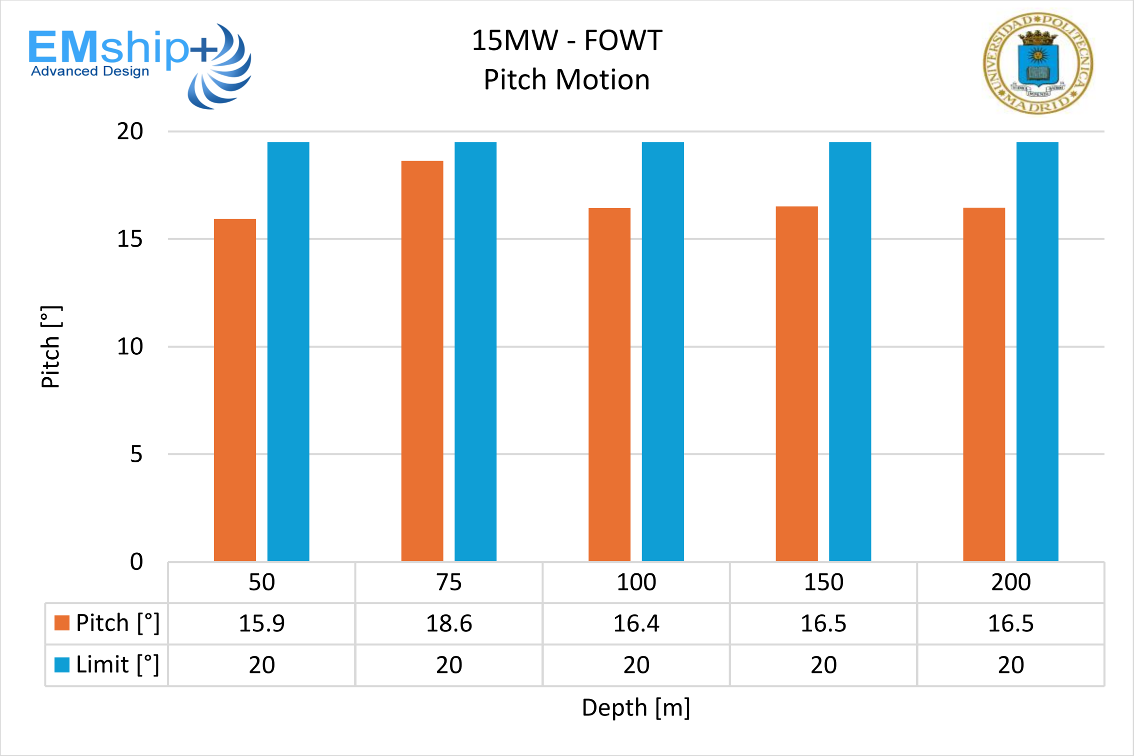


Figure 17.51: Pitch motion for Catenary layout [180°]

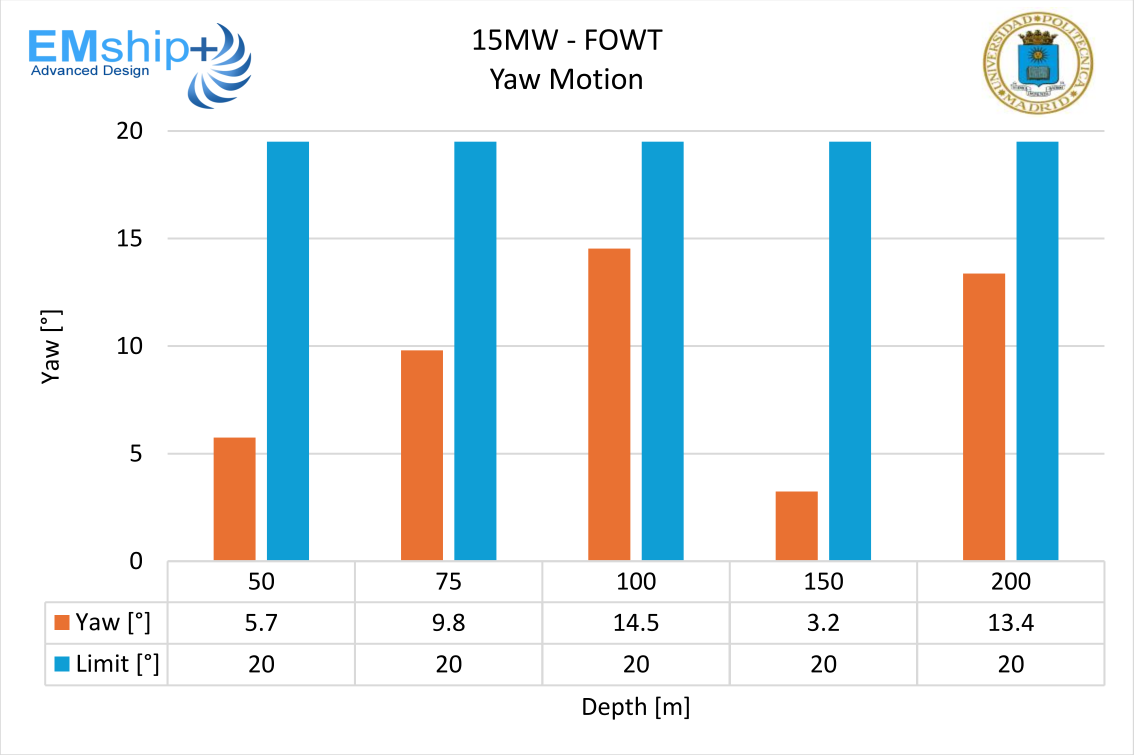


Figure 17.52: Yaw motion for Catenary layout [180°]

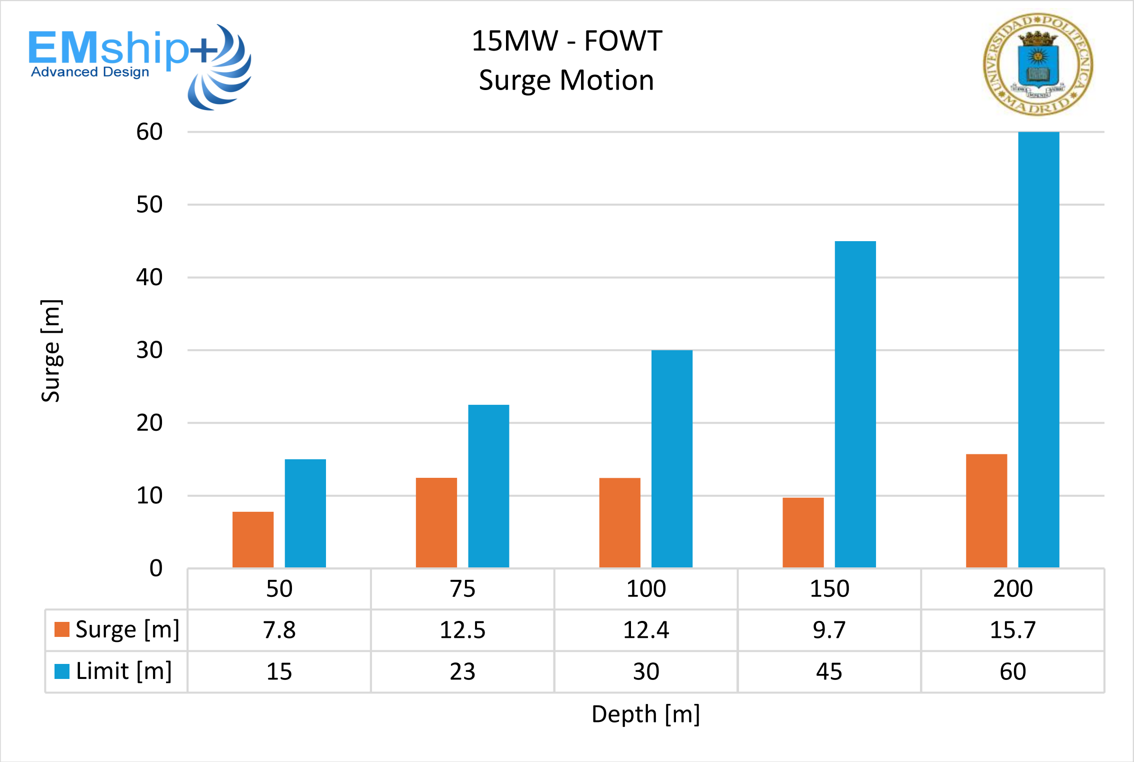


Figure 17.53: Surge motion for Lazy wave layout [180°]

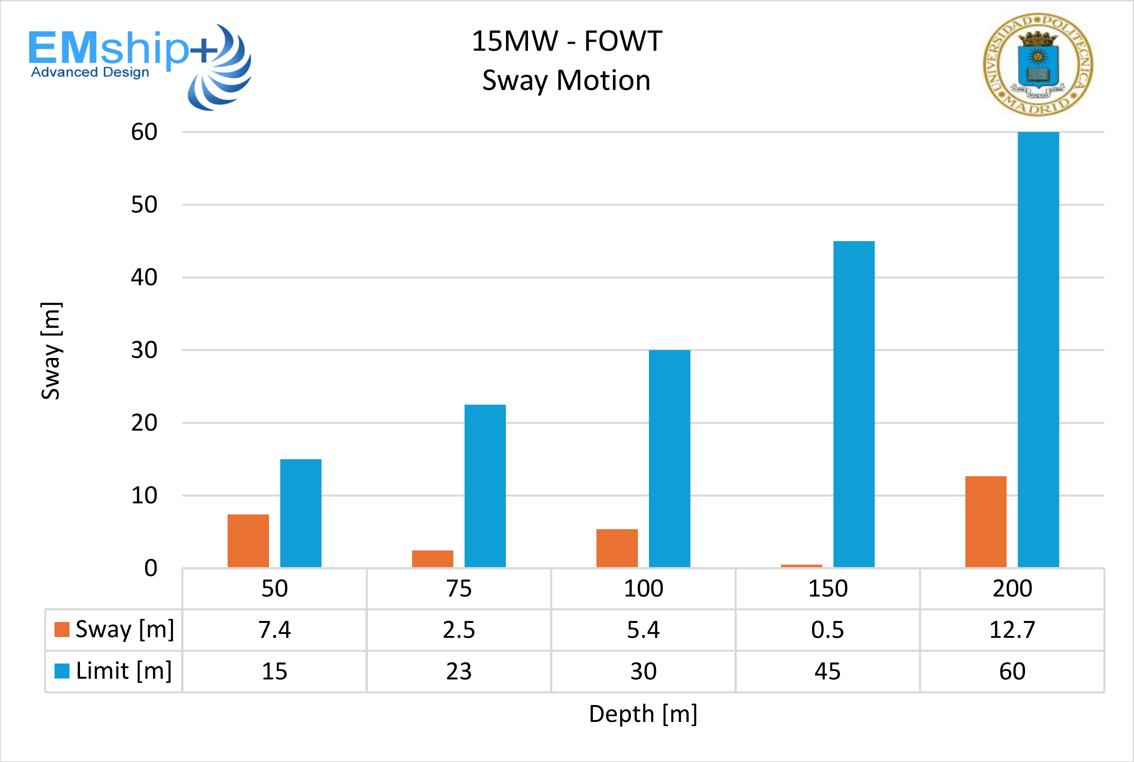
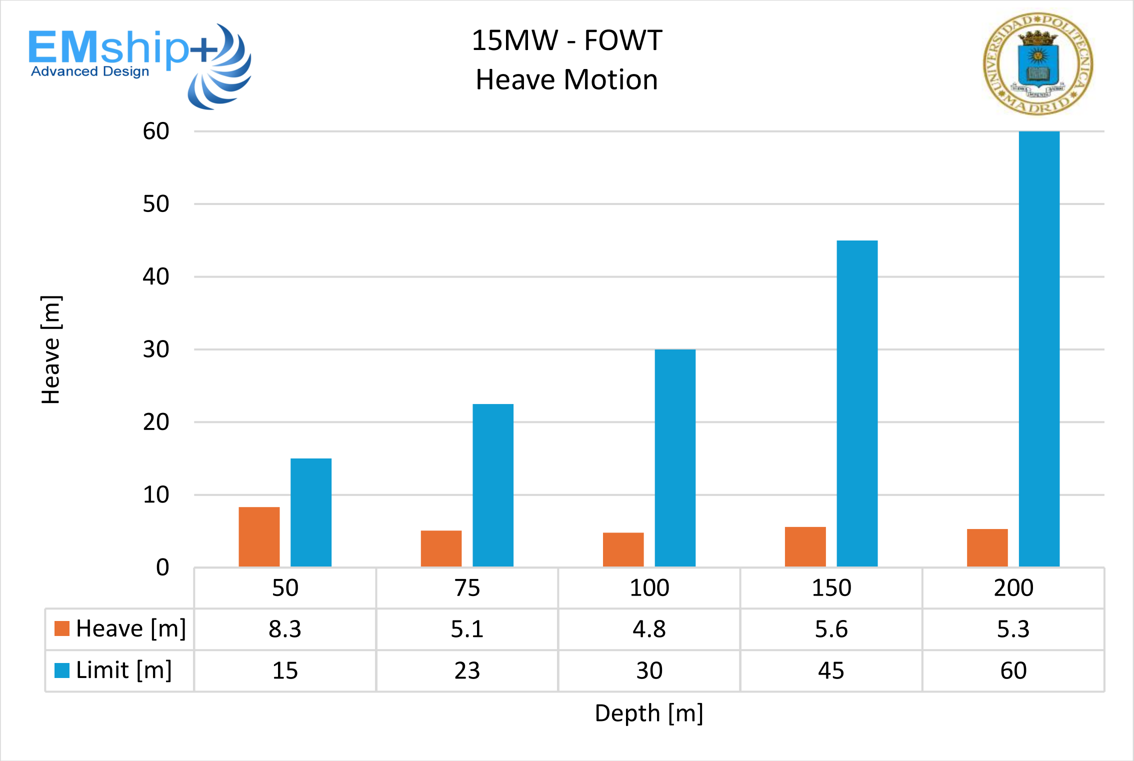
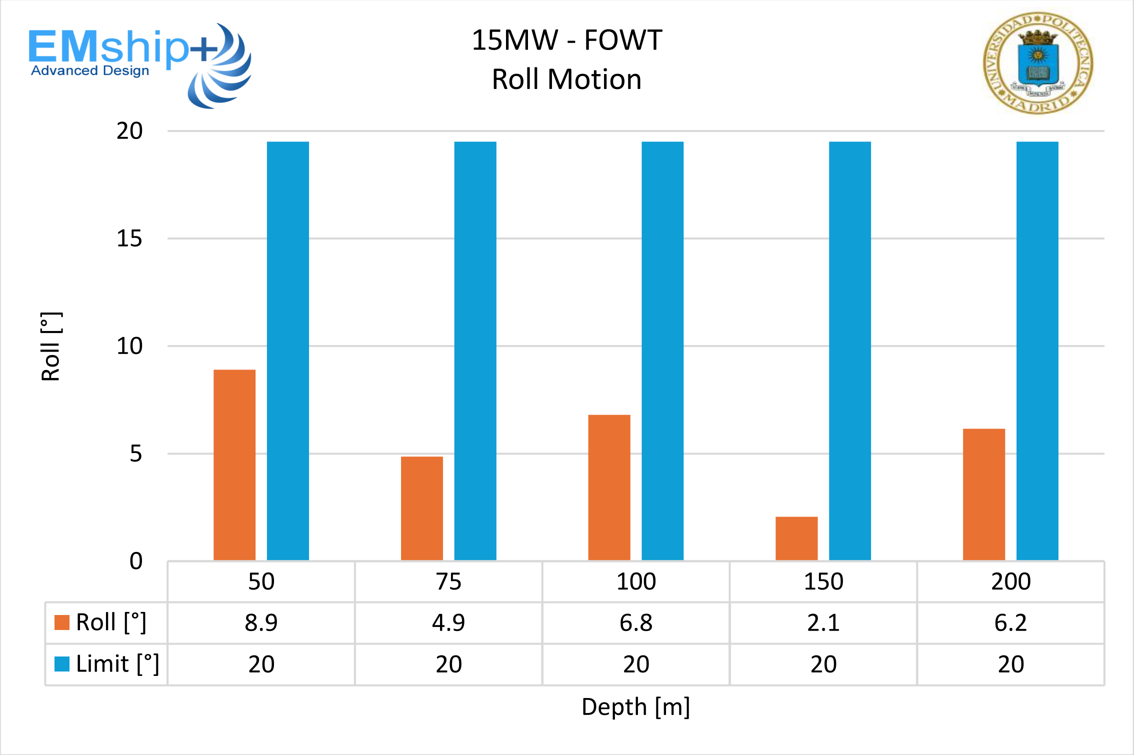


Figure 17.54: Sway motion for Lazy wave layout [180°]



	50	75	100	150	200
🟧 Heave [m]	8.3	5.1	4.8	5.6	5.3
🟦 Limit [m]	15	23	30	45	60

Figure 17.55: Heave motion for Lazy wave layout [180°]



	50	75	100	150	200
🟧 Roll [°]	8.9	4.9	6.8	2.1	6.2
🟦 Limit [°]	20	20	20	20	20

Figure 17.56: Roll motion for Lazy wave layout [180°]

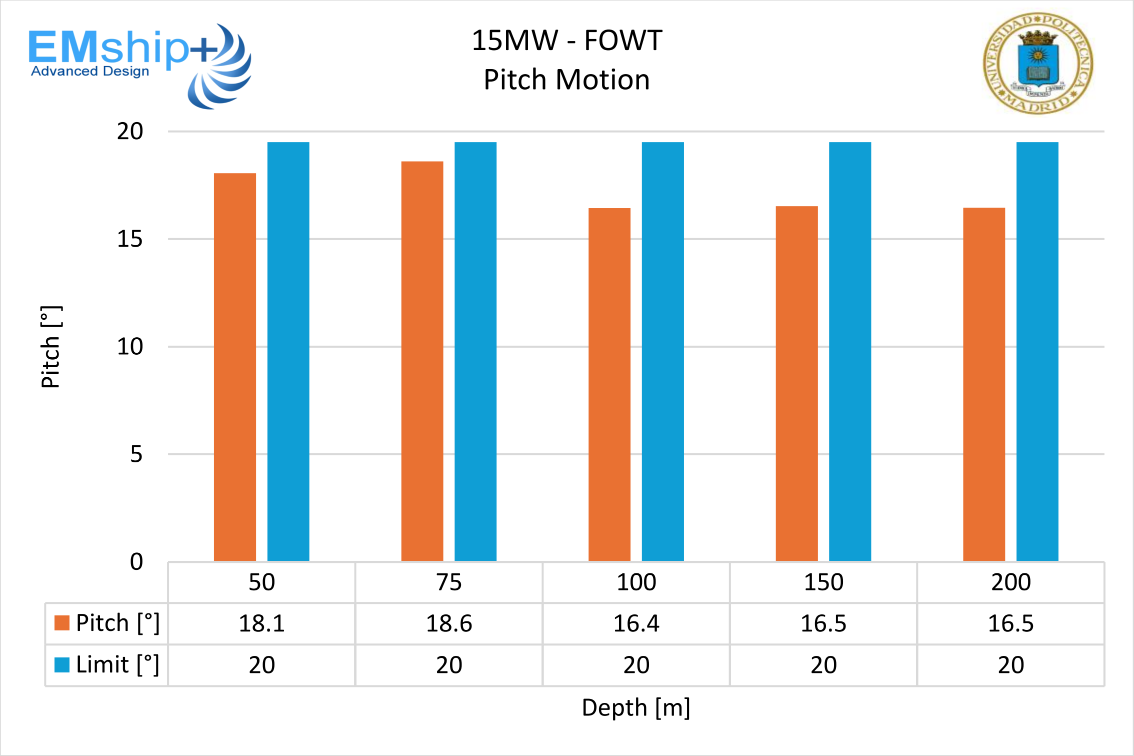


Figure 17.57: Pitch motion for Lazy wave layout [180°]

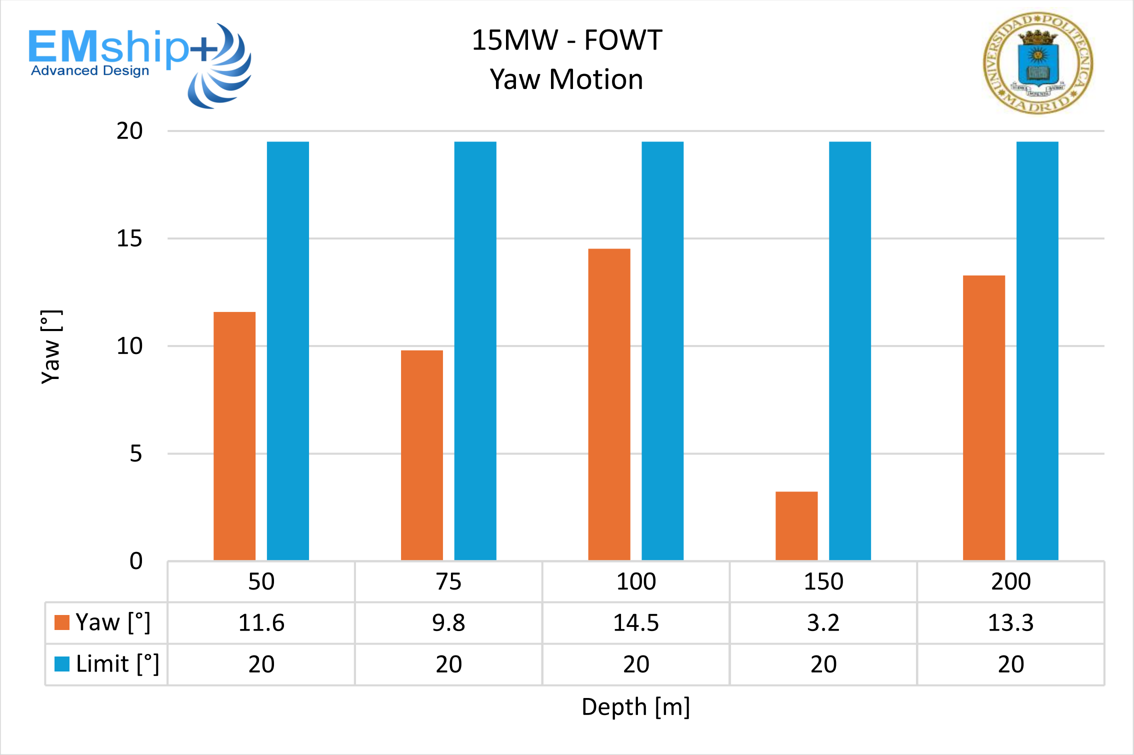
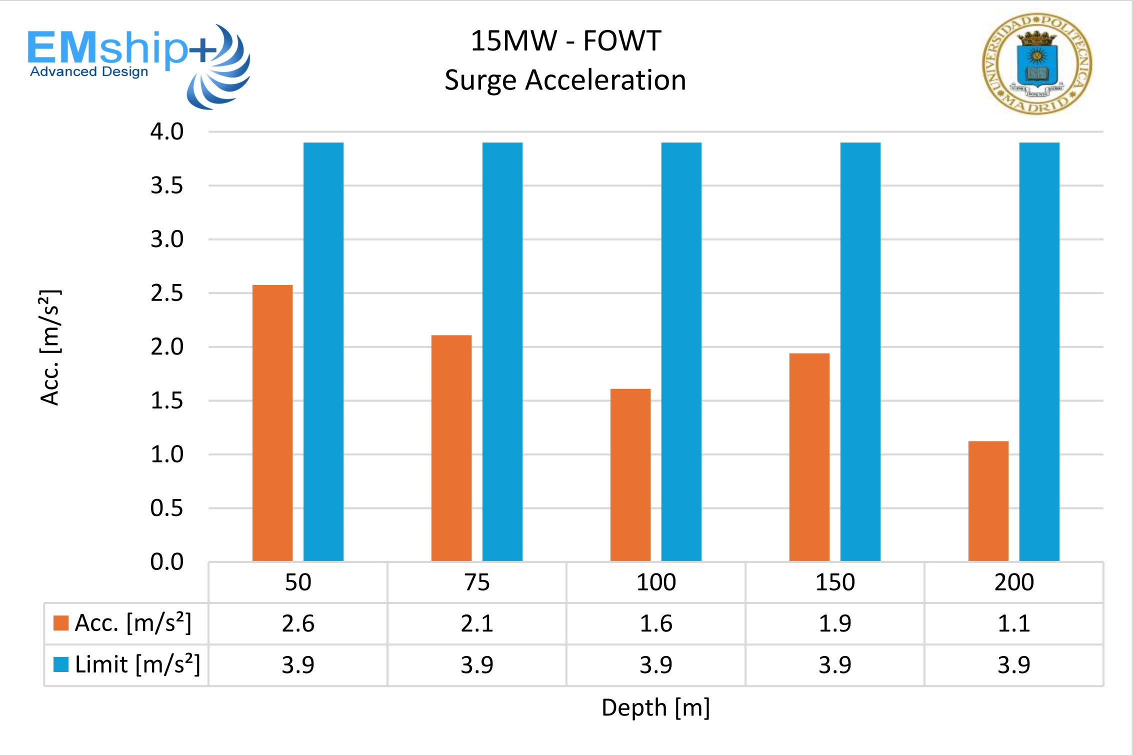


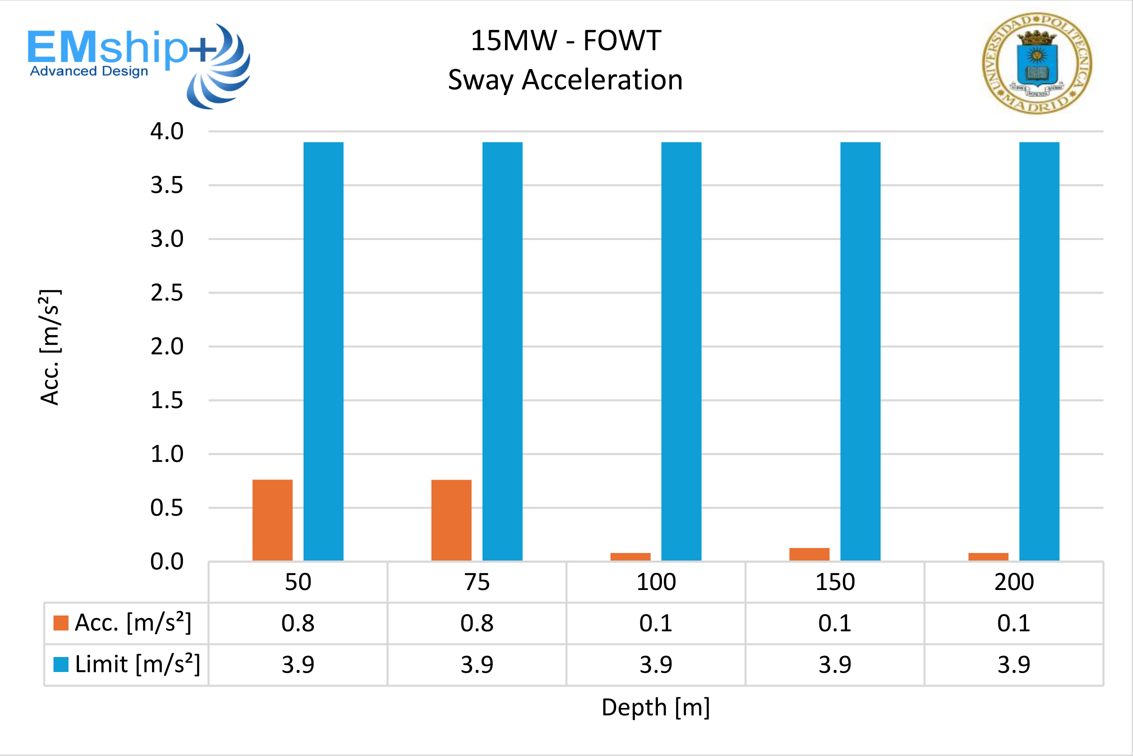
Figure 17.58: Yaw motion for Lazy wave layout [180°]

A.8 Acceleration of the Structure [180 °]



	50	75	100	150	200
🟧 Acc. [m/s²]	2.6	2.1	1.6	1.9	1.1
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.59: Surge acceleration for Catenary layout [180°]



	50	75	100	150	200
🟧 Acc. [m/s²]	0.8	0.8	0.1	0.1	0.1
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.60: Sway acceleration for Catenary layout [180°]

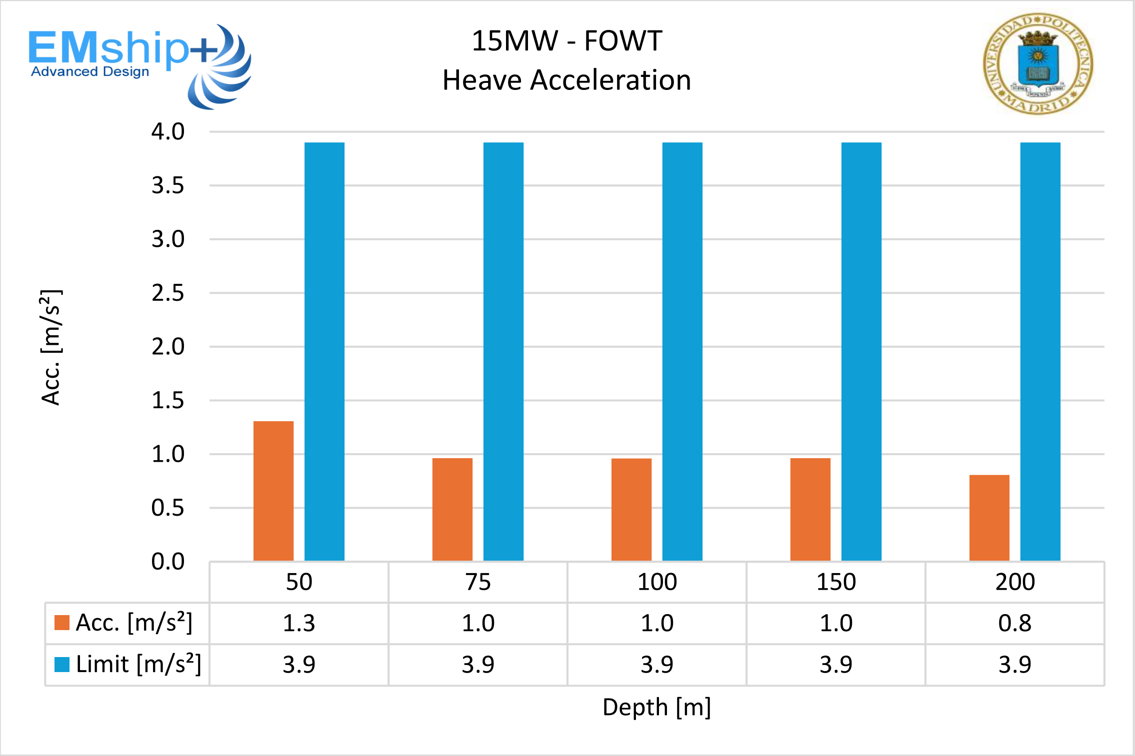


Figure 17.61: Heave acceleration for Catenary layout [180°]

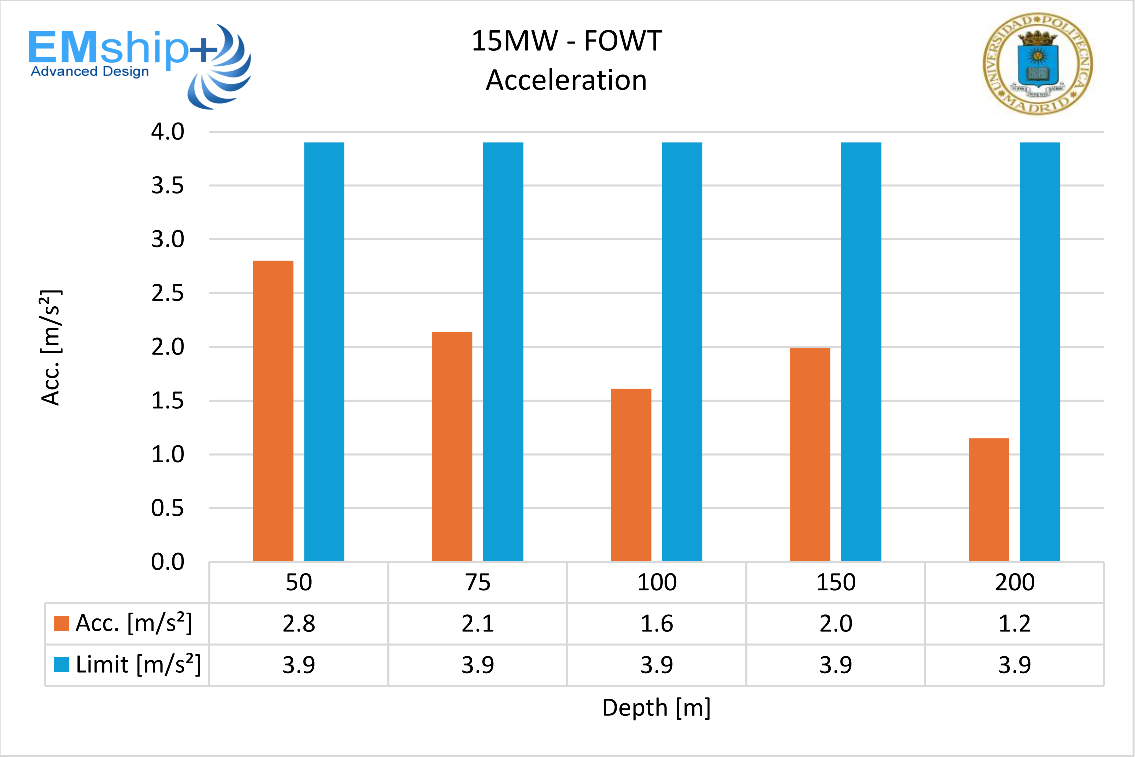
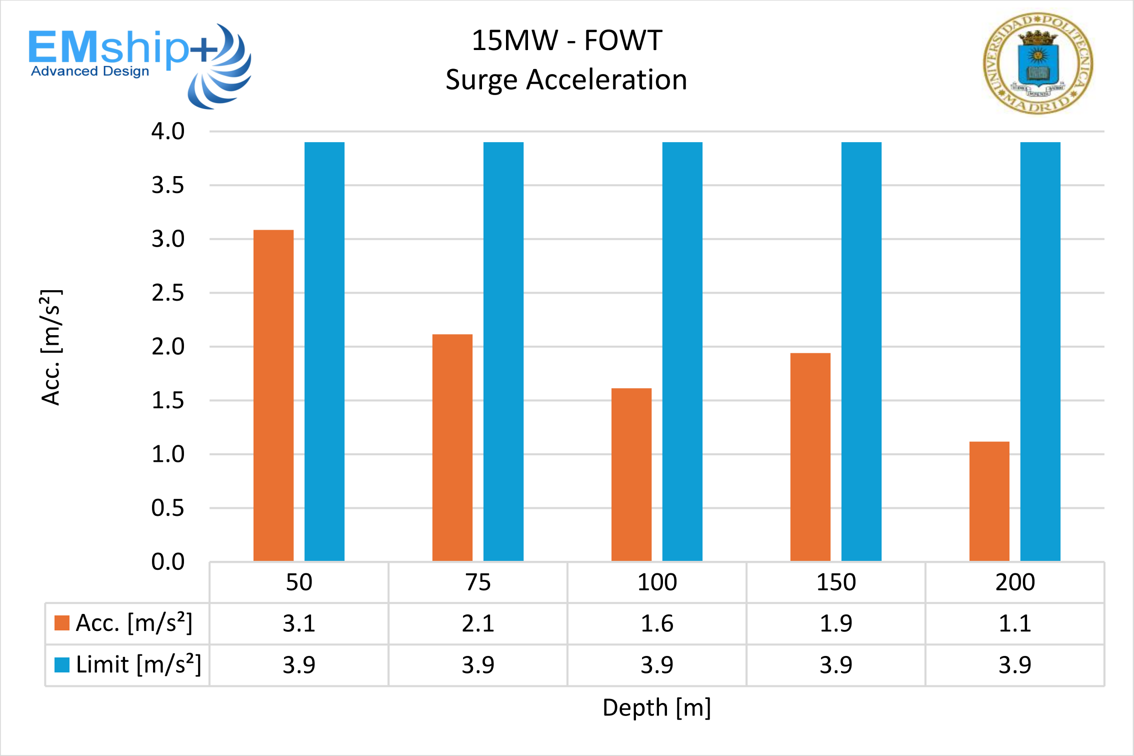
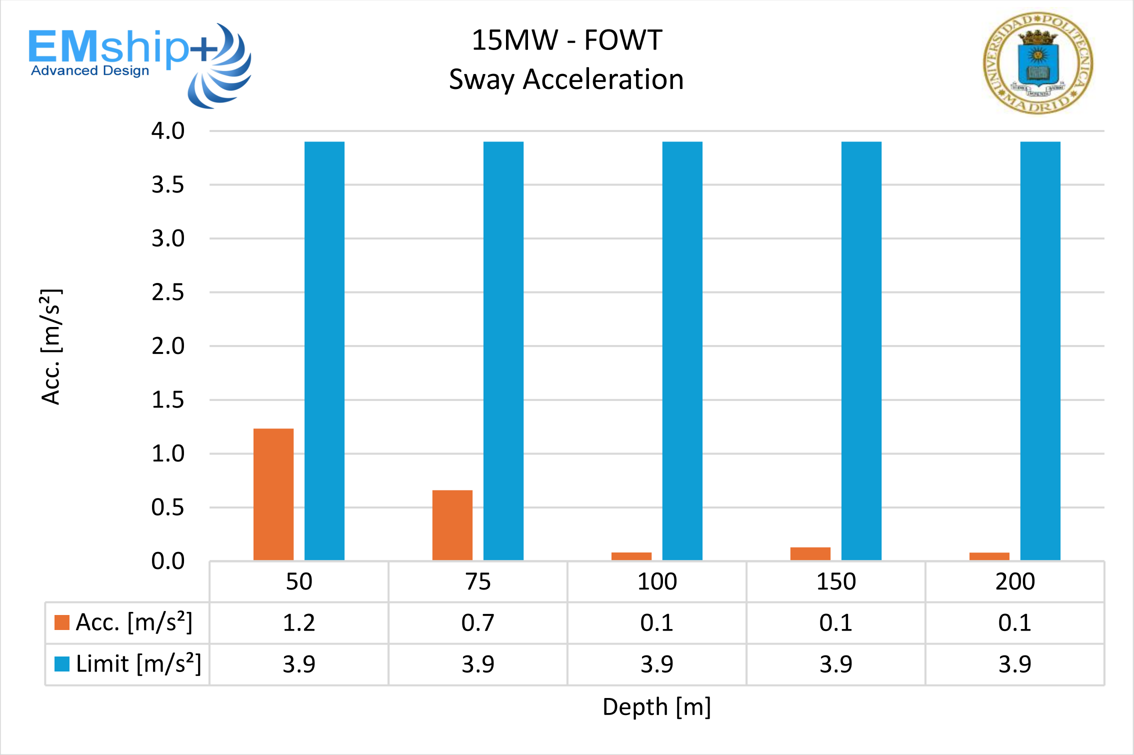


Figure 17.62: Acceleration (extreme) for Catenary layout [180°]



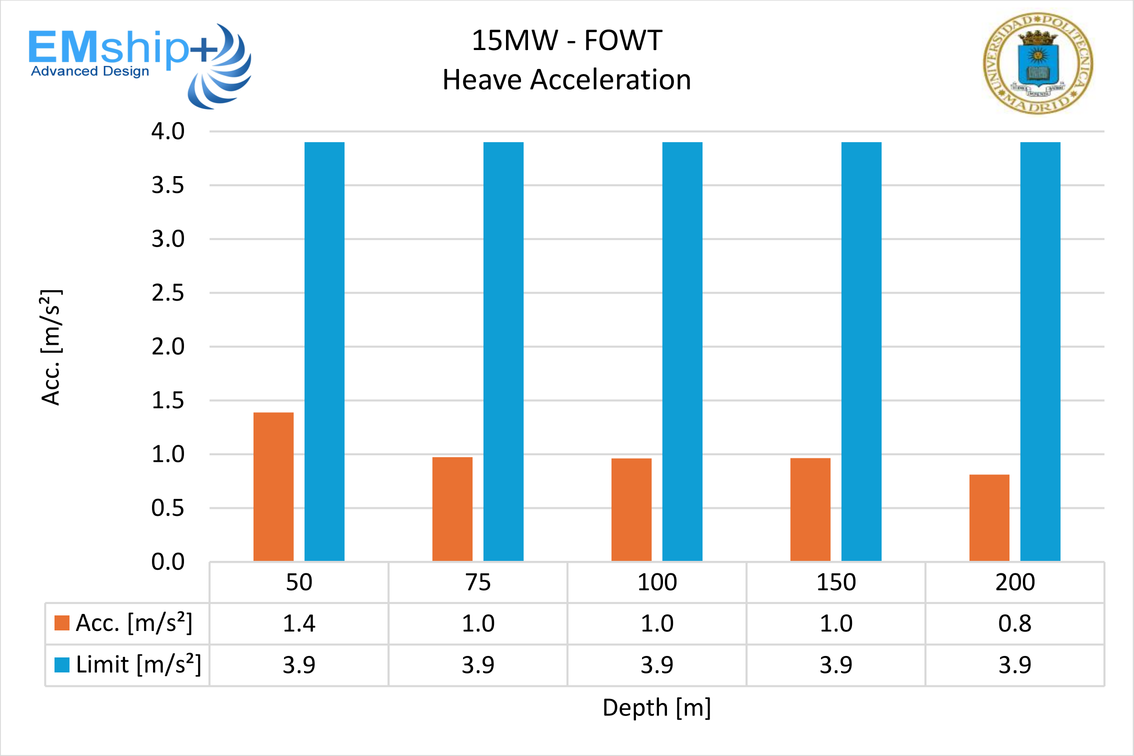
	50	75	100	150	200
🟧 Acc. [m/s²]	3.1	2.1	1.6	1.9	1.1
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.63: Surge acceleration for Lazy wave layout [180°]



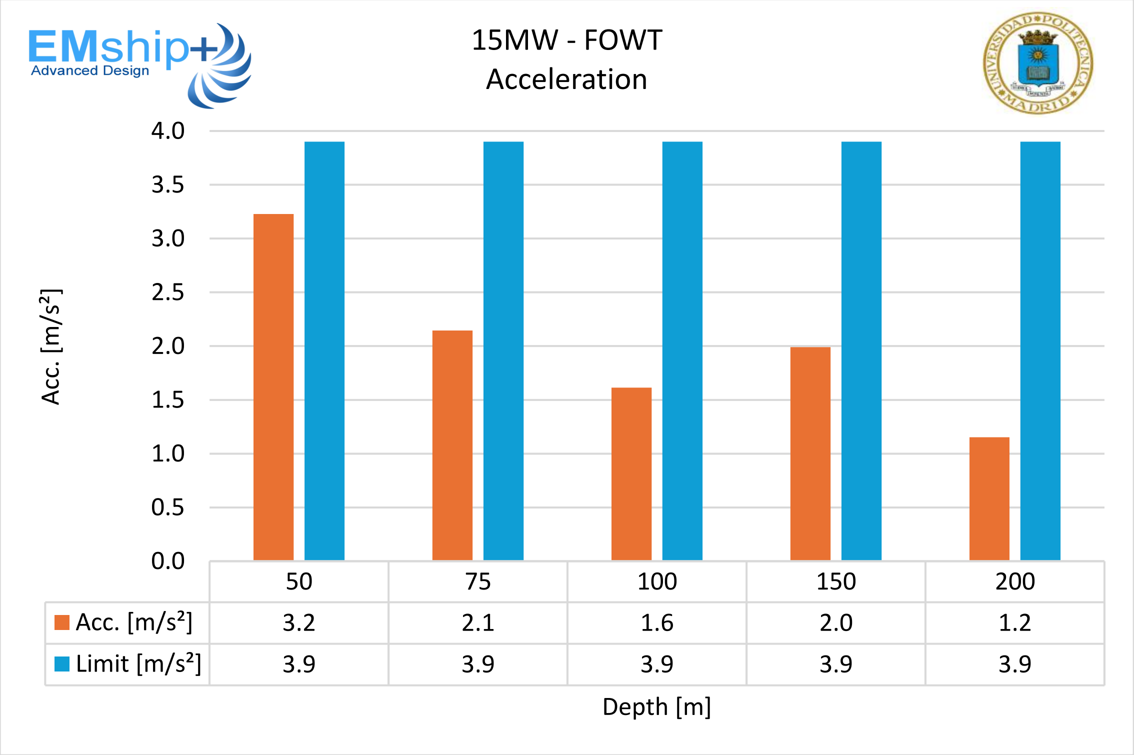
	50	75	100	150	200
🟧 Acc. [m/s²]	1.2	0.7	0.1	0.1	0.1
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.64: Sway acceleration for Lazy wave layout [180°]



	50	75	100	150	200
🟧 Acc. [m/s²]	1.4	1.0	1.0	1.0	0.8
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.65: Heave acceleration for Lazy wave layout [180°]



	50	75	100	150	200
🟧 Acc. [m/s²]	3.2	2.1	1.6	2.0	1.2
🟦 Limit [m/s²]	3.9	3.9	3.9	3.9	3.9

Figure 17.66: Acceleration (extreme) for Lazy wave layout [180°]

A.9 Cost Estimation [Reference to *BVG, 2023*]

Table 17.3: FOWT cost estimate for 15 MW floating offshore wind turbine

Item	Suppliers	Cost (€)
Wind Turbine	***GE Renewable Energy, Siemens Gamesa Renewable Energy and Vestas***	***24 million***
Nacelle		13 million
Rotor		7 million
Tower	CS Wind, Gestamp Renewable Industries, GSG Towers,	4 million
Electrical system	Nexans, NKT, Prysmian, ABB, Siemens, Crompton Greaves and Schneider Group.	Along with nacelle
Floating offshore wind farm	***BW ideol, Principle Power, Saitec, Stiesdal and SBM offshore.***	***510 million***
Primary structure	Aker Solution, Bladt, EEW, Harland 6 Wolf, Lamprell, Navantia, Sif, Smulders and Welcon.	427 million
Secondary structure	Hutchinson Engineering, Kersten, Smulders, Vallourec and Wilton Engineering.	36 million
Auxiliary systems	Ballast systems: Seaplace. Condition monitoring sensors: HBM and Strainstall. Davit cranes: Granada, Palfinger Marine and Protea Group. Navigation lights and markers: Oxley and Sabik Offshore. Personnel winching systems: Limpet Technology and Pict Offshore.	31 million
Corrosion protection	Cathodic protection systems: Corrosion, Imenco, Impalloy and Metec Corrosion protection coatings: Hempel, International Paint and Jotun.	26 million

Table 17.4: Mooring system cost breakdown for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)
Mooring System	***Bridon-Bekaert, Bruce Anchor, Delmar Vryhof, InterMoor, MacGregor, NOV and Vicinay.***	***95 million***
Anchor	Bruce Anchor, Delmar Vryhof, Global Energy Group, RCAM Technologies, Subsea Micropiles, Swift Anchors and Mooreast.	20 million
Mooring lines	Bexco, Bridon-Bekaert, Dynamica Ropes, Lankhorst, Vicinay and FibreMax.	60 million
Connectors	Hydrosphere, InterMoor, The Crosby Group and Vicinay Marine.	10 million
Clump weights	FMGC, Hydrosphere and InterMoor.	
In-line tensioner	Delmar Vryhof, Macgregor, Flintstone Technology and Vicinay Marine.	
Load reduction devices	Dublin Offshore, Intelligent Mooring, TfI Marine.	
Buoyancy elements	Balmoral, DeepWater Buoyancy, InterMoor and SBT Energy.	
Top side connections	First Subsea, Hydrosphere, InterMoor, Macgregor, The Crosby Group and Vicinay Marine.	5 million

Table 17.5: Power cable cost breakdown for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)
Cable	***Hellenic Cables, JDR Cable Systems, LS Cable & System, Nexans, NKT, Prysmian, Sumitomo Electric and TKF.***	***166 million***
Array cables		38 million
Export cables		105 million
Cable accessories	Balmoral, MacArtney, Oceaneering, Subsea Energy, Tekmar, CRP Subsea, Deepwater buoyancy, Pfisterer, SBT energy and WT Henley	24 million

Table 17.6: Onshore substation cost breakdown for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)
Onshore substation	***Same to offshore substation***	***44 million***
Electrical system	GE Grid Solutions, Hitachi Energy and Siemens Energy.	31 million
Buildings, access, etc.	-	13 million

Table 17.7: O & M and decommissioning cost for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)/ year
Operations and Maintenance (O&M)	***-***	***38 million***
Operations	Deutsche Windtechnik, James Fisher Marine Services,	13 million
Maintenance	-	24 million
Offshore vessels and logistics	James Fisher Marine Services, SeaRoc	1 million
Decommissioning	***-***	***78 million***

Table 17.8: Offshore substation cost breakdown for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)
Offshore substation	**-**	***80 million***
HVAC system	GE Grid Solutions, Hitachi Energy and Siemens Energy.	24 million
HVDC system	GE Grid Solutions, Hitachi Energy and Siemens Energy.	-
Auxiliary system	Communications and networks: Atos, Cisco and Semco Maritime. Cranes: Demag, Granada and Kenz Figee. Diesel generators: Aggreko, Caterpillar and Energyst. Fire and blast protection: InterDam and Mech-Tools. Heating, ventilation and air conditioning: Halton, Heinen & Hopman and Johnson Controls. Helicopter fuelling systems: Imenco, Swire Energy Services.	4 million
Top side structure	Helideck: Aluminium Offshore and Bayards. Structure: Babcock, Bladt, Chantiers De l'Atlantique, Heerema, Hollandia, HSM Offshore, Sembcorp Marine and Smulders.	38 million
Foundation	Bladt, Chantiers De l'Atlantique, Hollandia, HSM Offshore, Lamprell, Navantia, Sembcorp Marine and Smulders.	14 million

Table 17.9: Installation cost breakdown for 450MW floating offshore wind farm

Item	Suppliers	Cost (€)
Installation	***Boskalis, Heerema, Maersk, Saipem, Subsea 7, TechnipFMC and Van Oord.***	***202 million***
Offshore substation installation	Boskalis, DEME, Saipem, Seaway 7, Van Oord	13
Offshore cable installation	Boskalis, DEME, DeepOcean, Global Marine, Global Offshore, Van Oord. Cable manufacturers with installation capabilities: Nexans, NKT and Prysmian.	75
Onshore export cable installation	Balfour Beatty, J Murphy and Sons, NKT and Nexans.	4
Anchor and mooring pre-installation	Bourbon Offshore, Bridon-Bekaert, First Subsea, Kvaerner/DOF Subsea JV	37
Floating offshore wind turbine assembly	Given to turbine suppliers or others.	37
FOWT installation	Boskalis, Bourbon Offshore, Maersk, Saipem and Seajacks.	28
Inbound transport	Blue Water Shipping, Bourbon, Boskalis, Cadeler, Coordinadora Internacional De Cargas, DEME	5
Construction port	Construction ports used for early pre-commercial floating projects: Aberdeen (UK), Cromarty Firth (UK), Dundee (UK), Ferrol (ES), Lorient (FR)	-
Offshore logistics	Asco, DNV, Global Wind Service, LOC Renewables, Osprey, Rhenus Group, PSG Marine & Logistics	2