Western Norway
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MASTER'S THESIS

Sensitivity analysis of peak tension loads on subsea power cables during laying operations

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ABSTRACT

Offshore wind is an evolving sector within the renewable energy industry. We can see trends where the wind farms are expanding in size and power capacity, as well as moving to locations further from shore and to larger depths. This presents its challenges to the growing cable network. Today we can see that a majority of the insurance claims in the offshore wind industry is due to cable faults, where a large percentage of these failures occur during the instalment of the inter-array and export cables.

Although the industry is relatively young, effort has been put in to identify the root causes of failure for these cables. A review was conducted on historical data and reliability data, with the goal to seek knowledge about these failures and their causes. The reliability statistics of cable failure is essential for cable installer, as well as the cable designer. As the reliability of the cables depends on the location and instalment method, it is important to map the risks and hazards that are involved which can compromise the cable's integrity. A general hazard identification study (HAZID) was created in this thesis, based on voiced experiences within the industry through a workshop/brainstorming session and historical data found.

From the knowledge gained in the literature review, a sensitivity analysis was carried out to investigate crucial parameters in the cable laying process. The focus was on peak tension loads, and its relation to the key parameter of cable self-weight. This was conducted with both quasi-static forces and dynamic forces with irregular vessel motions. The findings of the sensitivity analysis illustrated the importance of proper cable design, related to each unique project.

The sensitivity of the cable's deployment position from a vessel in irregular seas was also examined, with a dynamic analysis in the time domain. Which illustrated the impact of vessel motion response, in waves and current, on the maximum tension loads in the subsea cable. The finite element analyses were all performed by the aid of the software OrcaFlex, a well-tested software for analysis of marine operations.

Keywords: Offshore renewables, cable installation, export cable lay, HAZID, sensitivity analysis

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

AC	Alternating Current
CLV	Cable lay vessel
DC	Direct Current
DP	Dynamic Positioning
HAZID	Hazard identification
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
IMO	International Maritime Organization
LB	Lay back
MBR	Minimum Bend Radius
OD	Outside Diameter
OFSS	Offshore Substation
OWF	Offshore wind farm
ROV	Remotely Operated Vehicle
SF	Safety factor
SWP	Side wall pressure
TDP	Touch Down Point
U.F.	Utilization factor
VIV	Vortex Induced Vibrations
WD	Water depth

CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

A current matter of discussion in these recent times and a considerable issue within the offshore wind industry is the failure rates of the subsea power cables. These failures are said to account for as much as 75-80% of the total cost of the insurance claims (GCube Insurance Services, 2015). The impact of these cables failing is quite significant. Regarding finances, the cost for locating and replacing a section of damaged subsea cable can vary from £0.6-1.2 million (Dinmohammadi, Flynn, Bailey, Pecht, Yin, Rajaguru & Robu, 2019). Additionally, comes the loss in revenue as the damaged cable no longer transmit power. Failed cables may also cause damage to the turbines and depending on the cable, bring a whole wind farm out of service while repairs are conducted.

During the instalment phase of the cable, there are many factors present that challenges the integrity of the cable. To ensure safe deployment to the seabed, it is vital to identify risks and hazards that are present or might occur in these operations. It is also of importance to understand the mechanical properties and specifications of the cable. The mechanical properties of the cable are in a large degree influenced by its cable protection system and this armour needs to withstand all handling required during the life cycle of the project. During installation, the cables should not be subjected to any mechanical loads that would exceed the cable's design limits (e.g., tension, bending, torsion and crushing). To ensure this, the laying parameters including minimum bend radius, minimum layback and maximum lay tension, needs to be adapted to the cable limits and be maintained during the whole process. (DNV-GL, June 2016)

Therefore, the knowledge of the static and dynamic installation processes is crucial to inquire, in order to meet the mechanical properties of the cable and avoid any damages. Tension forces on subsea cables during laying operations has been a topic amongst researcher for many years. The maximum tension force is in the need to be calculated and analysed in advance and during laying to avoid less favourable operation situations. By investigating the crucial parameters that inflict top tension on the cable, one could obtain knowledge on how to complete the cable lay operation without damaging the cable protective system and cause failure of the cable. (Yang, Jeng & Zhou, 2013)

1.2 PREVIOUS WORK

The review of literature unravelled many theories formed on cable tension (based on different assumptions), as a significant amount of research has been conducted on the matter through the years. In this section some examples of past work with relevance to the objectives of the thesis will be presented.

Prpic and Nabergoj (Prpic & Nabergoj, 2005) presented a 2D model of cable dynamics with the effects of head sea conditions. In their analysis, the vertical motion of the laying wheel was of main focus. Wang et al. (Wang, Huang & Deng, 2008) further investigated the vertical movement of a cable ship caused by wave induced vessel motion, illustrating the non-ignorable tension force at the laying wheel.

Yang et al. (Yang, Jeng & Zhou, 2013) proposed a semi-analytical estimate for the prediction of tension and cable configuration during laying operations. It was also conducted a parametric study to examine the effects of ocean current and wave characteristics on cable tension and profile.

Mamatsopoulos et al. (Mamatsopoulos, Michailides & Theotokoglou, 2020) developed a paper with the purpose of creating a custom-made analysis tool with analytic catenary equations, which accounts for cables with varying weights and stiffness properties. The paper also illustrates the difference in tension calculations by adding the cable part which extends from the water surface to the laying wheel.

Wang, Yuan and Li (Wang, Yuan & Li, 2010) presented a numerical approach for the laying of pipelines with a J-lay method, taking into account the importance of ocean currents. Senthil B. and Selvam (Senthil B. & Selvam, 2015), considers a simplified J-lay pipeline numerical model, analysed using OrcaFlex. Little research was found on the deployment of subsea cables with the J-lay method.

Although extensive research has been conducted on the phenomena of cable tension, investigating dynamic forces of the environment on the cable is a complex task and there is bound to be limitations withing the work due to set boundary conditions.

1.3 PRESENT WORK (SCOPE AND OBJECTIVES)

This research aims, in the first part, to investigate and gather qualitative knowledge of several aspects concerning cable laying operations of offshore power cables within the offshore wind industry. These aspects include reliability of the subsea cables, risk involved in laying operations, cable failure modes, structure and properties of the cable, general forces acting on the cable, and operational requirements of the cable. Included is the goal of identifying main hazards precent within a cable instalment project, with the aid of a HAZID analysis. This part of the research aims to build descriptive knowledge both wide and more specific, with the focus on the limitations and requirements of the cable protective layer.

For a second part, the research aims to investigate more closely the relationship between main laying parameters and cable tension. Here different parameters will be investigated for its importance/sensitivity in the cable laying process. The main focus of this thesis is to study the phenomena of maximum tension during cable installation, and possibly establish parameters which are considered crucial in order to maintain the design criteria of the outer protection of the cable. At the same time provide a level of detail during the study, such that the reader can be presented to a method of conducting such sensitivity analyses.

1.4 PROBLEM DEFINITION

In order to perform a sensitivity analysis of various cable laying parameters and achieve the objectives of the thesis, two main research questions were established:

When looked at maximum tension loads on an export cable during cable lay in irregular seas, can information be found about the sensitivity of the cable's configuration, if the subsea power cable's self-weight and stiffness properties is made a variable?

With different deployment positions of the subsea power cable onboard the CLV during cable laying, can a relation between vessel motion in irregular seas and maximum tension load be found?

Following sub-questions was formed in order to gain the knowledge needed to answer the main research questions:

– What hazards are present in a cable installation project?
– Which forces are imposed on a subsea power cable during installation?
– What are the main parameters in a cable laying operation?

1.5 ORGANIZATION OF THESIS

To arrive at an answer for these questions stated, the study is divided in five parts:

- Literature study where the structure and mechanical properties of a subsea power cable typically found within the offshore wind industry are described, along with descriptions of cable laying operations: Chapter 2
- Review of the subsea power cables failure rate, along with descriptions of various failure modes. Followed by a description of a HAZID analysis: Chapter 3
- Modelling of cable laying scenarios: Chapter 4
- Quasi-static analysis to validate and understand the governing mechanics in maximum tension loads: Chapter 5.
- Dynamic analysis with irregular motion of the vessel in irregular seas: Chapter 6

Followed by discussion of the results and concluding remarks within Chapters 7 and 8.

1.6 MAIN CONTRIBUTIONS

In this thesis, a review of historical failure data and the reliability rate of subsea cables within the offshore wind industry was performed, followed by a HAZID analysis to identify the main hazards present in the instalment of these cables.

Sensitivity analysis was carried out for key parameters in cable laying such as cable self-weight and deployment positions. With the intent of gathering an insight in the selected parameters relation to maximum tension loads in the cable, when the cable laying vessel is experiencing irregular motions in irregular seas. The dynamic analysis in the time domain was conducted and based on knowledge gained with quasi-static analysis and catenary equations. The finite element software, OrcaFlex, was implemented as a tool to achieve this.

CHAPTER 2 – SUBSEA POWER CABLES IN THE OFFSHORE WIND INDUSTRY

2.1 OWF ELECTRIC POWER SYSTEM

In all its simplicity, the electrical power system in an offshore wind farm can be divided by electricity at different phases; generation, transportation, distribution and usage. The electricity is generated by a wind turbine, with the renewable energy source of wind. The electric power is transported through a transmission network before entering the distribution network and then made available to the consumers. The offshore wind system operates in real time, where the energy must be used straight away, as the electricity is only produced when consumers use it. This is typically due to the very few ways of storing the generated energy. (Marine Scotland, 2018)

Offshore wind farms may include different layouts, but in general the system consists of a number of wind turbine generators, with a grid of subsea cables placed along the seabed. Array cables connect the wind turbines to each other and to an offshore substation if present. Export cables connect the wind farm to the onshore transmission system. (Marine Scotland, 2018) In larger offshore parks the wind turbines are connected to an offshore platform (substation), which has the purpose of a transforming the energy by increasing the voltage, before export cables transports the energy further. For export cables, it mostly common to see HVAC three-phase cables (>100 kV) when the cable route exceeds 30 km. HVDC is also an option for export cables, however this requires the presence of a converter station (both offshore and onshore). The convertor station transforms the power from alternative current (AC) to direct current (DC). As the construction of a converter station is a costly matter, this solution is often only desirable when a large amount of power needs to be transmitted over longer distances. (Worzyk, 2009) An illustration of a layout for a larger offshore wind farm may be seen in figure 1.

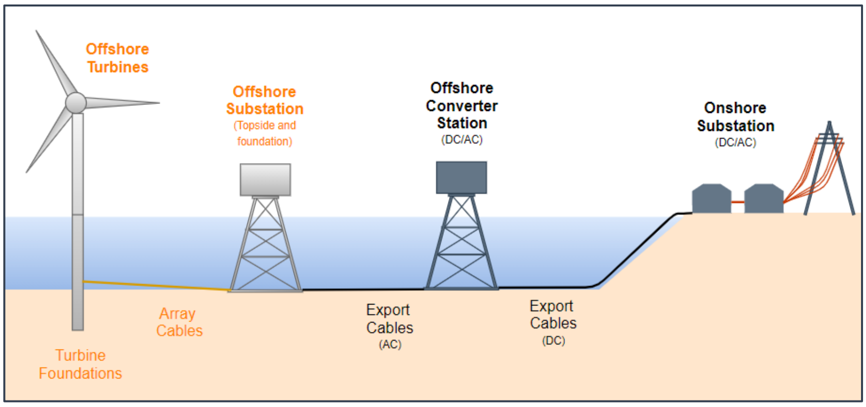

Figure 1 OWF electric power system. Own illustration (DNV-GL, 2016)

2.2 CABLE STRUCTURE & LAYERS

The structure of a subsea power cable depends on whether it is alternating current or direct current which is to be transported. Here, DC cables usually incorporates a single conductor while AC cables normally consist of 3 conductors transporting current at three phases. AC cables have been the dominating the cable network within offshore wind farms, as the power generation is generated with alternative current. (Worzyk, 2009)

A cable is basically an assembly consisting of one or more power cores (depending on the need of the cable) with individual/common screen and sheath, assembly fillings and covered by a outer protection. The cables may also include packages of optical fibres. The design of the cable depends on the conditions of the renewable energy project being developed. Such factors include: number of turbines, location, turbine size, if convertor is needed, cable route, installation method and cable protection method. The majority of high voltage cables are individually designed for each single project (DNV-GL, 2016(a))

Several demands are set to subsea power cables. Not only must the cables ensure a high efficient electrical transmission, sufficient protection against the marine environment and handling during instalment, but the cables also have to be designed with considerations to the environment. These considerations includes: incorporating properties to ensure high reliability, good abrasion and corrosion resistance, water protection and overall minimized environmental impact. (DNV-GL, 2016(a))

An illustration a typical cross-section of a HVAC can be seen in figure 2. Technologies and materials used to produce HVAC subsea cables are presented in following sections, as the focus of the thesis is primarily on these export cables. Further description of the mechanical properties, typical specifications, and limits of a subsea power cable can be found in Chapter 3 and 5.

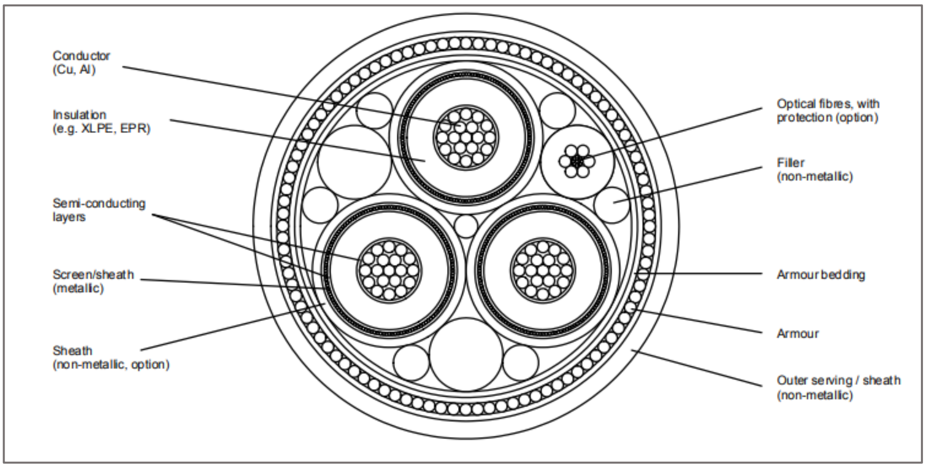

Figure 2 Typical 3-phase AC subsea power cable cross-section (DNV-GL, 2016(a))

2.2.1 Conductor

Conductors relay mostly on copper or aluminium to transmit energy to shore. In cases where weight is of critical concern, aluminium is more suitable as it has one third of the weight compared to copper. At the same time, copper is often the most preferred type as it has higher electrical conductive properties. This also has its benefits where a smaller cross-section is required and hence less insulation, armouring and other material are needed. These two conductor types can however, be jointed together, providing a lighter cable. The conductor comes in many shapes (figure 3). The type and shape of the conductor to be used depends on power demand, environment and length of the cable. (Worzyk, 2009)

Some examples include (Worzyk, 2009):

- Round conductor (single strand)
- Oval conductor (single strand)
- Hollow conductor (single strand)
- Stranded round conductor
- Profile wire conductor
- Profile wire hollow conductor
- Segmental conductor
- Segmental hollow conductor

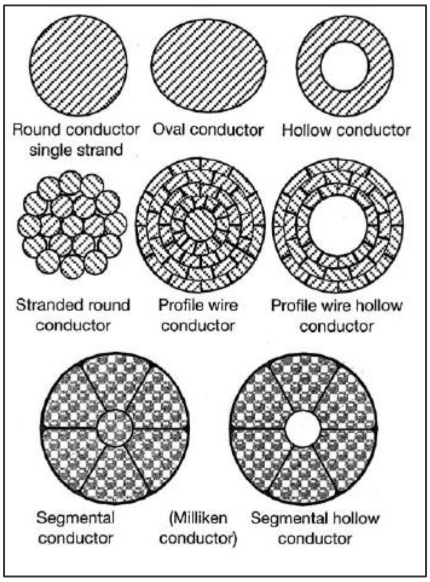

Figure 3 Conductor configurations (Worzyk, 2009)

2.2.2 Insulation

The insulation in a cable has the objective to shield the conductors against external contact. This layer must withstand temperatures and aging, as well as to be robust against mechanical loads the cable might be subjected to when handled and when in operation. The most common used insulation types are Cross-Linked Polyethylene (XLPE) and Mass-Impregnated paper (MI). However, here are three exists several solutions for insulation of different types of cables (Das & Nicolaos, 2017):

- Self-contained fluid-filled cables
  - SCFF/SCOF (self-contained fluid-filled / self-contained oil-filled)
  - HPFF/HPOF (high-pressure fluid-filled / high-pressure oil-filled)
  - HPGF (high-pressure gas filled) and GC (gas compression)
- Paper insulated (lapped insulated) cables
  - MI (mass-impregnated) or PILC (paper-insulated lead-covered); it consists of mass impregnated paper with high-viscosity insulating compound
  - PPL (paper polypropylene laminate)
- Extruded cables
  - EPR (ethylene propylene rubber)
  - PE (polyethylene)
  - XLPE (cross-linked polyethylene); it consists of a network molecular structure suited for high temperatures

2.2.3 Fibre optics

Optical fibres may be present in some subsea cables and can have several different purposes. Such purposes include distrusted measurement of temperature, transmission of data, measurement of cable strain/vibrations, as well as fault detection and locating. (Worzyk, 2009) More information about fault detection and monitoring can be found in chapter 3.

2.2.4 Water protection/sheath

Outside of the insulation is a layer of metallic sheath. The sheath has the task of protecting the insulation from moisture and water ingress. Several materials can be used, i.e., copper, aluminium and lead. Lead alloy sheaths can be seen to be more common. The sheat may also be applied to have a level of function as a conductor. This semi-conductive sheath will hinder a voltage difference between layers. (Worzyk, 2009)

2.2.5 Armouring

The armour of a cable has the task of providing the majority of the cable's own protection against the environment and mechanical stress. This layer depends on the need of the specific project of which the subsea cable is to be installed. The tensional strength of the cable relays heavily on the structure and stiffness properties of this layer. (Worzyk, 2009)

The armouring consists of metal wires which are helically wound around the cable with a certain lay length (pitch). The lay length, can be measured by which the armouring wire completes one turn around the cable. With long lay-length armouring, the wires will run almost parallel to the cable's axis, providing large tensional stability. However, this would result in increased bending stiffness. With short lay length, the outcome is the opposite, giving lower tensional stability and lowering the bending stiffness. To add extra strength, another layer of wire can be applied. By placing two layers with the wires in opposite directions, this will also reduce the torsional stress on the cable. The armouring wires are also often designed with a thin layer of synthetic tape to reduce friction, and corrosion protection where the wires are coated in zinc. The wires may also be protected by a layer of bitumen followed by two layers of polypropylene (PP) yarn. (Worzyk, 2009)

Single armoured cables are typically used in conjunction with cable burial, which will provide the cable with sufficient protection. Double armoured cables are significantly heavier and more inflexible, making these more difficult to install. Double armoured cables are often used when additional protection against the marine environment are needed, i.e. in locations where there is a high risk of crush damage and hostile seabed intervention. (Marine Scotland, 2018)

2.2.6 Outer serving

On top of the corrosion protection of the armour wires, is another protective layer, the outer serving. This layer presents first-hand protection of the cable during all handling. Today these two main types of servings include extruded polymeric outer servings and servings made from wound yarn layers. The outer serving of a cable has an impact of the installation procedure, where these two outer serving types include different friction coefficients. The wound yarn layers will provide a good grip for the tensioners onboard the CLV. While the extruded servings, on the other hand, are more slippery. (Worzyk, 2009)

2.3 CABLE LAYING OPERATIONS

There are many steps in the instalment of an export cable. Typically, there is a requirement for a beach pull-in, normal lay, possible splicing of two cable ends and a pull in to a platform/substation if present. The level of steps that are included in such a process depends on the size and location of the wind farm. As the objective of the thesis are to investigate several cable laying parameters, only normal laying operations will be mentioned further.

2.3.1 Cable laying parameters

Installing a subsea cable may not be as simple as it might sound. It is quite a complex procedure to place the subsea cable on the seabed without issues, as there are many aspects of such an operation that need to be considered, carefully calculated and monitored. As seen in Figure 4, the laying operation is influenced by many factors. One of the largest concerns is to keep a proper balance of tension in the cable.

Controlling the tension can be achieved by monitoring all the variables, which includes vessel speed & pay-out speed of the cable, layback length, bend radius, departure angle and cable tension. Influencing these variables are water depth, wave forces & current forces on the cable, and vessel motion in waves and current.

The cable tensioner on the laying vessel has the objective to brake and control the speed of the laying process, as well as to prevent product slippage during installation. The tension of the cable machine depends on several factors and puts demands on the outer protection of the cable. The speed of the vessel and pay-out speed from the tensioner needs to be coordinated so the proper tension in the cable can be achieved. With too high axial tension in the cable, the cable is naturally in the risk of getting damage, or if the design limit is reached, the cable will break. On the other side, too low tension might cause the cable to compress at touch down point, bend excessively or fall uncontrollably to the seafloor. (Worzyk, 2009).

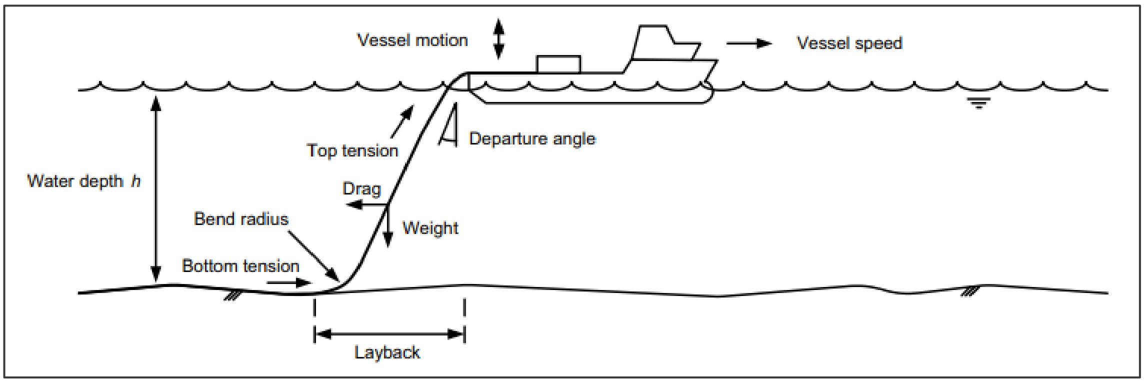

Figure 4 Main parameter in a cable laying process (DNV-GL, 2016(a))

The tensioner's pull and pay-out speed can be controlled and monitored on the CLV. While an ROV (remotely operated vehicle) can monitor the cable as it is being placed on the seafloor. These ROVs are equipped with cameras and positioning device, which can allow the crew onboard to monitor the cable's position related to the vessel, the layback length and its catenary shape. This provides a higher level of control on the laying operation.

2.3.2 Cable laying vessel and cable deployment methods

The cable laying platform may take the role of a cable laying barge or a cable laying vessel (CLV). The choice of a cable laying platform depends on the need of the project, and often the CLV or the barge are equipped and specially designed/adapted to each unique operation.

The most influencing factor for a selection of such a platform lays with its loading capacity, deck space, handling equipment and manoeuvrability properties.

Good manoeuvrability at sea is crucial to reduce unwanted dynamics on the cable and achieve a successful cable lay operations. Waves and currents will force a vessel to move in its degrees of freedom. To obtain a correct position, anchors, tugs and DP (dynamic positioning) system of a vessel are tools which can be seen applied. While in shallow water, usually anchors and tugs will aid a vessel in keeping the correct position. When there is enough clearance under the keel of the vessel, DP system will normally be the main method for position control. Tugs may also aid the vessel during different phases of the operation or in some cases throughout the planned cable route. (Gudmestad, 2015)

There are many methods of deploying a subsea cable from a vessel. The main methods include: S-lay with a chute/stinger, J-lay over the side of the vessel or J-lay through a moon pool. The most common method in the industry is S-lay with the cable being deployed over a chute. The chute is formed as a rounded part of the vessel stern and will have a radius that equal to the MBR (minimum bend radius) of the cable or larger. With the J-lay method, the cable is deployed almost vertically down to the seabed, allowing to have shorter layback lengths. With this method the cable is normally supported by a tower which guides the cable into the water. The largest difference between these methods are the bending shapes of the cable as its being deployed. S-lay will have a bend over the chute and a bend at TDP (giving the S shape), while with J-lay, no bending of the cable at the top is present (forming a J shape). (Ventikos & Stavrou, 2013)

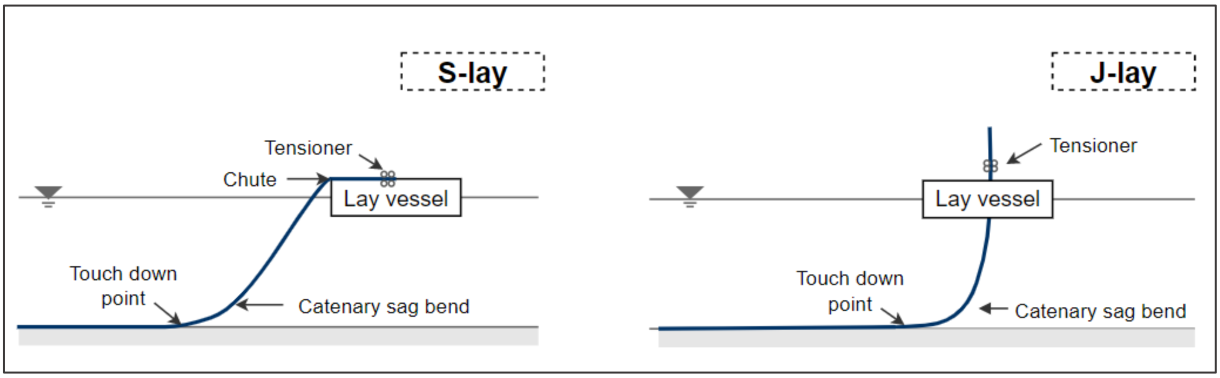

Figure 5 Deployment methods: S-lay and J-lay. Own illustration (Senthil & Selvam, 2015)

CHAPTER 3 – CABLE FAILURE & CABLE INSTALLATION HAZID

This chapter takes a closer look on damages and failures of subsea power cables. A review was performed on the historical failure data and the reliability of power cables in the offshore wind industry, with a comparison to subsea cables in other industries. The review is followed by descriptions of the cable's various failure modes and a mentioning of methods for cable damage detection.

The importance of risk-based procedures in a cable installation project, and how a hazard identification analysis (HAZID) can aid in reducing the risks for cable damage, will also be highlighted in this chapter.

3.1 HISTORICAL FAILURE DATA AND RELIABILITY

In the process of conducting a literature review about the reliability of subsea power cables and the causes for cable failure, detailed information was difficult to obtain. There can be seen a shortcoming in information shared about subsea cable activities within the offshore wind sector, and subsequently a need for experience-based knowledge and innovative solutions to become of commercial status. For this reason, the few existing public metrics (which has its own limitations) are the main source for estimating the reliability in the planning processes. (Worzyk, 2009) Sharing the experiences amongst the industry and obtaining a larger set of data upon cable failure could improve decision making, as well as to reduce both the probability and the impact of future failures.

By the end of 2020 there were currently installed 116 offshore wind farms in Europe between 12 countries (with 6 more waiting to be connected to the grid), where the majority of these existing OWFs just exceeding the 10-year mark. It is expected that 29 GW of new offshore wind to be developed over the next five years (2020-2025), which is almost a doubling of the annual installation rate. (Wind Europe, 2020a) Even with significant growth in the near future, the industry is fairly young, and the availability of failure rate statistics will probably not improve in a significant scale over these next few years. Historical data for the cables during early life, however, may aid in getting an understanding of the reliability of subsea cables.

In order to investigate cable failures, a failure is needed to be defined. In the reports produced by the International Council on Large Electric Systems (Cigre), a failure was defined as: "*…Any occurrence on a cable system which requires the circuit to be de-energised.*" (CIGRE, 2020). The public metrics provided by Cigre is a source that many in the offshore wind farm rely on, when planning for reliability and operational risks.

Cigre updated their public metrices in 2020. This survey covers the service experience (based on questionnaire) gained in a 10-year period from 2006 to 2015, for AC and DC transmission cable systems. The survey resulted in 21 replies being received from 14 countries. Key points found in the survey were (CIGRE, 2020):

- 64 % of reported faults were internal failures, 29 % were external faults, and the remaining 7 % of the faults were not specified.
- 56 % of all faults have been located to the cable itself, where the rest was located to cable accessories and other components.
- 82 % of all external faults across were due to third party mechanical damage afflicted upon the cable.
- A total of 22 faults were reported on the subsea cable. Where, 8 faults were reported on DC cables (36 %), and the remaining 14 faults were on AC cables (64 %).
- The majority (89 %) of cable faults with external cause were on unprotected cables. The majority (67 %) of internal faults are on buried cables.
- Most failures on the subsea cables with external cause are due to anchor damage.
- All reported cable failures with external cause are on cable installations with an age more than 10 years.

The failure rates were estimated by the following formula (CIGRE, 2020):

$$Failure\ rate = \frac{\sum_{i=1}^{10} N_i}{\sum_{i=1}^{10} A_i} \times 100$$

Where:

Failure rate =	Number of cable failures per 100-circuit-km-years or number of component failures per 100-component-years
N_i =	Number of failures of the component considered during the i'th year of the period concerned
A_i =	Quantity of the component in service at the end of the i'th year (circuit-km or number)

The reported failures are grouped in three main categories: Internal failures, external failures and unknown. Internal failures considered failure origins from one or more of the layers of the cable by i.e., water ingress, poor workmanship, or damage during installation. External failures considered failures as a result of human interaction like construction/excavation works, anchoring, trawling or fishing activities. Included are also failures caused by the environment. Reported faults by this categorization across water depths can be seen in table 1.

Reported faults – AC & DC						
Submarine Cable failures (Cable faults only)	Water depth at fault					
	0-10m	11-50m	51-100m	101-200m	more than 200m	Total
External – anchor	4	3	-	-	-	7
External - other physical external	-	-	-	1	1	2
Internal fault	1	8	-	-	-	9
Unknown	1	2	1	-	-	4
Total	6	13	1	1	1	22

Table 1 Reported faults by type and water depth (CIGRE, 2020)

Cigre has performed several investigations of cable failure in the industry over the years. A comparison of the results from these surveys can be found in table 2. When examining the results of the surveys, a reduction in the failure rate can be seen. This can be assumed to be because of improvement in surveys, cable routing, cable laying and cable protection. While the outage time has seen to have increased over the latest years. Reasons here may be due the more subsea cable that are being installed in locations with challenging environmental conditions and weather conditions (i.e., the North Sea).

	Comparison			
	CIGRE Session Paper 2-07, 1991	CIGRE Symposium Paper 2-07, 1991	CIGRE TB379 2008	CIGRE WG B1.57, 2020
Years of survey	30	10	15	10
Period of survey	1950-1980	1980-1990	1991-2005	2006-2015
Quantity of cables (km)	3610	N/A	7100	6098
Number of failures	154	116	49	24
Failure rate (number of failures/100 km/year)	0,32	N/A	0,12	0,055
Average outage time (days)	37	70	60	105

Table 2 Comparison of surveys conducted by Cigre working groups (CIGRE, 2020)

Based on other sources, the fault cause data from the Submarine Cable Improvement Group (Wang, Yan, Li, Zhang, Ouyang & Ni, 2021) showed that external aggression is one of the main causes for cable failure (Figure 6). At the top of the failure list comes fishing activities and fishing equipment. Still a reduction can be seen of this category in latest years, which might be because of improved cable protection or the established laws against fishing in proximities of the cables. While buried subsea cables are less vulnerable for fishing equipment, anchors still pose as a threat and is another main cause for failure. While heavy fishing gear can normally penetrate less than approx. 0,5m in soft soil, a heavy anchor (30 T) can penetrate more than 5 m in soft soil. (Wang, Yan, Li, Zhang, Ouyang & Ni, 2021)

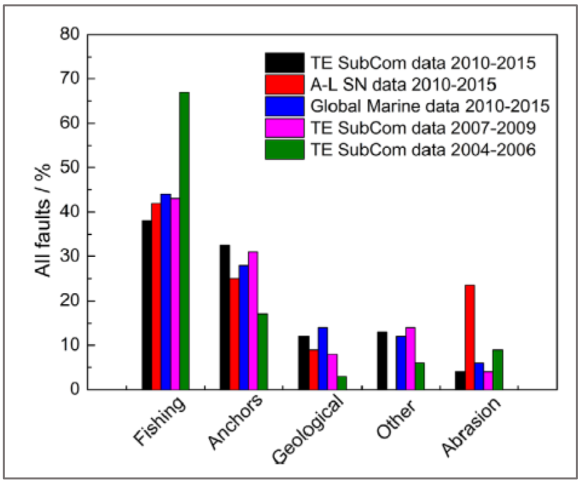

Figure 6 Fault statistics of submarine cable system for external aggression. (Wang, Yan, Li, Zhang, Ouyang & Ni, 2021

Another statistic on cable failure can be found (Strang-Moran, 2020) were only a small part of the recorded cable failures were due to external damage (Figure 7). The majority of recorded failures were due to improper installation, including cables limit specifications that were neglected and insufficient burial. Also included in this survey is cable design fault, where the opinion is that the cable was not properly designed for its environment of operation.

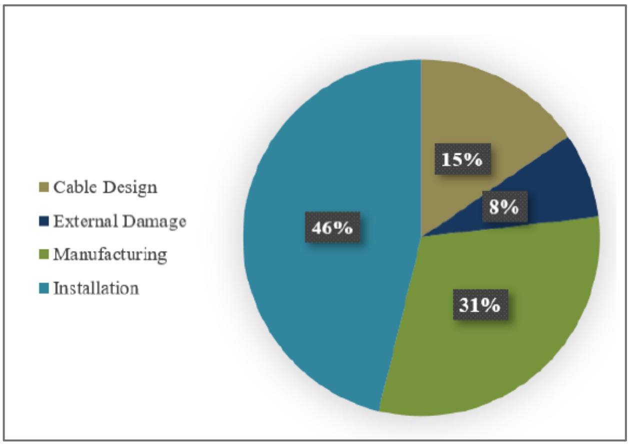

Figure 7 Causes for cable failure (Strang-Moran, 2020)

Concerning the telecom cable industry there have been performed comprehensive studies on statistics of subsea cable damages, due to the fact of the vast amount of subsea telecom cables installed. Here, the fishing industry remains one of the main causes for failure. This have had great consequences for the telecom cable industry over the years. One example here is when Greenland suffered the loss of two subsea cables within a short time frame, where one of these have been stated officially to be caused by a trawler. This resulted in loss of internet service for a part of the country for months, as repairs were put on hold due to bad weather conditions.(Commsupdate, 2019) When comparing the failure statistics between subsea telecom cables and subsea power cables in the offshore wind industry, the challenge lay in the differences between the cables dimensions and mechanical properties. Subsea power cables are not as vulnerable to external aggression due to the larger diameter and greater armour strength. (Worzyk, 2009).

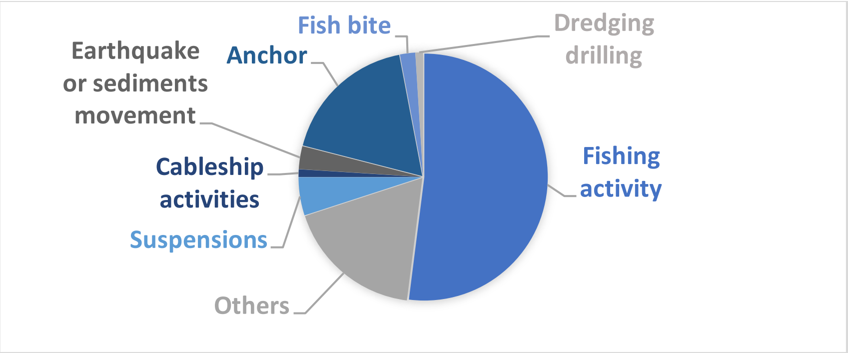

Figure 8 Causes of damage to telecom cables in the Atlantic (Worzyk, 2009)

While similarities could be seen across the different subsea cable types, the findings from the literature review showed that the failure characteristics and causes are strongly linked to location, methods for cable protection and the cable configurations. Hence, to improve the statistics, the most important considerations are cable protection, proper handling of the cable, more environment adaptive cable design, and a greater understanding of the cable's limits and mechanical properties.

3.2 FAILURE MODES

The majority of the subsea cable failures origin from degradation and breakdown of the insulation, which allows for water to come in contact with the conductor and the transmission is lost. There are several failure modes that can compromise the integrity of the cable, which can be classified as electrical-, thermal-, chemical-, and mechanical failures. (DNV-GL, 2016(a)) Some mentioning of these failure modes with an emphasis on tension related mechanisms will be followed in this section.

External damage to cables can cause failures occurring rapidly or in a slow process. Due to the subsea cables high-strength armour, it would take a significant amount of force to directly break the cable and cause loss of transmission. More usually, external aggression will cause deformations in the multiple protective layers before chemical-, electric- and/or thermal stress occurs at the damaged location causing degradation of the cable. (Wang, Yan, Li, Zhang, Ouyang & Ni, 2020)

3.2.1 Electrical failure & Thermal failure

Subsea power cables can fail during their service life due to electrical and thermal causes. When it comes to electrical failures, insulation breakdown, treeing and partial discharge are some examples of main failure modes here.

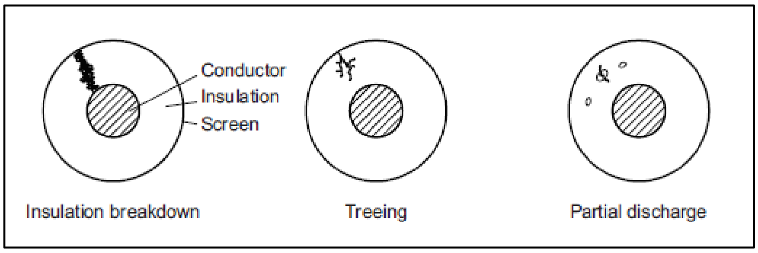

Figure 9 Electrical failure modes (DNV GL, 2016(a))

Insulation breakdown is where the dielectric strength of the insulation has been compromised. Numerous factors can cause this failure mechanism, which may can lead to a full discharge between conductor and insulation screen. (DNV GL, 2016(a))

Partial discharges occur due to voids or imperfections in the insulation system and will eventually lead to electrical treeing. Treeing can be caused by voltage or by contamination to the insulation. In addition to electrical trees, water trees can form inside the insulation. These two mechanisms have different structure and growth features. Both occurs from defects where a high electric field is exposed followed by discharges, chemical products, and breakdown. (Wang, Yan, Li, Zhang, Ouyang & Ni, 2020)

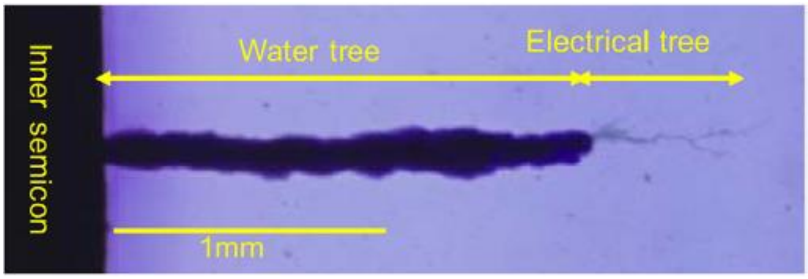

Figure 10 Cable faults: Water tree and electrical tree (Wang, Yan, Li, Zhang, Ouyang & Ni, 2020)

Overheating of a cable can result in thermal failure, where the main causes are electrical current, external heat and solar irradiation. This can produce an increase in conductor temperature and ageing of the insulation. (DNV GL, 2016(a)) Cold temperatures can also inflict failures in a cable. Often subsea cables use galvanized steel wires as armour with polymer modified bitumen (PMB) to protect these wires from corrosion. At low temperatures (0°C and below) the PMB will become stiff and provide high shear forces between the armouring wires, reducing the cable’s capacity (allowed combinations of axial tension and bending curvature) and increase the fatigue damage. Bird-caging may also arise where the armour wires become fixed due to the stiff bitumen. (Konradsen & Ouren, 2014)

3.2.2 Chemical failure

A chemical failure can be said to be caused mainly by the environment, where corrosion and UV irradiation are some examples. UV irradiation can cause degradation of the sheath, depending on the cable’s adsorption, by aging or cracking of the outer cable sheath. Corrosion primarily affects the design life of a subsea cable, where the cable becomes weak and vulnerable to the external forces. Abrasion is one of the main causes of corrosion, where this can damage these protective layers of the cable. (DNVGL, 2016(a))

3.2.3 Mechanical failure

Mechanical failures can occur in the cable's service life, installation phase, during manufacturing and transport. These failures typically occur when the mechanical properties of the cable are comprised.

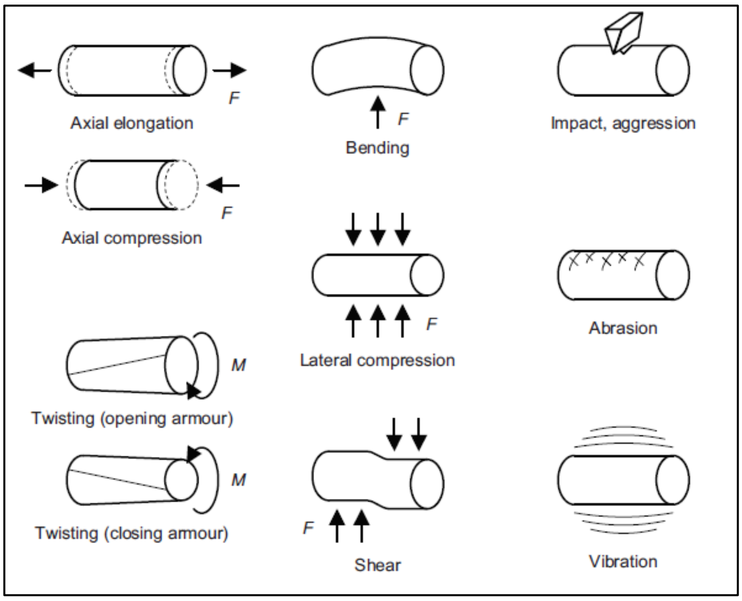

Figure 11 Mechanical failure modes (DNV GL, 2016(a))

Cable suspension and Vortex Induced Vibrations

Often cables are being placed on an uneven seabed, depending on seabed preparation and whether the cable is to be buried or not. In laying operations, high bottom tension in areas of irregular seabed can cause the cable to be suspended between two elevated points, creating point loads with high tension and friction. Reducing the tension onboard the vessel will aid in avoiding such situations. However, a cable can be suspended by other means, Tidal currents can cause a "scouring effect" which will remove some of the surrounding soil and leave the cable in free span. The shore landing of a cable is also vulnerable for soil removal due to tide and wave motions. (Worzyk, 2009)

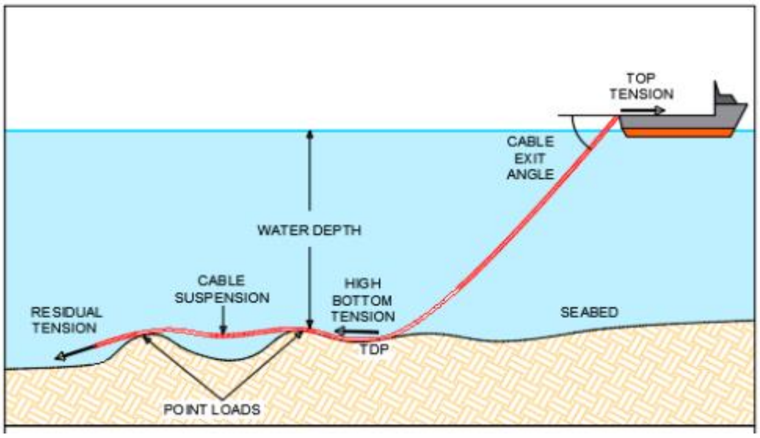

Figure 12 Cable suspension over uneven seabed (Mamatsopoulos, Michailides & Theotokoglou, 2020)

With strong current present, the cable suspension may be subjected to vortex induced vibrations (VIV). This phenomenon is explained further in Chapter 5. VIV will in the end cause fatigue damage to the cable and is depended on the length of the span and cable stiffness. Free spans are also more at risk for damage by a dropped objects or impact loads. (DNV-GL, 2016(a))

Figure 13 Cable suspension and exposure due to wave action on a sandy beach in Great Britain (Source: www.aphotomarine.com)

Abrasion

Another common cause of failures is external abrasion of the outer serving of the cables, which lead to sheath faults from the outside of the cable. (DNV-GL, 2019)

Abrasion of the subsea cable takes place as a result of the relative motion of the cable against rough surfaces. Examples include cable movement on the seabed, sediment transport, shore pull of a subsea cable, anchor dragging an exposed subsea cable on the seafloor, cables in a free-hanging position against a bellmouth and cable crossing locations. (Reda, Thiedeman, Elgazzar, Shahin, Sultan & Mckee, 2021)

Figure 14 Abrasion failure to subsea power cable (Reda, Thiedeman, Elgazzar, Shahin, Sultan & Mckee, 2021

Torsion and bending

Torsion is caused by a twisting moment and internal friction. The objective of helical armour laid in opposite directions, for instance, is the intent to keep the axial rotation at zero during tensioning. Here, the cable strength and stiffness are key factors in how the cable will respond to torsion loads. Torsion will usually start to build up in the cable until either the cable is damaged or takes the shape of a corkscrew (whriting) which is may be difficult to correct (figure 16). Damages by torsion includes amongst other; strain to the cable, opening or closing of the armour, buckling, and bonding failure. (Benjaminsen & Heggenhougen, 2020)

Excessive bending of a cable can cause deformations and is highly dependent on the cable's strength and stiffness. A large bending moment can cause elongation, compression, strain and bonding failure. Under low tension and torsion on the seabed, cables can form unwanted geometries such as loops (or hockles) and tangles. The loops may cause localized damage as well as damage to fibre optics if present. If tension in the cable rises after a loop formation, the radius of the loop decreases and a kink can form, which is considered as failure of the structure as the minimum bed radius limit of the cable is compromised (figure 15). (Goyal, Perkins & Lee)

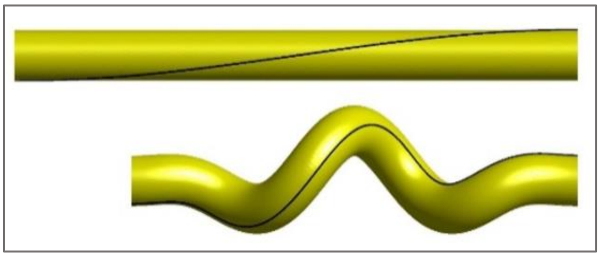

Figure 16 A cable exhibiting torsion (above) and writhing (below) (Benjaminsen & Heggenhougen, 2020)

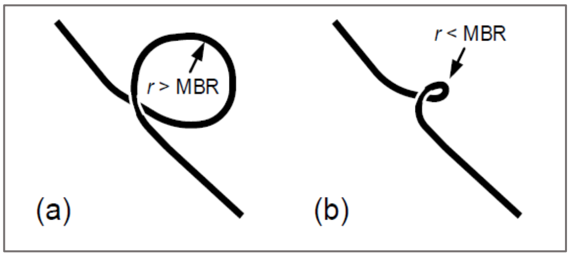

Figure 15 Loop formation (a) and kink formation (b) (DNV.GL, 2016(a))

Axial tension

A subsea cable is subjected to large tension loads during cable installation. Based by the design of the cable, only the outer serving and armour are configured to resist these tensile forces. Therefore, the cable's ability to withstand loads that may occur during its designated life span, depends on the mechanical characteristics of these cable layers. With too low tensile stiffness, the cable is vulnerable to excessive deformation of its structure. Due to the nature of the helical structure of the cable's armour, axial tension and torsion are coupled to each another. Both axial elongation and torsion angle are produced, when either a tension load or torsion load is applied to the cable. Axial stresses origin therefore from dynamic tension and local torsion, included are also bending stresses. (Chang & Chen, 2019)

Axial tension can cause failures such as elongation, compression, strain and bonding failure between conductor and insulation. Maintaining cable tension within required tolerances is critical to avoid risk of situations such as the cable cores becoming crushed, outer layer torn off or the minimum bend radius being exceeded. (Worzyk, 2009)

In the case of large vertical movements of the vessel, the cable can be subjected to axial compression (negative tension). The compressive force onto the cable will be distributed between the different cable components based on their relative axial stiffness in compression. Excessive axial compression can result in bird-caging or buckling of the helical armour wires. The process of buckling and bird-caging of armour wires can be divided into three main failure modes (Tyrberg, 2015):

- Bird-caging – Here the armour wires move radially, lifting from the supporting inner layers. If the radial force in the wires becomes too large, failure of the outer layer occurs giving a sudden radial expansion of the armour wires. This deformation (bird-caging) is related to the strength of the outer serving and is not a buckling phenomenon.

- Radial buckling – In this case, the outer serving is sufficiently strong and remains intact, while the armour wires are a deflected radially.
- Lateral buckling – This failure occurs when the strength and stiffness of the outer layer is strong enough to prevent both bird-caging and radial buckling. Here, the armour wires moves sideways instead, creating a lateral or transverse buckling.

Figure 17 Images from left to right: 1. Bird-caging, 2. Lateral buckling, 3. Radial buckling (Tyrberg, 2015

3.3 FAILURE DETECTION & MONITORING

The current monitoring technologies on the market today for subsea cables focus primarily on the internal failure modes associated with partial discharge (PD). This is mainly performed with use of online partial discharge monitoring, or by distributed strain and temperature (DST) measurements via embedded fibre optics. Given the challenges associated with subsea cable inspection and repair due to remote locations and accessibility, precursor to failure can have a great impact on the reliability of subsea cables. (Dinmohammadi, 2019)

Prior to failure, many cable insulation faults precursors produce PD activity. This can be detected and located online and provide the opportunity to carry out preventative maintenance to avoid unplanned outages. In order to detect PD activity online, non-intrusive sensors are utilised. There are many variations of these, including: high frequency current transformers (HFCT's) to detect PD in the cables and switchgear, and transient earth voltage sensors (TEV) for detection of electromagnetic radiation from PD activity nearby the sensor from sources in the cable termination or switchgear. By using a combination of sensors, different types of PD can be detected and the measurements combined can aid in the diagnosis. (Renthford, 2012)

There exist several cable fault location techniques, in general these can be divided into two categories: prelocation and pinpointing. With prelocation one can test the circuit from the cable terminations to estimate the distance to the fault. Pre-location can determine the fault position to within a few percent of the cable length. While on very long cables, the margin of error can be significant. Techniques for pre-location include: Time Domain Reflectometry (TDR), Burn Down Techniques, Arc Reflection Methods (ARM/SIM/MIM), Decay Method and Differential Decay Method, Impulse Current Method (including Comparison and Differential Modes), Frequency Domain Reflectometry and Bridge Methods (CIGRE, 2019(a))

Pinpointing is a test to confirm the exact position of the cable fault following pre-location, and is carried out directly over the cable. Fault pinpointing techniques can include: Acoustic Method, Step Voltage Method, Magnetic Field Methods, Impulse Magnetometry (primary faults), Audio Frequency Methods and Sectionalising Methods. (CIGRE, 2019(a))

Other methods for monitoring and light inspections of subsea cables are limited to diver observations in shallow waters or by inspections followed by a ROV which can encounter the challenges of low visibility, accessibility and locating the cable. (Dinmohammadi, 2019)

3.4 HAZARD IDENTIFICATION

Risk assessment and management techniques have been incorporated into the maritime and offshore industry in a larger degree over recent years. A reason for this growth is the increased focus on risk-based procedures in the standards and guidelines from IMO conventions, which again are adopted by classification societies. By including these risk-based methods in the design phase of a cable system, one can map the potential hazards and the consequences of the failure modes, giving an insight into the level of probability that cable would remain operational throughout its intended lifespan (DNV-GL, 2016(a)). For offshore wind farm installers, the statistical assessment of subsea cable failures is of great interest. The reliability of the cable and the grid, together with the risk of high repair costs, depends in a large degree upon the specific route. With the knowledge of the greatest threats present along the route, the cable designer can optimize the design of the cable's armour and protective system to its environment. At the same time, the cable operator can find a balance between the cost of cable protection investment and the financial risk of cable failure.

The aim of a hazard identification study, HAZID, is to provide primary input to the following risk analysis. The HAZID is a small contribution to the overall planning phase of a project, yet the value added from the HAZID work is a more focused risk analysis through an understanding of the existing (and possible future) hazards that might disrupt the project. Identification of hazards is a process that should be conducted early in a risk analysis, preferably as a first step. Early identification and assessment of hazards provides essential input to the decision making at a time when a change of design or method has the least consequences. The result of such work is a list of relevant hazards linked with causes, consequences, probability and possible safety barriers. (Siddiquia, Nandana, Sharmaa, & Srivastavaa, 2019)

HAZID studies are conducted in a workshop format, bringing together a multi-disciplined team. In which, the workshop utilizes a clearly pre-defined step-by-step methodology. To conduct a HAZID study, one divides a project into component parts for detailed analysis. In such a study, the hazards can be prioritized in relevance to likelihood of occurrence and impact level. The qualitative HAZID study may be performed though the following steps (Siddiquia, Nandana, Sharmaa, & Srivastavaa, 2019):

1. Familiarization with the design intent and normal operating conditions of the area;
2. Identify hazards that could be present in the project, along with possible causes and consequences of the hazard.
3. Identify any existing safeguards, mitigations and control measures
4. Identify recommendations and action parties if no safeguard is provided or safeguards are insufficient.

Before the procedure of identifying threats initiates, a probability and impact matrix is often created. This act like a categorization system of the hazards. By colourization and numbering, one can map the hazards with various probability and various outcomes. An example can be seen in table 3, which is the base for the HAZID performed in this thesis. The matrix contains different levels of severity of the hazards (0-5) where the highest number gives the largest consequences. The likelihood/probability is divided by letters (A-E), with E giving the largest possibility of occurrence.

Severity	Consequences					Likelihood				
	Health & Safety	Cable integrity & Assets	Environment	Reputation	Project	A Never heard of in the industry	B Heard of in the industry	C Has happened in the organization / more than once per year in the industry	D Has happened at the location ore more than once per year in the organization	E Has happened more than once per year at the location
0	No injury or health effect	No damage	No effect	No impact	No delay					
1	Slight injury or health effect	Slight damage	Slight effect	Slight impact	Slight delay					
2	Minor injury or health effect	Minor damage	Minor effect	Minor impact	Minor delay					
3	Major injury or health effect	Moderate damage	Moderate effect	Moderate impact	Moderate delay					
4	PTD or up to 3 fatalities	Major damage	Major effect	Major impact	Major delay					
5	More than 3 fatalities	Massive damage	Massive effect	Massive impact	Massive delay					

Table 3 Risk assessment matrix

The following colour codes in the matrix forms a risk rating (Table 4), where this provides an insight into which of the hazards that have a higher priority in the sense of mitigation measures. Risks with small importance can be put aside on a "to watch list". The ALARP principle (As Low As Reasonable Practicable) should be implemented for hazards posing greater risks. The ALARP principle is a clear division of levels on acceptance, to distinguish what risks are acceptable and which are not. If regarded not tolerable, one should implement risk reducing measures, if practical. (Jones-Lee & Aven, 2011)

Risk Rating		Low	Manage for continuous improvement
		Medium	Tolerable. Incorporate risk reduction measures. Control to ALARP.
		High	Intolerable. Incorporate mitigation measures. Control to ALARP.

Table 4 Risk rating

A HAZID study was performed with the basis in knowledge gained from literature study conducted on subsea cables failure modes and reliability studies, as well as other sources which have identified hazards that are of relevance to cable installation. A brainstorming session amongst 4 individuals with relevant experience with subsea cables contributed to the study. Combining these elements and HAZID analysis was performed (Appx. A). It should be noted that this is a generic analysis. As every project differ from one another, a HAZID analysis should be created after the specific frames of the project. Information regarding impact and probability are gathered mostly from the reliability review. The study identified several hazards, causes and effects that oppose risks to a cable installation project, along with control barriers which may aid in reducing the risk of these threats.

CHAPTER 4 – MODELLING OF CABLE LAY SCENARIOS

This chapter will describe the cable laying scenarios of which sensitivity analyses was carried out. Here the modelling of these scenarios with following boundary conditions and assumptions will be defined, with a mentioning of limitations present within these models.

4.1 ORCAFLEX

The static and dynamic models were created in the software OrcaFlex 11.0f. Developed by Orcina, OrcaFlex is a leading and well recognized software for static and dynamic analysis of offshore marine systems. The full 3D non-linear time domain finite element program can calculate the dynamic response of a system based on several user defined conditions. With static calculation the goal is to find positions and orientations for each element within the created model such that all forces and moments are in equilibrium. From here, the static calculation can be used as a starting configuration for a dynamic simulation. (Orcina, 2021)

OrcaFlex provides all the functionality to perform the in-place and installation analyses needed for inter-array cables and export cables for an offshore wind project. This includes: VIV, fatigue, modal analysis (for the whole system or for individual lines), as well as extreme response analysis in different sea-states. The software can perform code checks which can be useful when analysing an offshore operation, where the current version (11.0f) includes following codes (Orcina, 2021):

- API RP 2RD.
- API STD 2RD.
- API RP 1111.
- DNV OS F101.
- DNV OS F201.
- PD 8010.

After the model of which to be analysed has been created in the software, the analyst is required to define the marine environment by providing data specifying e.g., the water characteristics, water depth, seabed characteristics, wave motions (regular sea/irregular sea) and current profile. Followed are general simulation settings which can dictate the accuracy of results and the computational effort needed. A wide range of results can be provided by OrcaFlex, where it is up to the analyst to extract the relevant results for the job at hand.

4.2 SCENARIOS AND SENSITIVITY ANALYSIS

Main objective of the sensitivity analysis performed is to seek information about the restrictions of the subsea HVAC cable's armour and outer layer, considering tension load. Allowable tension must be within the range x – x kN to avoid damaging the cable, and at the same time, the tension should be kept well under the tensioner's limits. The analyses seek to reveal some of the parameters that affect the rise and fall of the tension, with the emphasis on maximum tension in the cable. The focus is on an export cable installation scheme, which is further divided into two main scenarios:

1. Cable lay with alternative cable weights and stiffness properties, by analysis of three different subsea HVAC cables configurations.
2. Cable lay with three alternating deployment positions: over stern starboard chute (S-lay), midships through a moonpool (J-lay) and to the vessel's amidships external starboard side (J-lay).

The modelled scenarios considered have its basis in a past project by DeepOcean, a well-recognized subsea services provider. DeepOcean were contracted to instal two HVAC export cable routes from shore to an offshore substation for an offshore wind farm located in the North Sea. Three separate cable types were used in each export cable route and deployed over a chute (S-lay) from the CLV. The information that was incorporated into the modelling are mainly environmental conditions, the three different HVAC cables, and the main particulars of the vessel and chute. There are many steps in such an instalment, but this analysis will focus primarily on normal lay and investigate the sensitivity of the main scenarios with additional variations in selected parameters. These additional selected parameters will be presented in section 4.2.1.

The S-lay model and J-lay models are used to perform a sensitivity analysis of main catenary cable configuration laying parameters exposed to current- and wave forces. By alternating cable deployment position, the interest lays here in the vessel motions, imposed by the environmental forces, and its impact on the cable's integrity regarding tension load.

Cables with alternative weight along with various stiffness properties is to be investigated for the variation in tension during laying operations in different environmental conditions. Three cable configurations were investigated (further described in chapter 4.5) along with variables such as water depth, current velocity and layback length.

A sensitivity test is used to identify which independent variables can have big individual influence on a dependent variable. The sensitivity analysis is conducted as a range of analyses, where one parameter is altered at the time with minimum of three variations of the same parameter. While the sensitivity analysis will seek to test the limits of the cable specifications with conditions than can be considered non-operable, one needs to define and assess operable conditions for cable installation.

Operability can be defined as: "…. *the ability to keep an equipment, a system or a whole installation in a safe and reliable functioning condition, according to pre-defined operational requirements*" (Wikipedia, 2021). An operability assessment is an important tool for any installation process, as to when and in which conditions the instalment can take place. Operability, for cable installation, can be determined/examined by the test of various sea-states and vessel headings, combined with other project specific settings in time domain simulations. If the predetermined operational limits can be maintained within the simulation time set, this combination of parameters can be seen as operable. At the same time, if the load conditions or a vessel motion response for a given sea state are found to be excessive, lesser conditions should be tested until satisfactory limits can be found. The cable installation criteria for operability are further described in section 4.7.

4.2.1 Key parameters

The accuracy of sensitivity simulations is heavily dependent on the method of simulation and the chosen parameters that should represent realistic values. The scope of the analyses depends on variables chosen where the total number of simulations can easily escalate into a significant amount. This visualizes the need for well thought off variables. A matrix containing the key parameters was developed for each of the two scenarios (Table 5 and Table 6). Combined, these variables gives an insight in the required number of simulations and hence the computational effort required.

For scenario 1, following independent variables where investigated:

$nLayback \cdot nWaterDepth \cdot nCablesConfigurations$

While for scenario 2, the independent variables and number of simulations equals to:

$nHs \cdot nTp \cdot nWaveHeadings \cdot nDeploymentPositions$

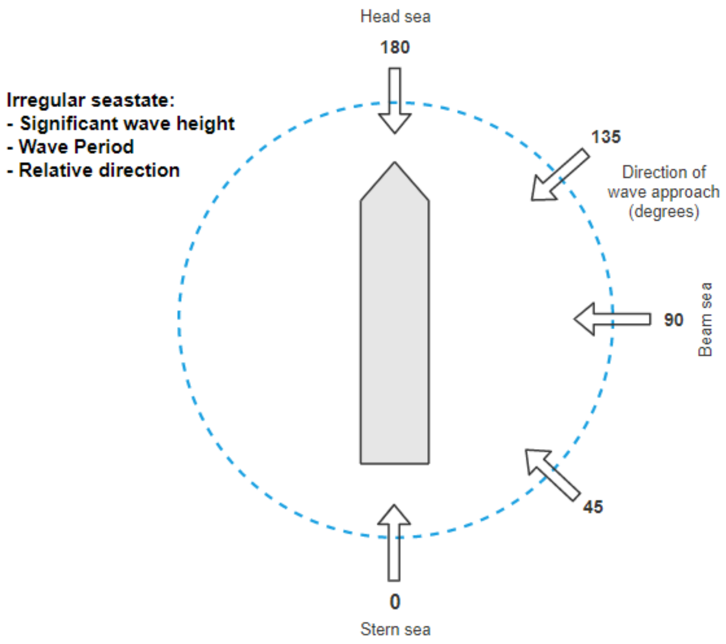

Figure 18 Figure 17 Sea state assessment conditions

Key parameters – Scenario 1	
Vessel - Relative heading [deg.] - Deployment speed [kts]	(head sea) 180 0
Cable - Configuration (properties see chapter 4.5) - Deployment speed [m/s] - Deployment position	HVAC C. A HVAC C. B HVAC C. C 0 Stern chute (S-lay)
Environment (JONSWAP) -Collinear surface current speed [ms^{-1}] -Wave height [m]/period [s] -Water depth [m] -Seabed friction coeff. [-]	0 2/5 30, 60, 100 0,5
Layback distance	0,5 x wd 1 x wd 1,5 x wd 2 x wd

Table 5 Key parameter matrix for simulated scenario 1

Key parameters – Scenario 2					
Vessel - Relative heading [deg.] - Deployment speed [kts]	(head sea) 180 0	 135 0	(beam sea) 090 0	 045 0	(stern sea) 000 0
Cable - Configuration - Deployment speed [m/s] - Deployment position	HVAC C. A 0 Stern chute Moonpool M. Starboard	HVAC C. A 0 Stern chute Moonpool M. Starboard	HVAC C. A 0 Stern chute Moonpool M. Starboard	HVAC C. A 0 Stern chute Moonpool M. Starboard	HVAC C. A 0 Stern chute Moonpool M. Starboard
Environment (JONSWAP) -Collinear surface current speed [ms^{-1}] -Significant wave height [m] -Wave period [s] -Water depth [m] -Seabed friction coeff. [-]	1,0 2, 3, 4 1,2,3…→10 100 0,5	1,0 2, 3, 4 1,2,3…→10 100 0,5	1,0 2, 3, 4 1,2,3…→10 100 0,5	1,0 2, 3, 4 1,2,3…→10 100 0,5	1,0 2, 3, 4 1,2,3…→10 100 0,5
Layback distance	1 x wd	1 x wd	1 x wd	1 x wd	1 x wd

Table 6 Key parameter matrix for simulated scenario 2

4.3 GENERAL SIMULATION SETTINGS

4.3.1 Coordinate system

When creating a model in OrcaFlex, there are multiple coordinate systems to be considered. This compromises a global frame of reference (G_{XYZ}), a number of local coordinate systems for each object in the model (L_{XYZ}), line end orientations (E_{XYZ}) and a coordinate system for a giving vessel (V_{XYZ}). All the coordinate systems are right-handed, and positive rotations are clockwise in the direction of the axis of rotation. (Orcina, 2021)

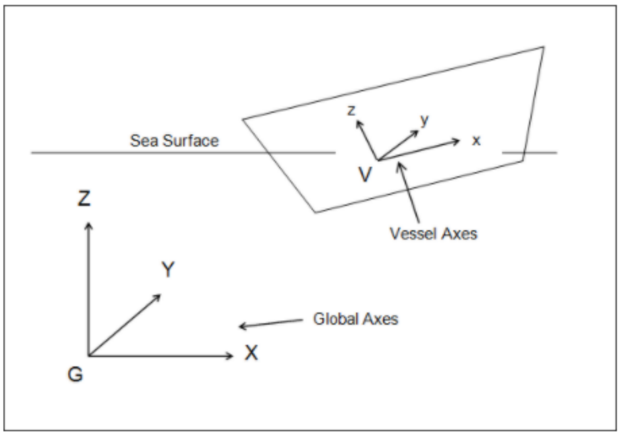

Figure 19 Coordinate systems in OrcaFlex (Orcina, 2021)

4.3.2 Time integration method

OrcaFlex allows two methods of time integration: the explicit and implicit integration scheme. The explicit scheme used by OrcaFlex implies a semi-implicit Euler, while for implicit integration OrcaFlex uses a generalised-α integration scheme. (Orcina, 2021)

When comparing the two, explicit schemes are conditionally stable which means that, to achieve stability, the time step must be small compared to the shortest natural nodal period. This results in prolonged simulation time, especially if the modelled system includes high stiffness and/or fine segmentation. Here, the implicit scheme, which is unconditionally stable for linear systems, can be significantly faster as it allows for larger time steps as well as variable time steps. By default, OrcaFlex will automatically set the time step. (Orcina, 2021)

However, the analyst should perform a sensitivity check to see if following method chosen does not affect the accuracy of the results in the pursuit to seek reduction in simulation time. An assumption was, in this case, that an implicit integration method would fulfil the objectives for following dynamic analyses when including this reduction in simulation time.

4.3.3 Simulation period

A description of how the simulation time is specified in OrcaFlex and how this can be divided into different stages is shown in Figure 21. This information can be useful if a one wants to capture a specific part of the simulation rather than the entire simulation period, or time-shift one aspect of the model relative to the others. Different parts of the model have its own user-specified time origins. By default, the time origins of all the parts are zero and in line with global time. (Orcina, 2021)

The period of simulation is defined as a number of stages, the durations of which are to be specified according to analysis objectives. The first stage is usually set as a build-up stage where the motions of the environment and vessel are ramped up from zero to their full size, before main simulation stage(s) start. This aids in a smooth transition from static positions to dynamic motions. The simulation time (t=0) starts then at the end of the of the build-up stage. (Orcina, 2021)

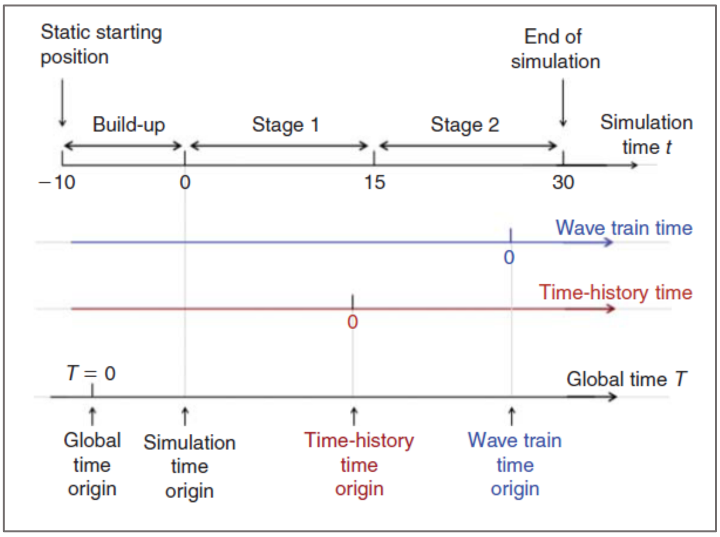

Figure 20 Simulation time setting in OrcaFlex (Orcina, 2021)

4.4 MODELLING OF VESSEL AND CABLE DEPLOYMENT SYSTEMS

4.4.1 Default vessel

The simulations were performed with a modified OrcaFlex default vessel. The normal default vessel in OrcaFlex compromises data that correspond to a particular 103 m long tanker. OrcaFlex automatically Froude scales vessel type data to the vessel length given, so this default data can be useful if the vessel to be analysed is a tanker of same / different length. So in reality it's important to add the vessels true data, but in this case the assumption was made that the default vessel could be used to reach the objectives of the sensitivity analyses. It should be noted that the default tanker has a significant heave resonance in beam seas at 7s period. The main particulars that were used to modify the default vessel can be found in Table 7.

CLV Default vessel	
Length overall [m]	138.05
Length between perps. [m]	121.65
Deadweight [t]	9300
Breadth [m]	27.45
Depth [m]	9.60
Draft [m]	According to load condition

Table 7 CLV Default vessel particulars (S&S, 2021)

The vessel loading conditions for the cable lay scenarios was considered to be homogenous for the entire analysis and for the three HVAC cable types (Table 8). In general, the removal of the cable will lower the centre of gravity (CoG), which generates an increase in metacentric height (GM). This results in a stiffer vessel with a shorter natural period, making the vessel experience greater accelerations in motions imposed by waves which can have an unfavourable effect on the cable installation. (Worzyk, 2009) The motion response of the vessel in different loading conditions should be calculated, where the worst case in the operation(s) is to be considered. If this is found to be to limiting for parts of the cable route, less conservative loading condition could be used for these sections to increase improve operability.

Load case CLV					
Displacement [t]	Draft FP [m]	Draft AP [m]	Draft mean [m]	$\overline{GM}_T$[m]	$\overline{GM}_L$[m]
14,266.65	5.45	5.65	5.55	4.94	215,83

Table 8 CLV load condition (S&S, 2021)

The scenarios are modelled with a stationary vessel and with no cable being paid out during the simulation. One reason for this is that the cable would have to be modelled with a significantly extended length in order to achieve a simulation period which would capture the vessels peak movements. With an increased cable length comes an increase in cable segments, which requires significantly more calculation time. As the pay-out speed of the cable can be matched with the vessel velocity, a stationary vessel can be assumed to give similar results.

When modelled with a stationary vessel, one needs to account for the capstan effect around the chute as no cable will be paid out. This has been applied to the analysis of maximum cable tension results for the S-lay model (how this was conducted is further explained in Chapter 6). For the J-lay, capstan effect is here neglected.

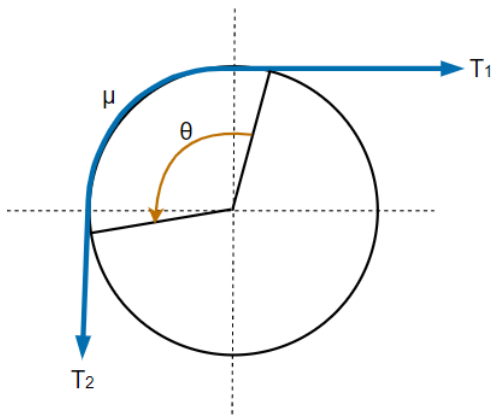

Figure 21 Cable with capstan effect overboarding the chute in S-lay model

Because of the interaction of frictional forces and tension, the tension on the cable "wrapped" around the chute, will be different from one side to the other. The capstan equation can be found by (Jung, Kang & Youn, 2004):

(Eq.1)

$$T_2 = T_1 e^{\mu\theta}$$

Where:
T_2 = Outgoing tension over chute [N]
T_1 = Tension from tensioner [N]
μ = chute friction coefficient [-]
θ = chute contact angle [rad]

The tension over the cute and the need for tension in the tensioner in the analyses will be calculated with a chute friction coefficient of 0,6 and the chute contact angle is depended on the layback distances in this case. The chute friction coefficient was obtained due to the specific steel type of the chute and is project specific following the base case (S&S, 2021).

The sensitivity analyses will include forces caused by the vessel's motions imposed by waves. The behaviour of the vessel is represented through a set of transfer functions, termed "response amplitude operators" (RAOs), which is unique to each vessel. In order to properly assess the effect of which a sea state will have on a vessel's motion, this unique set of RAOs for the particular vessel should be applied. For this assessment however, the OrcaFlex default vessel RAO's was utilized and can be found in appendix C.

4.4.2 S-lay chute model

For the S-lay model the cable will be deployed over a chute at the stern. Here the cable was modelled with one end fixed to the vessel 3 m above deck 6 m forwards of the chute and 4,3 m to starboard from centreline. The cable is held in position with supporters, forcing the cable to follow the motions of the vessel and the chute. The other end of the cable is anchored to the seabed. The anchor length and length of the cable resting on the seabed varies according to the water depths and layback distances analysed. In order to reduce line segments (explained further in section 4.5) and simulation time, this length was reduced to a minimum with a small margin. A minimum length of the total cable (from top to anchor point) can be calculated with Eq. X found in Chapter 5. A check of the anchor length and its effect on the cable tension was also performed in OrcaFlex for every water depth and layback length.

The chute was modelled using shapes to have a radius of 5 m, centred 3 m inboard from the vessel transom, and 4 m to starboard from the centreline.

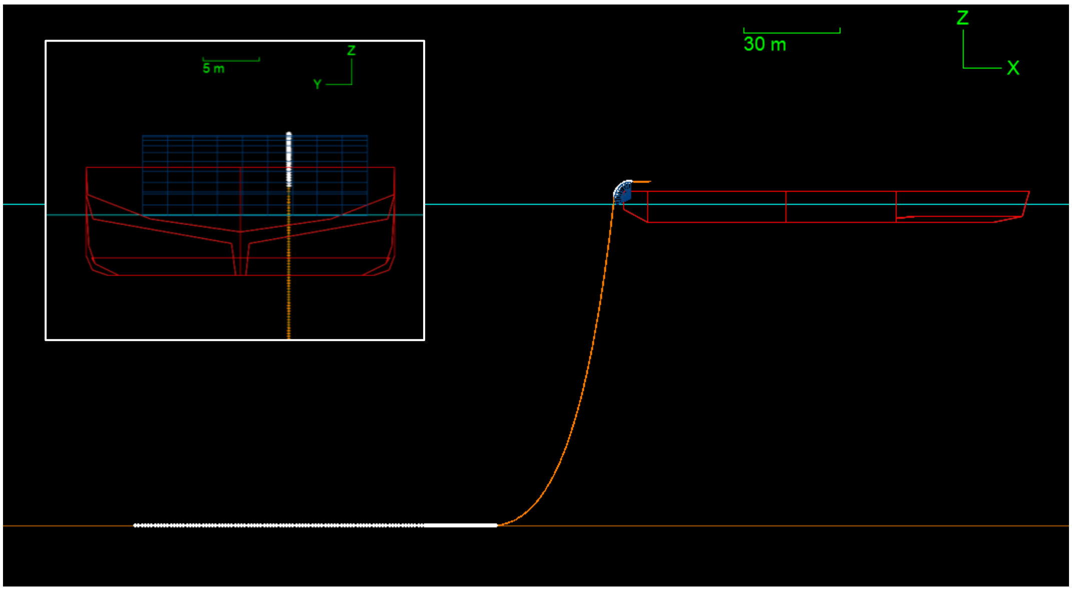

Figure 22 S-Lay model - Simulation setup (100 m water depth)

4.4.3 J-lay system: midship starboard deployment

For this J-lay model, the cable is fixed on the vessel 54 m from the vessel's transom, 9,4 m above deck and 15 m to starboard from centreline. The cable is held in place by supporters and a vertical tower (16m height) created by shapes. The vertical tower was created to avoid unwanted movement of the cable due to vessel motions.

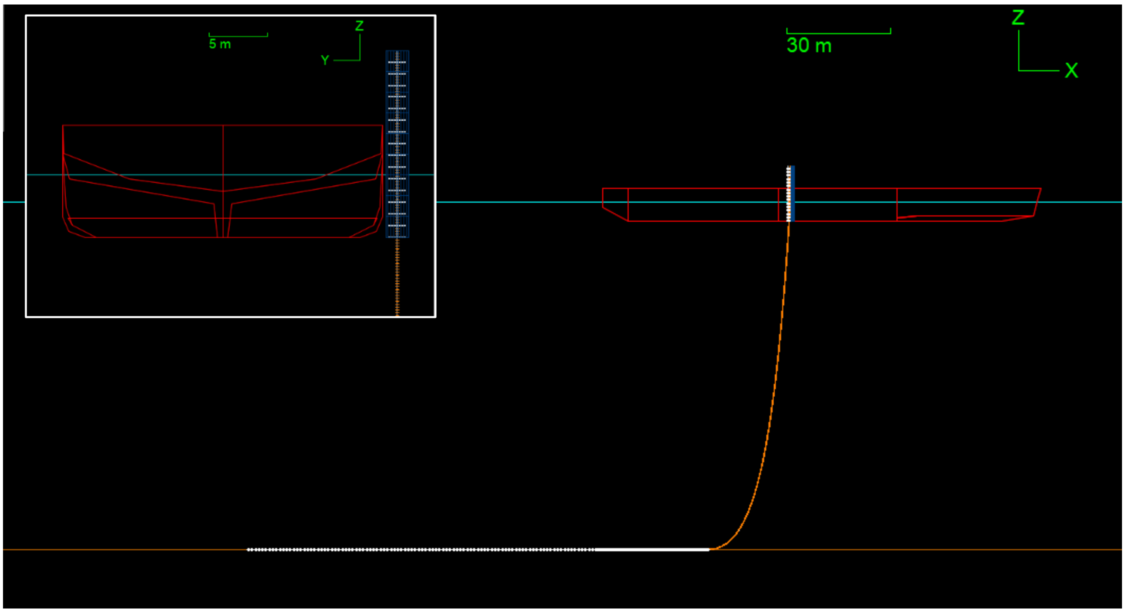

Figure 23 J-lay model – Mid-starboard – Simulation setup (100 m water depth)

4.4.4 J-lay system: moonpool deployment

With cable deployment trough the moonpool, the setup is similar to that of the midship starboard model. Here the cable is moved from starboard to the centre of the vessel. The moonpool was created using shapes (trapped water), with a diameter of 7 m and length of 11 m.

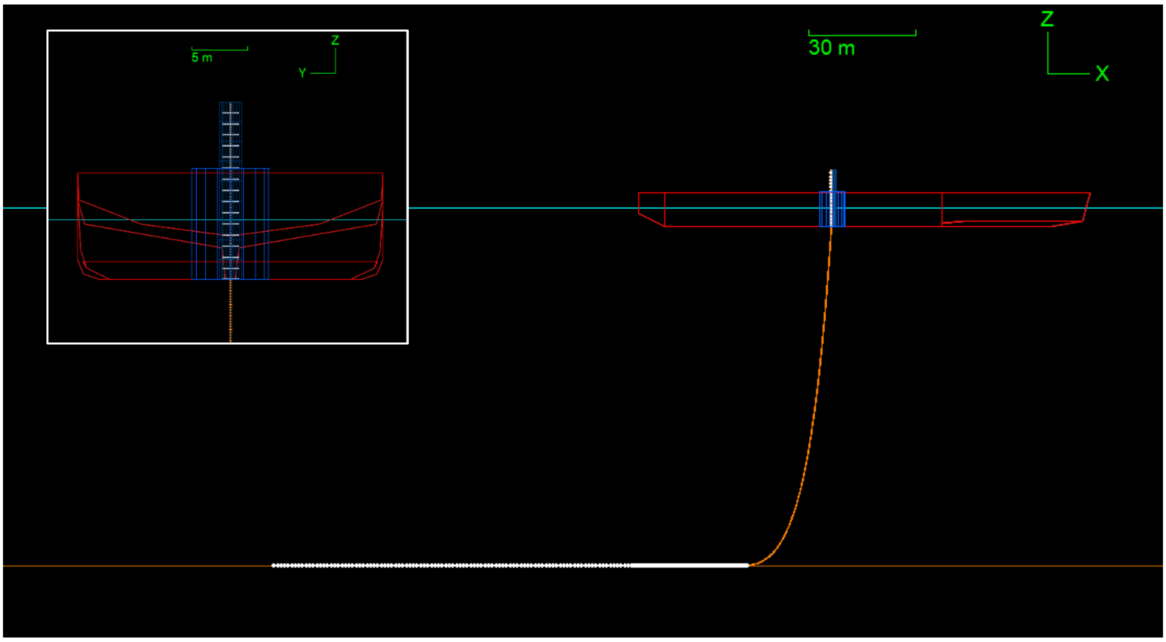

Figure 24 Moonpool deployment – Simulation setup (100 m water depth

4.5 MODELLED CABLE CONFIGURATIONS

OrcaFlex applies the lumped mass method for numerical calculations in the time domain for analysis of flexibles in fluids. This method models a line as a series of lumps of mass joined together by massless springs. The lumps of mass are called nodes and the springs connecting them are called segments. Each segment represents a short piece of the cable, where the cable properties (drag, mass, buoyancy etc.) have been "lumped" at the nodes at its ends. The model segments only model the axial and torsional properties of the line. To be able to analyse the cable's integrity, the lumped mass method calculates the dynamic equilibrium for each node, giving set of discrete equations of motions. These equations are then solved in the time domain with finite difference techniques, giving the nodes displacement, stress and tension. (Orcina, 2021) An example of a 2D mass-spring system is illustrated in Figure 25.

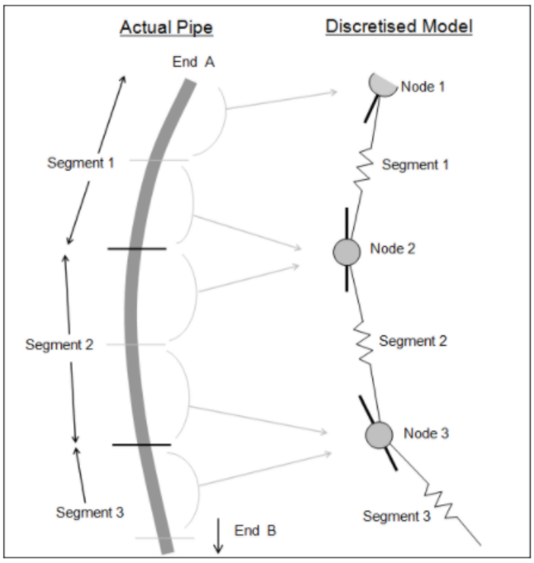

Figure 25 Lumped mass method in 2D (Orcina, 2021)

For finite element methods, the discretization of elements plays a major role in the accuracy of the model. An assumption was made that the following line segment lengths of the cable was substantial for the analyses; 0,25 m for the cable section over the chute, 0,5m for the mid span, 0,25m for the bend at TDP and 1m for anchor length. This was assumed for all three models analysed (S-lay and J-lay).

For the first scenario, three different HVAC export cables were utilized. The configurations assumes three copper conductors, extruded XLPE isolators, two fibre optic cables and with a single layer of steel armour wires embedded in bitumen for cable A-B and two layers of the same type for cable C. The outer serving of all three cables consists of a two-layer PP yarn. The cables cross-sections, along with full specifications and limits, can be found in appendix B. Main specifications are listed in Table 9. For scenario 2, only HVAC cable A was analysed.

		HVAC Cable A	**HVAC Cable B**	**HVAC Cable C**
Property	**Unit**	**Value**	**Value**	**Value**
Overall diameter	mm	243	251	263
Weight in air	kg/m	99.0	113.0	138.0
Weight in seawater	kg/m	61.0	72.0	92.0
Axial stiffness (No rotation)	MN	635	727	1122
Bending stiffness	kNm^2	Non-linear hysteretic See Appx. B	Non-linear hysteretic See Appx. B	Non-linear hysteretic See Appx. B
Torsion stiffness (clockwise):	kNm^2	121	107	398

Table 9 Cable configuration specifications (S&S, 2021)

The axial stiffness of a subsea cable is normally derived from simulation of the axial elongation of the cable when subjected to axial tension. The axial stiffness can be defined as the ratio (S&S, 2021):

$$EA = \frac{\Delta T}{\Delta \varepsilon}$$

Where
EA : Axial stiffness [MN]
T : Axial tension [MN]
ε : Axial elongation [-]

The torsion stiffness can be derived by simulating a sequence of cable torsion angles and observing the calculated torsion moments that are necessary to achieve these torsion angles. Torsion stiffness thereby can be defined as the ratio of torsion moment to torsion angle (S&S, 2021).:

$$GI_p = \frac{\Delta M_t}{\Delta \alpha}$$

Where
GIp : Torsion stiffness [kNm^2]
Mt : Torsion moment [kNm]
α : Torsion angle [rad/m]

Bending stiffness is defined as the ratio bending moment to bending curvature (S&S, 2021):

$$EI = \frac{\Delta M_y}{\Delta C_y}$$

Where;
EI : Bending stiffness [kNm^2]
My : Bending moment around y-axis [kNm]
Cy : Curvature around y-axis [m^{-1}]

The cables were modelled with non-linear hysteresis bending stiffness (appendix B). Subsea power cables tend to show a so-called non-linear bending stiffness behaviour. The curve for bending moment versus curvature is here described by a hysteresis loop due to internal stick-slip effects (caused by friction) and elastic-plastic material behaviour in the lead sheaths and the copper conductors. (DNV-GL, 2015) Hysteresis effects in non-linear bend stiffness can provide a source of damping for the cable close to the touch down point. OrcaFlex models can show high frequency noise when the cable is compressed at the seabed. This can impair the accuracy of the model and may be damped by the bending stiffness or several other methods, i.e. Rayleigh damping which is a viscous damping that is widely used to model internal structural damping. (Orcina, 2021) The non-linear behaviour of bending stiffness is data that only within the last years have been provided by manufacturers, compared to previously, were constant bending stiffness was the norm for analyses.

When a cable is modelled without bending hysteresis or Rayleigh damping, high frequency compression and tension waves can travel along the cable in the simulation, which can effect the values obtained for tension.

A simple sensitivity analysis was conducted on the effects of bending stiffness, concerning minimum and maximum tension, when looked at HVAC cable A (cable with lowest bending stiffness). Here, 3 configurations of the cable were investigated:

- Constant bending stiffness (4,29 kNm/0,2m^{-1}=21,45kNm^2, calculated as highest stiffness by curvature, see fig x in appendix B)
- Cable with non-linear bending stiffness
- Cable with non-linear bending stiffness and hysteresis

The bending stiffness was investigated with a superimposed vessel motion of the S-lay model with negative 0,4m surge and 3m heave in a 9s period, with a water depth of 30m and with a layback distance of 30m.

The effects of these various bending stiffness configurations can be clearly shown (Figure 26) for minimum tension along the arc length. Constant bending stiffness and bending stiffness without hysteresis can be seen to be conservative in regards to compression. However, for maximum tension the different configurations pose a less variance in tension magnitude (Figure 27).

The top of the cable leaving the chute is at approx. 12,5m along the arc line, and TDP can be found at approx. 54m when compressed and at approx. 69,5 when cable experience maximum tension.

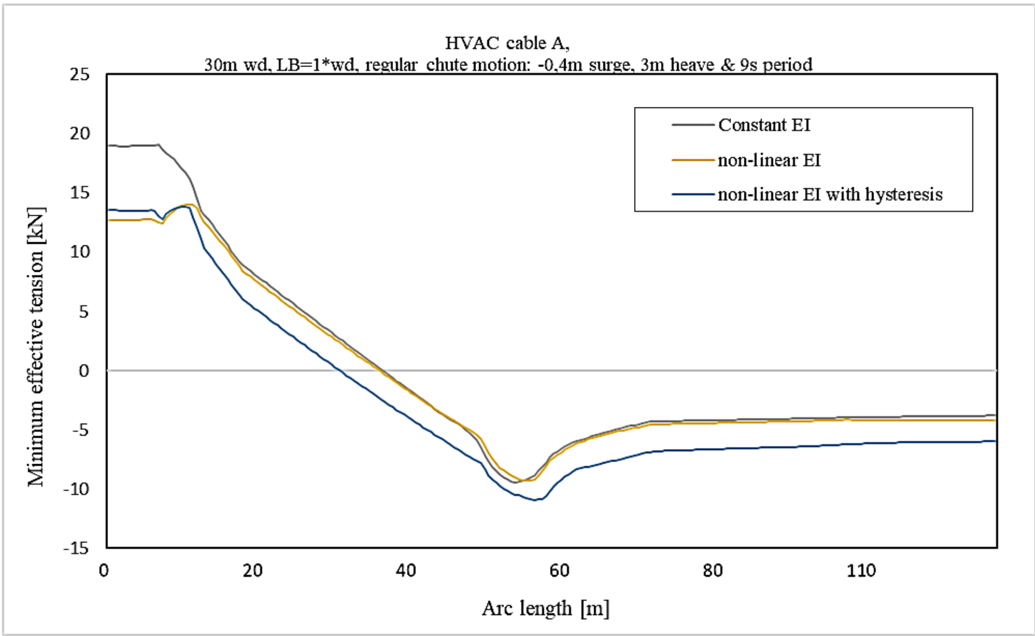

Figure 26 Minimum effective tension along arc with various EI configurations

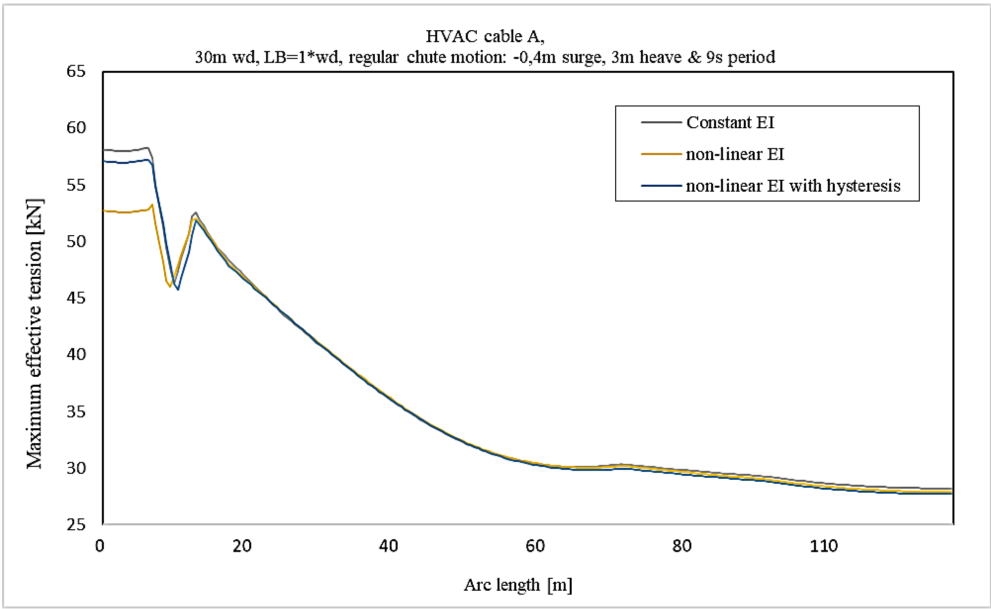

Figure 27 Maximum effective tension along arc with various EI configurations

In regards to minimum tension, the effects of the various bending stiffness configurations can clearly be seen for compression in the cable at TDP (figure 28). Here, bending stiffness with hysteresis will dampen the bending of the cable in a larger degree compared to the other two configurations, creating a smoother bend,

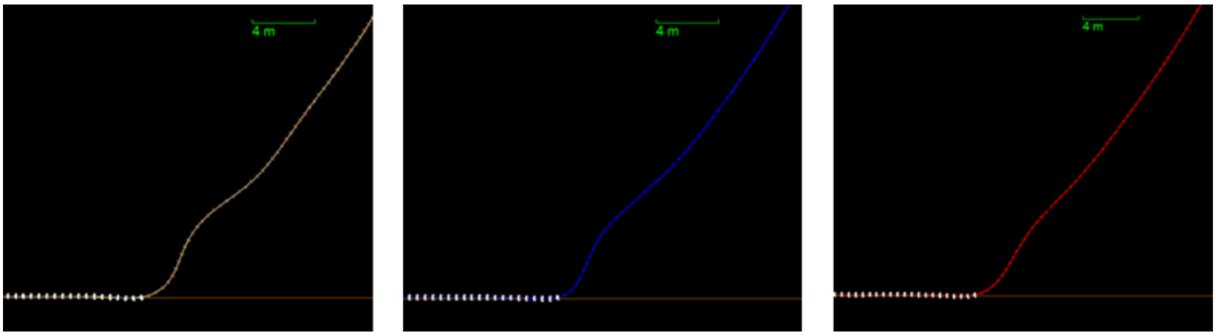

Figure 28 Bending behaviour of the cable in compression (at t=25,4s). From left: 1. Constant bending stiffness, 2. Non-Linear bending stiffness, 3. Non-linear bending stiffness with hysteresis.

4.6 MODELLED ENVIRONMENT

4.6.1 Wave parameters and spectrum

The dynamic simulations in this case are all performed by directly considering irregular waves for the analysis, applying a JONSWAP wave spectrum.

A wave spectrum represents the wave amplitude distribution of individual wave frequencies when considering a stationary sea state. The JONSWAP spectrum was developed from wave measurements in the Southern North Sea, during a joint research project, the "JOint North Sea WAve Project," This spectrum describe sea conditions under developing wave conditions but can also describe fully developed sea conditions. Young sea-states are often a part of the working environment for offshore windfarms. The spectrum is determined by the significant wave height and wave period parameters, and the spectrum is unidirectional without wave energy spreading. (Gudmestad, 2015)

The wave spectrum is formulated as a modification of the Pierson-Moskowitz wave spectrum (fully developed sea), which is described by (DNV-GL, 2018):

(Eq.2)

$$S_{PM}(\omega) = \frac{5}{16} \cdot H_S^2 \omega_p^4 \cdot \omega^{-5}\, exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_P}\right)^{-4}\right)$$

Where:
H_S: Significant wave height [m]
ω_P: spectral peak frequency = $2\pi/T_P$ [rad/s]
ω: wave frequency [rad/s]

The JONSWAP spectrum can thereby be described as follows (DNV-GL, 2018):

(Eq.3)

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\gamma^{exp\left(-0,5\left(\frac{\omega-\omega_P}{\sigma\omega_P}\right)^2\right)}$$

Where:
A_γ: 1-0.287 ln(γ), a normalizing factor
γ: non-dimensional peak shape parameter (Average value: 3,3)
σ: spectral width parameter
  σ_a for $\omega \leq \omega_p$ (Average value: 0,07)
  σ_a for $\omega > \omega_p$ (Average value: 0,09)

The peak-enhancement factors γ, can be found by (DNV-GL, 2018):

$$\gamma = 5 \qquad for \qquad \frac{T_p}{\sqrt{H_s}} \leq 3,6$$

$$\gamma = e^{\left(5,75-1,15\frac{T_p}{\sqrt{H_s}}\right)} \qquad for \qquad 3,6 < \frac{T_p}{\sqrt{H_s}} < 5$$

$$\gamma = 1 \qquad for \qquad 5 \leq \frac{T_p}{\sqrt{H_s}}$$

Where the combination of significant wave height and wave period can be found in combinations within following frame (DNV-GL, 2018):

$$3,6 < T_p/\sqrt{H_S} < 5$$

The significant wave height (H_s) is a term used to denote the characteristic height of the random waves in a sea state. It is defined as the average height of the 1/3 of the highest waves measured over a period of 20 minutes. For each project, locally occurring significant wave heights, directions and periods are typically deduced from met-ocean studies and wave scatter diagrams. (Gudmestad, 2015)

When considering irregular seas, it is desirable that the extreme waves have a certain probability of exceedance to include the extreme response of the vessel in the analysis. Statistical estimation can be used to obtain extreme value from random waves time series. (Gudmestad, 2015) With operability often being defined as a 3-hour operable sea state, performing simulations of this magnitude would require significant computational effort. In order to reduce the simulation time for the sensitivity analyses, a selection of this 3h period is extracted. For each combination of wave height and wave period, a 3h irregular wave sequence is generated in OrcaFlex. From this sequence, the point in time where the highest waves occur are pointed out, where this point will be the centre of which 200 seconds is simulated. The highest waves can be found by measuring the wave height between two zero upward crossings or two zero downward crossings (Highest rise & highest fall). An example of such a wave profile is presented in figure 29 and 30.

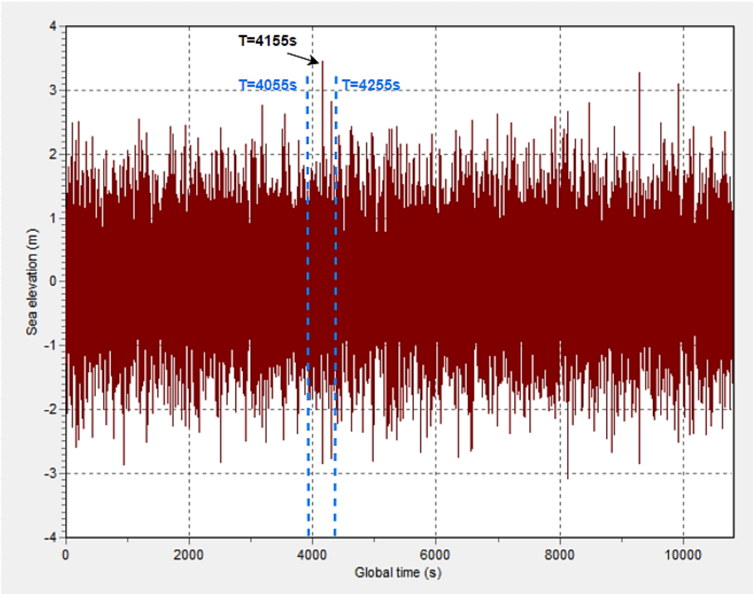

Figure 29 Characterising the Largest Rise and Fall From a 3h period to reduce simulation time

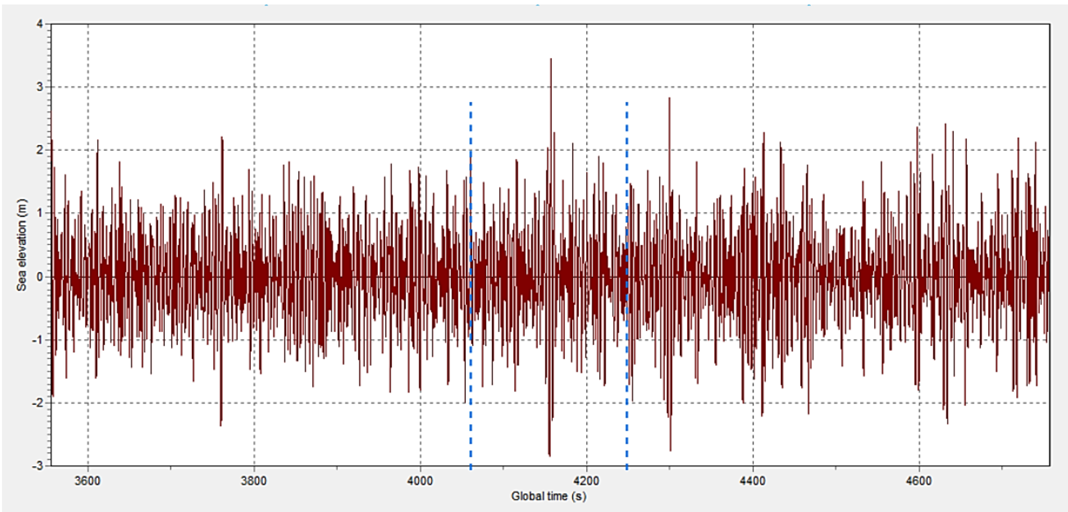

Figure 30 Wave spectrum selection in a 20min timeframe

4.6.2 Current modelling

Currents should be taken into account for projects in areas with strong currents which would bring stress to cable as well as induce route offset (depending on current direction). However, the current is sometimes neglected under the assumption that current will dampen the dynamic system, resulting in a conservative model. This may also depend on the direction of the current velocities. The effects of currents on the subsea cable will be further examined in chapter 5.

A collinear (unidirectional) surface current was considered for the sensitivity analyses as it can be considered to cause large hydrodynamic loads on the cable. The current profile was modelled using the power law with an exponent of 1/7 applied through the water column (DNV-GL, 2010):

(Eq.4)

$$v(z) = v(0) \cdot \left(\frac{z + d}{d}\right)^{1/7}$$

Where;
V(z) = current speed at depth z
V(0) = surface current speed
z = depth (negative number)
d = water depth

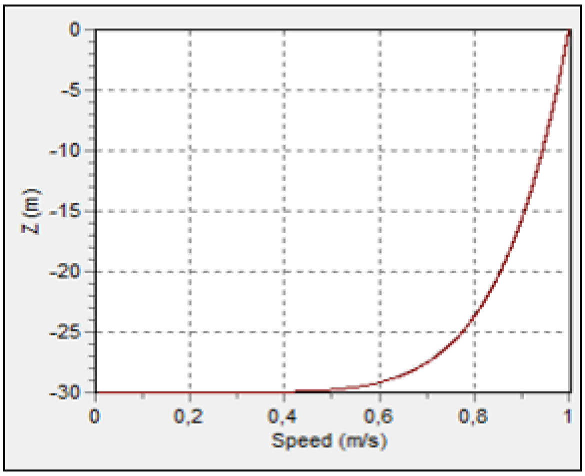

Figure 31 Current profile for 30 m water depth with collinear surface speed at 1 m/s

4.6.3 Modelling of seabed and water characteristics

OrcaFlex provides a number of settings for modelling the seabed, making it possible to analyse several scenarios, i.e., of which the cable is laid with free span over an uneven seabed for fatigue and VIV analysis. A seabed friction coefficient can be added, which often is project specific to the soil type found along the cable route. For this case, a seabed friction coefficient of 0,5 will be used for the dynamic analyses, based on known values for similar soils that are found along the cable route in the North Sea, in correspondence to the base case. (S&S, 2021) A horizontal seabed was considered in all models.

The water depth is also very project specific. Export cables may be laid in various depths following the cable rout and will generally also contain a shore landing. A water depth range of 30m, 60m and 100m have been considered for the sensitivity analysis of scenario 1, while a water depth of 100m were selected for scenario 2. The properties of the modelled sea compromises a density of 1025kg/m^3, kinematic viscosity of 1,35*10^{-6}m^2/s and a temperature of 10 degrees.

4.7 CABLE LAY CRITERIA

When installing a cable at the seabed there are certain criteria that need to be fulfilled to ensure a successful installation without compromising the cable's integrity. Some of the main limiting criteria, which are in focus in this case, are maximum allowable tension, compression, minimum bend radius (MBR) and side wall pressure (SWP). (DNV-GL, 2016(a))

Sidewall pressure can be considered to be the radial force which is applied on a cable when pulled around a conduit bend, sheave or bended in a J-tube. SWP may crush and flatten a cable, when the pressure exceeds the limit. This limit is determined by the manufacturer and can be defined as (S&S, 2021):

SWP = MHT/MBR [kN/m]
MHT = Max Handling Tension
MBR = Min Bending Radius

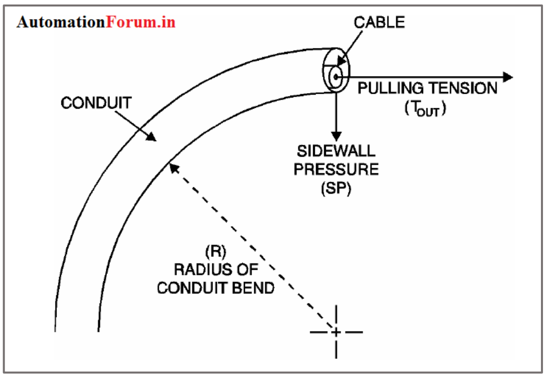

Figure 32 Illustration of SWP (AutomationForum, 2018)

The minimum bending radius is often determined by the manufacturer as a combination of axial tension and bending curvature. As the MBR is a variable, depending on the applied tension, maintaining the MBR during cable installation is sometimes the limiting factor in operability. (Worzyk, 2009) The limits for minimum bending radius in combination with tension values can be found in appendix B for all three HVAC cables investigated.

A compression limit was set to -10kN, to include the effects of compression in the sensitivity analyses. Common practice is to avoid compression altogether as there is no accepted industry standard for determination of compression limits in subsea power cables. (Worzyk, 2009).

When considering limits for maximum axial tension, this can be set by either the limit of the tensioner onboard the CLV or the breaking design limit of the cable (the combination of tension and curvature). For the sensitivity analysis the tension limit was set equal to the tensioners limit which is set to have a pulling capacity of 80kN. The simulation results also monitored loads on the cable posing a threat to the cables breaking limit. When analysing top tension in the results for the dynamic analysis, this was measured in different ways for the two scenarios due to different deployment methods, which will be described further in chapter 6. A list of the cable-laying criteria used for this analysis can be found in table 10.

Cable type:	**Max tension Capacity of tensioner [kN]**	**Breaking tension [kN]**	**Compression [kN]**	**MBR: [m]**	**SWP [kN/m]**
HVAC cable A	80	See appendix B	-10	See appendix B	42,7
HVAC cable B	80	See appendix B	-10	See appendix B	81,1
HVAC cable C	80	See appendix B	-10	See appendix B	89,0

Table 10 Cable lay criteria

CHAPTER 5 – QUASI-STATIC ANALYSIS AND THE RISK OF RESONANCE

A quasi-static analysis was performed to seek validation for the results obtained from the software OrcaFlex by a comparison of applied catenary equations. The analyst should be able to verify the outcome of an analysis produced by the applied software by the use of simple checks or other means of verification such as hand calculations. Simulated results by OrcaFlex represents high validity through multiple testing. Nevertheless, software will always contain bugs and a simple validity analysis can therefore be useful.

A second quasi-static analysis was performed with the intent of illustrating current forces in static seas and the effects these various current velocities would have on cables of various weight and dimensions when approaching from several directions.

The results obtained from the validation case and analysis of currents, provided an insight and knowledge about the relationship between tension and cable self-weight, which formed a basis for the dynamic analysis.

Additionally, in this chapter an assessment of the risk of resonance was made when the vessel is subjected to wave forces in different headings, to predict peak vessel motions in the degrees of freedom: heave, pitch and roll.

5.1 CATENARY EQUATION

A geometric catenary is the curve that a hanging cable assumes under its own weight when supported at its ends. In order to perform a simplified analysis with catenary equations some idealizations of the cable are required. This includes zero bending stiffness, no current and wave forces, continuous homogenous material and zero elastic elongation. (Faltinsen, 1990)

In order to find the necessary tension of the cable, following formula (Eq.9) for catenary mooring lines may be applied due to its similarity in the static theory. The tension at the top of the cable is caused by the cables own weight, gravity and the horizontal force at the bottom from anchoring. Eliminating the horizontal force and the cable is hanging straight down, giving the absolute minimum tension. However, this gives a small bend radius at the touch down point and increases the risk of compression in the cable. Therefore, it is recommended to increase the bend radius by adding a layback length and hence horizontal tension force is added at the top. (Faltinsen, 1990) The main parameters of the catenary equations can be seen in figure 33 below.

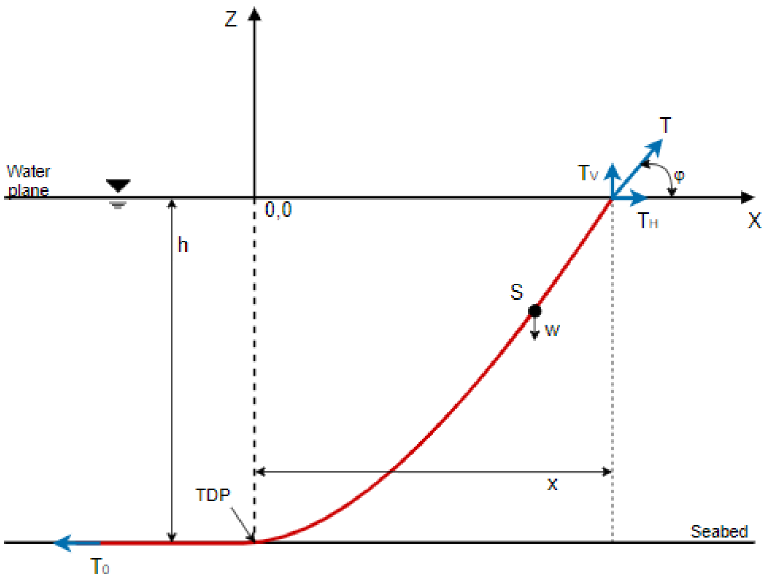

Figure 33 Catenary parameters (Faltinsen, 1990)

Definitions of parameters:
T_0 [N]: Horizontal bottom tension
S [m]: length of hanging line from touchdown to a random position on the cable
h [m]: Water depth
L [m]: Layback distance
w [N/m]: Weight in water per unit length
T [N]: Cable tension
T_V [N]: Vertical tension at the cable's upper position (waterline)
T_H [N]: Horizontal tension at the cable's upper position (waterline)
φ[-]: orientation (angle) of cable element with the horizontal

In this case it is assumed a horizontal seabed. The cable lays in the x-z plane. Placement of origin (0,0) can be found at touchdown point in x direction and at the waterline in z direction. It should be noted, that this model of catenary equations only considers the cable part submerged in seawater.

In order to check the cable's configuration in the 2D plane, following equation can be used according to given assumptions (Faltinsen, 1990):

(Eq.5)

$$z + h = \frac{T_H}{w}\left[cosh\left(\frac{wx}{T_H}\right) - 1\right]$$

To measure the cable's layback length:

(Eq.6)

$$x = \frac{T_H}{w} arccosh\left[\frac{hw}{T_H} + 1\right]$$

The arc length of the cable can be derived from:

(Eq.7)

$$s = \frac{T_H}{w} sinh\left(\frac{wx}{T_H}\right)$$

In order to find the minimum cable length (l) necessary (from waterplane to anchor point) in order to avoid vertical tension forces on the anchor point, following formula may be used:

(Eq.8)

$$l_{min} = (z + h)\left(2\frac{T_{max}}{w(h + z)} - 1\right)^{\frac{1}{2}}$$

Tension in the cable can be found as the sum of the horizontal- and vertical tension, where the horizontal tension equals the bottom tension ($T_H = T_0$):

(Eq.9)

$$T = T_H + w(h + z)$$

Calculating the dynamic contribution to the tension, however, is a complex task. Due to current and ocean waves, the cable is exposed to dynamic forces. The wave induced vessel motion causes the laying wheel or chute to move vertically. This will alter the layback length and can give an increase or decrease of tension. While current might provide damping or drag to the cable. (Worzyk, 2009)

5.2 VALIDATION CASE

In a quasi-static situation, none of the dynamic excitations investigated involve accelerations. This means that the movements changes so slowly that the object can be considered to respond in a static manner to the external loads. Quasi-static horizontal loads can be exerted on a subsea cable by currents and wind, while vertical forces can form from wave induced vessel motion. (Gudmestad, 2015)

The benefit of a quasi-static analysis is that it provides useful insights about the nature and magnitude of the stresses experienced by the cable due to its configuration alone. When neglecting forces from current, waves and vessel interaction, the primary loads now causing stresses in the cable are effective tension, bending moment and hydrostatic pressure. Study of these load components gives a better understanding about the general behaviour of the cables.

To carry out quasi-dynamic analysis in OrcaFlex, the analytic catenary representation for lines can be used to avoid the full finite element calculation and reduce computational efforts. The line loads are then calculated from classical analytic catenary equations. Here, the tension is evaluated from the response of the static line to loads/displacements applied on the unit as static actions. (Orcina, 2021)

Assumptions for quasi-static analysis (Orcina, 2021):

- Bending stiffness is neglected
- Cable weight per unit length is constant
- Only calculated degrees of freedom in the system are those of the vessel
- Zero inertia & damping
- The seawater is ideal liquid: irrational, inviscid and incompressible
- The cable experiences no drag while moving through the water

A simple scenario was used in order to compare the catenary equations results against results gathered from OrcaFlex. Here a regular sea state (airy wave) was chosen with a wave train encountering the vessel at 180° (head seas). The wavelength was set to be >> length of the vessel, so that the heave movement equals to the wave amplitude and the pitch angle equals to the derivative of the wave rise. The model (S-ay) of the vessel and chute equals to the description found in Chapter 4.

Following data used in the analysis:

	HVAC cable A	HVAC cable B	HVAC cable C
Cable weight in water [N/m]	610	720	920
Pre-tension (T_0) [N] (by no waves)	10569	12431	15897
Pre-tension (T_0) [N] (by Max tension in waves)	21402	22773	29361
Layback distance (no waves)			30 m
Water depth			30 m
Vessel speed / pay-out speed			0 kts
Wave height [m]			4
Wave period [s]			14

Table 11 Parameters for validation case

Pre-tension was found by freezing the moment were the vessel lays on the wave crest and where the largest layback length is found for each of the three cables. This was compared to a Pre-tension found in a static scenario (no waves).

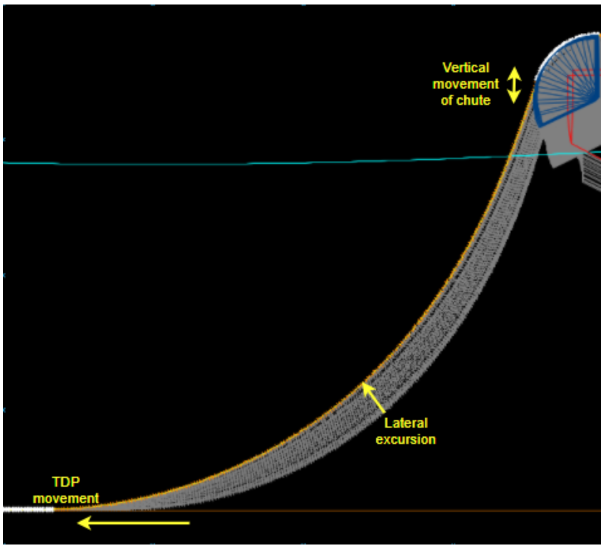

Figure 34 Maximum tension and layback length when vessel rests on a wave crest

The overall configuration, the effective tension along arc and the effective tension along water depth, are compared between results from simulation in OrcaFlex and the catenary equations. The results can be seen in figure 36-41. It is observed that the graphs are in good agreement in static seas. The effective tension is at its highest at the top of the catenary and reduces along the suspended span own to the TDP. While the tension distribution of the cable can be seen to be linear through the water depth (Fig. 40-41).

When comparing the scenarios of the results in static sea and the quasi-static results, a significant difference can be seen in the cables configuration (Fig. 2 & 3). The results from simulation in OrcaFlex gives a steeper curve when the vessel is resting on the wave crest compared to curves obtained by catenary equation, Consequently, a slight difference can be seen for the tension distribution along the arc and water depth (Fig. 36-37).

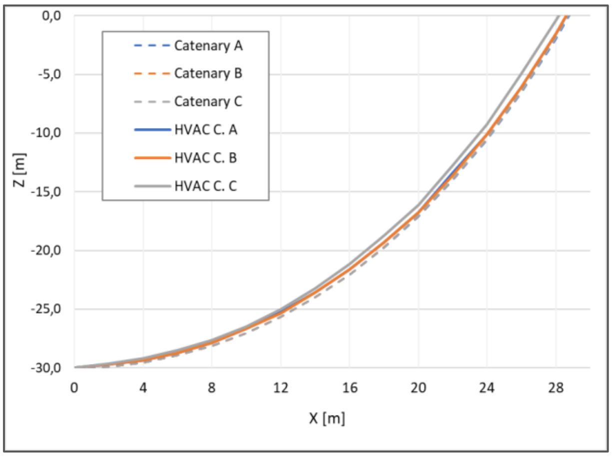

Figure 36 Cable configurations – Static sea

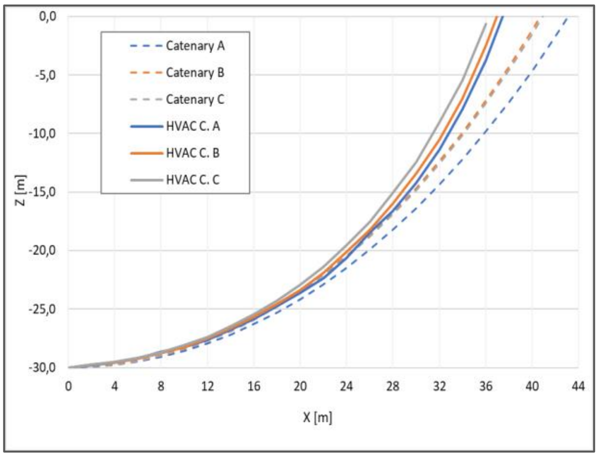

Figure 35 Cable configurations – vessel resting on wave crest

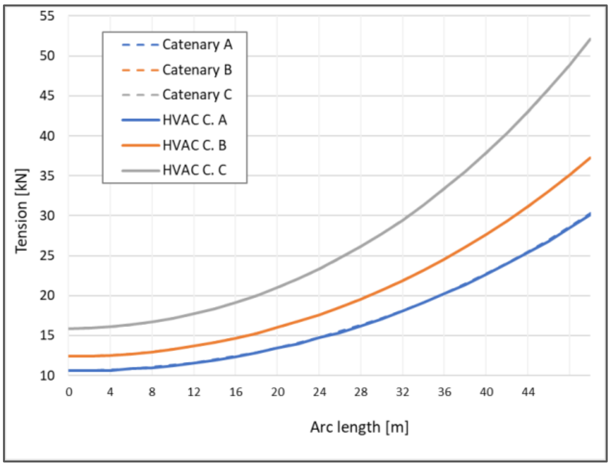

Figure 38 Tension along arc – Static sea

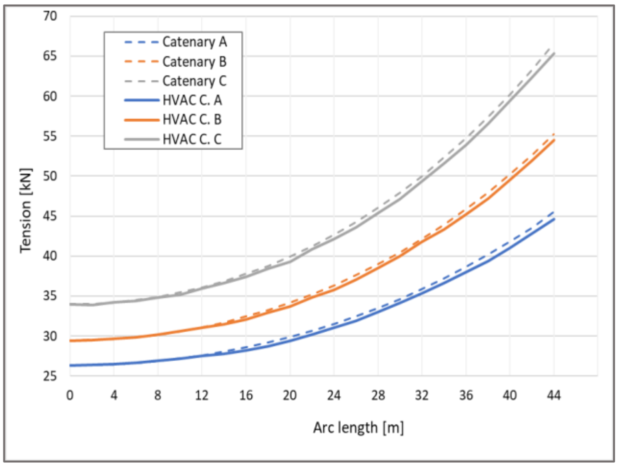

Figure 37 Tension along arc – vessel resting on wave crest

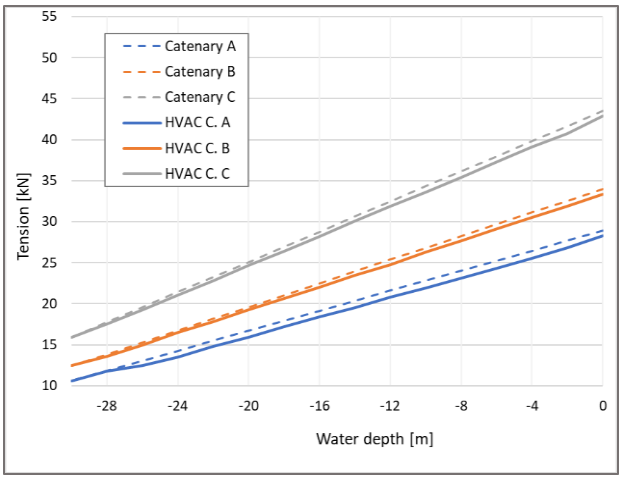

Figure 40 Tension along water depth – Static sea

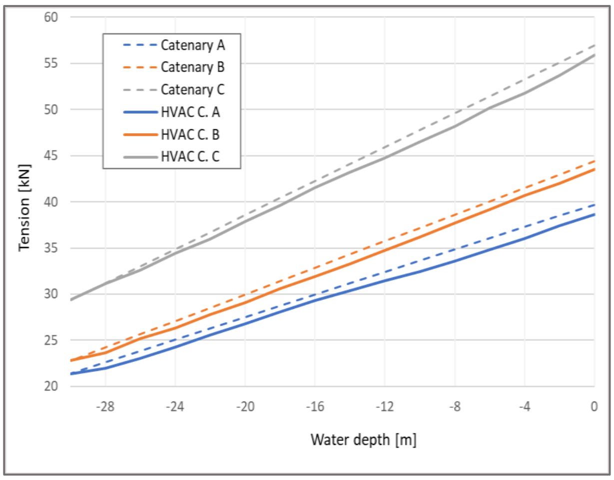

Figure 39 Tension along depth – vessel resting on wave crest

5.3 RISK OF RESONANCE

In order to find the vessel's encounter angle with the waves which can produce a high risk for large roll, heave and pitch motions, the encounter frequencies are set close to/equal to the peak of the wave spectrum (ω_p). When ω_e and ω_p are close in proximities ($\omega_e \approx \omega_p$), resonance will occur, and high peaks in following motions are to be expected. (Faltinsen 1990)

Each degree of freedom of a vessel that has a restoring force has an associated natural frequency (ω_n). So, for a vessel, there is a natural frequency in heave, roll and pitch ($\omega_{3n}, \omega_{4n}, \omega_{5n}$). These natural frequencies depend on the mass and stiffness properties of the system. The natural frequencies (uncoupled and undamped motions) of the vessel can be found by (Faltinsen 1990):

(Eq.10) Roll:

$$\omega_{4n} = \sqrt{\frac{C_{44}}{I_{44} + a_{44}}}$$

(Eq.11) Heave:

$$\omega_{3n} = \sqrt{\frac{C_{33}}{m + a_{33}}}$$

(Eq.12) Pitch:

$$\omega_{5n} = \sqrt{\frac{C_{55}}{I_{55} + a_{55}}}$$

Estimation of added mass and ship inertia can be made by following (Lloyd, 1998):

Roll:

$a_{44} \approx 0{,}25 I_{44}, I_{44} = m{k_{44}}^2$

Where: $k_{44} = 0{,}30 B_{WL}$

Heave:

$a_{33} \approx m$

Pitch:

$a_{55} \approx I_{55}, I_{55} = m{k_{55}}^2$

Where: $k_{55} = 0{,}25 L_{pp}$

The restoring force coefficients can be found by (Faltinsen, 1990):

$C_{33} = \rho g A_{WP},\ C_{44} = \rho g V \overline{GM_T},\ C_{55} = \rho g V \overline{GM_L}$

The calculations in this analysis considered regular sinusoidal waves and linear wave theory. Parameter used can be found in table 14.

Following assumptions were made (Faltinsen, 1990) :

- Flat bottom (seabed)
- Constant water depth
- Nonbreaking waves
- Incompressible water
- Constant density (water: 1,025kg/m^3)
- non-rotational fluid motion

With following boundary conditions (Faltinsen, 1990):

- No water flow through the seabed (no penetration of the seabed)
- water pressure at surface shall be equal the atmospheric pressure
- A water particle on the surface will stay on the surface, following the wave motion

H_s	Significant wave height	3 m
T_p	Wave period	5,6,8 s
U	Ship speed	1,2,3,4 kts
B	Ship breadth	27,45 m
T	Mean Draught	5,55 m
L	Ship length	121,65 m
$\overline{GM_T}$	Transversal Metacentric height	4,94 m
$\overline{GM_L}$	Longitudinal Metacentric height (estimate)	215,83 m
m	Ship Displacement	12266,65 t
ρ	Density seawater	1025 kg/m^3
g	Gravitational force	9,81 m/s^2

Table 12 Parameters for analysis on the risk of resonance

The encounter frequency can be found by following formula (Faltinsen, 1990):

(Eq.12)

$$\omega_e = \omega_n + \frac{{\omega_n}^2 U}{g} \cos\beta$$

Placing the encounter frequency equal to the natural frequency and following general heading angles (β) between the wave direction and the vessel can be found:

$$\beta_1, and\ \beta_2 = \pi - \beta_1$$

Where β_2 = wave encounter from behind

Following headings that estimated to bring risk for resonance can be seen in table 15. The angle of encounter depends heavily on the vessel's speed. In order to avoid peak vessel motions which can bring risks to the stability of the vessel and to the integrity of the cable under influence of unwanted vessel motion, the speed or the vessel heading can be altered.

The values obtained here, however, can't be compared to the default vessel in OrcaFlex used in the simulations, as the default vessel have a different water plane area when compared to the CLV. This method remains as a description of how one may estimate peak vessel motions.

Vessel speed [kts]:	Roll: ω_{4n} =0,76rad/s T_{4n} = 8,26s			Heave: $\omega_{3n} = 1,37 rad/s$ T_{3n} = 4,58s			Pitch: ω_{5n} =1,15rad/s T_{5n} = 4,33s		
	T_p = 8s	T_p = 8,3s	T_p = 9s	T_p = 4s	T_p= 4,6s	T_p= 5s	T_p = 5s	T_p = 5,5s	T_p = 6s
1	β_1:14° β_2:166°	β_1:88° β_2:92°	–	–	β_1:92° β_2:88°	–	–	β_1:93° β_2:87°	–
2	β_1:61° β_2:119°	β_1:89° β_2:91°	β_1:165° β_2:15°	–	β_1:91° β_2:89°	β_1:125° β_2:55°	β_1:35,5° β_2:144,5°	β_1:91° β_2:89°	β_1:135° β_2:45°
3	β_1:71° β_2:109°	β_1:89° β_2:91°	β_1:130° β_2:50°	β_1:47° β_2:133°	β_1:91° β_2:89°	β_1:112,5° β_2:67,5°	β_1:57° β_2:123°	β_1:91° $\beta_2$89°	β_1:118° β_2:62°
4	β_1:76° β_2:104°	β_1:89,5° β_2:90,5°	β_1:119° β_2:61°	β_1:59° β_2:121°	β_1:91° β_2:89°	β_1:107° β_2:73°	β_1:66 β_2:114°	β_1:91° β_2:89°	β_1:111° β_2:69°

Table 13 Frequencies and heading angles of encounter

5.3 CURRENT FORCES

The combinations of cable motion, wave particle velocity and currents create water particle velocities relative to the cable. These can be split into velocities normal and parallel to the axis of the cable. The horizontal forces that the relative horizontal velocities u and a_1 exert on the normal direction of a stationary cylinder can be described by the semi empirical Morison equation (Faltinsen, 1990):

(Eq.13)

$$F = \rho\pi\frac{D^2}{4}C_m a_1 + \frac{1}{2}\rho C_d u|u|$$

Here, C_d is the drag coefficient and C_m is the mass coefficient. Typical value for $C_m = C_a + 1$ where C_a = added mass coefficient for the cable segment. These values normally need to be empirically calculated. (Faltinsen, 1990)

A similar equation can be written for the vertical component of the force due to water particle motions relative to the cable where the water particle velocities and accelerations relative to the cable motion are applied.

In addition to the mass and drag loading terms, water particle motions in one direction generate a lift force which is normal to the flow direction. The lift force has the form of the drag loading term with a lift coefficient C_l replacing the drag coefficient. (Faltinsen, 1990)

OrcaFlex uses a modified Morison equation to incorporate the local horizontal motions of the cable segments. This equation is used to calculate the horizontal hydrodynamic loads on each cable node for every time step (Orcina, 2020):

(Eq.14)

$$F = (\Delta a_f + C_a \Delta a_r) + \frac{1}{2}\rho C_d A|v_r|v_r$$

Where:
F = total force applied on a cable segment at a given time [N/m]
Δ = mass of displaced fluid by the cable [kg] ($\Delta = \rho\pi\frac{D^2}{4}$)
a_f = local fluid acceleration with respect to the earth reference system [m/s^2]
C_a = added mass coefficient for the cable segment [-]
a_r = fluid acceleration relative to the cable segment [m/s^2]
ρ = the water density in [kg/m^3]
C_d = drag coefficient for the cable segment [-]
A = drag area or displaced volume per m length [m^2]
v_r = fluid velocity relative to earth reference system [m/s]

A simple test in OrcaFlex was performed to investigate the cable movements and top tension for all three HVAC cables (as described in Chapter 4), when current is present and with the absent of waves. Different current forces were applied in 0-, 90- and 180-degrees directions related to the vessel and cable in a water depth of 30m. Here, the vessel with cable deployment over the chute (as described in Chapter 4) were the basis for the setup. The current profile is equal to the one described in Chapter 4. Further description of the analysis and full results can be found in appendix D. The analysis of the current effects was approach by a quasi-static view.

The analysis showed a significant lateral displacement and increase in tension (compared to tension in static state) in currents approaching at 90 degrees, where both the displacement and tension increases along with the current velocity. The weight of the cable has an impact on this movement, where the lightest cable showed the largest displacement (figure 34).

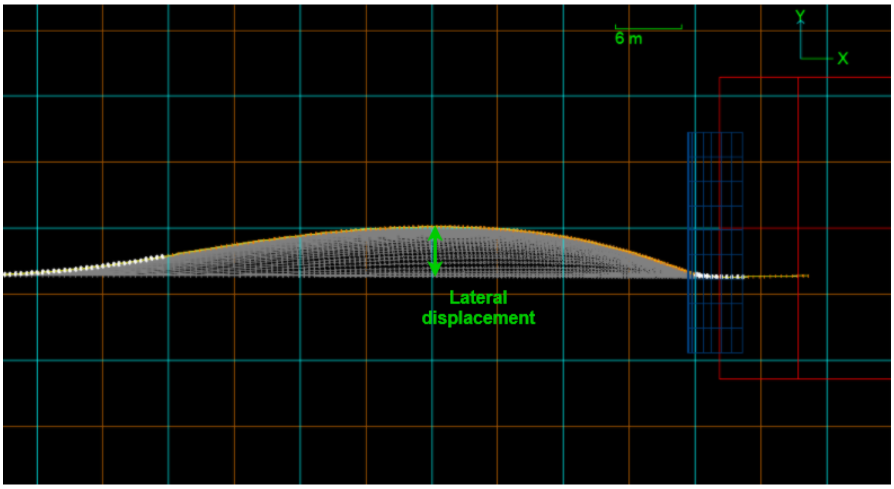

Figure 41 Lateral displacement of HVAC C. A, in static seas with a current surface speed of 1,5m/s in a 90 degrees direction

With current in direction 0°, a small increase in tension can be seen as the TDP movements leads to a greater layback length, and more cable weight is in free span. The current profile, which has the largest current velocity located near the surface, will push the cable down. Whereas in a 180° direction will lift the cable. Current in this direction will dampen the tension slightly, as the TDP moves closer to the vessel (figure 35 & 36).

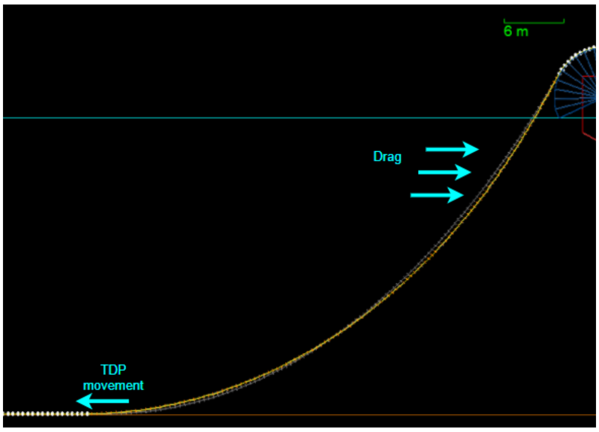

Figure 43 Cable displacement with 1,5 m/s collinear surface current at 0 degrees

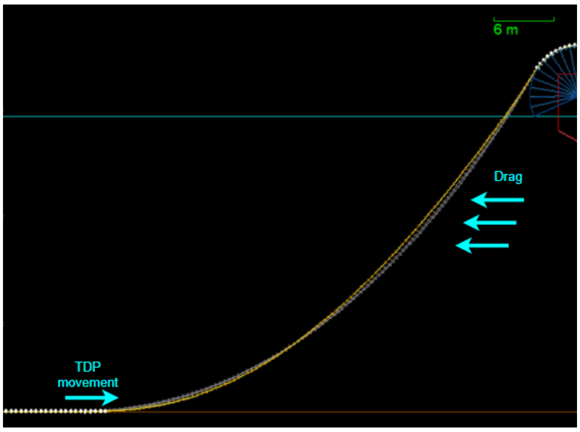

Figure 42 Cable displacement with 1,5 m/s collinear surface current at 180 degrees

Occurrence of flow separation on the cable strongly affects the drag forces. When the water flows around the cable, the water which is in contact with the cable will move slower than the water around it, and form a boundary layer. At the back of the cable this layer will separate from the cable surface. With high flow (i.e., current) velocities, vortices will be shed, causing a small hydrodynamic force which will act on the cable and force it too oscillate (vortex induced vibrations). Even if the cable has no external forces applied, the cable will oscillate with a frequency which can be found by Strouhals number (Sn = Fv x D / U = approx. 0.2 – 0.25). When the vortex shedding frequency gets equals to as or close to this frequency of the cable, oscillations with larger amplitudes can appear (resonance). (Faltinsen, 1990) This can be critical for the cable integrity and can cause severe fatigue damage.

CHAPTER 6 – DYNAMIC ANALYSIS

The dynamic forces and motions and their effect on subsea power cables during laying is significant and will determined the design of the cable and the method of instalment. As the cable laying process is an offshore activity, the sensitivity of the vessel motions defines the weather window of operation. This sensitivity is usually expressed in a cable installation analysis as an operational limitation. (Gudmestad, 2015)

In reality, the vessel will have to cope with irregular sea-states and therefore irregular motions of the vessel. To see how the different deployment methods will act in irregular motions, a number of irregular sea-states with a JONSAWP wave spectrum were simulated. This was performed to includie wave conditions which would provide dynamic situations that is considered as non-operable.

The stresses in the cable during the installation process will get magnified with the dynamic effects of waves and vessel motions. In order to test the sensitivity of cable self-weight, the dynamic behaviour of the cable was examined under wave excitation with vessel interaction. For the sensitivity analysis of different deployment positions, the dynamic behaviour was examined under same conditions but with the presence of current loads.

With the dynamic analysis in the time domain, forces are included by the marine physical environment. These loads can be found by mathematical models such as Morison equations as described in chapter 5, with the addition of wave velocities (u_W) to the equation (Eq.13). (Gudmestad, 2015).

When considering dynamic loads to the vessel, winds and currents give rise to horizontal motions, while the waves will generate motions in six degrees of freedom (Figure X).

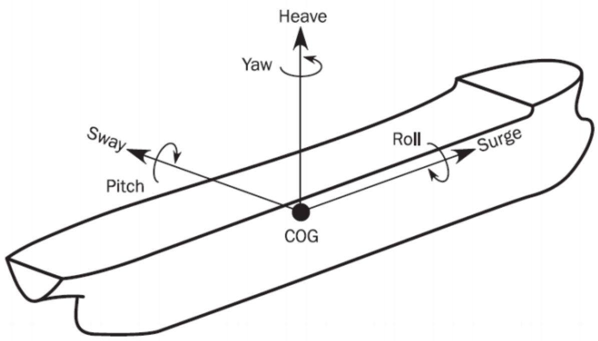

Figure 44 Rigid body motion of a ship (6 degrees of freedom). (DNV-GL)
Translational motion: surge, sway and heave
Rotational motion: roll, pitch, yaw

However, in reality we can also see other forces acting upon the vessel pushing the vessel to move in its degrees of freedom. Adding to wave-, wind- and current forces, other influencing factors are radiation forces arising from the change in fluid momentum as a reaction of the vessel motion, hydrostatic restoration forces by buoyancy and gravity, thruster forces regulated by the DP system and tensional forces at the top of the cable acting upon the vessel. (Zan, Yuan, Huang, Ding & Wu, 2018)

6.1 SIMULATION RESULTS – SCENARIO 1

Cable weight per unit length in water is a key parameter in the analysis of cable behaviour during laying operations. The sensitivity of three different cable weights (61 kg/m, 72kg/m, 92kg/m) and the relation to maximum tension is here analysed, with water depth and layback distance as varying parameters.

For this scenario, the tension limit for top tension when the cable is leaving the chute was calculated for each layback distance according to the capstan effect (Eq.1). Where at each layback distance the contact angle in a static state was measured.

The following chute contact angle was found:
LB 0,5 x wd=80,21°, LB 1,0 x wd=68,76°, LB 1,5 x wd= 57,30° & LB 2,0 x wd= 51,57°.

This will give following available top tension (in static seas, no waves) according to the Capstan effect:
LB 0,5=185,31kN, LB 1,0=164,35kN, LB 1,5=145,77kN & LB 2,0=137,28kN

A system was created to divide the levels of tensions, with a utilization factor (U.F.), taken the following limits just defined (table 17). It should be noted that no safety factors were added in this case. The full result of the dynamic analysis of scenario 1 can be found in appendix E.

Maximum tension criteria of tensioner [kN]:	
	U.F </= 0,5
	0,5 < U.F >/= 0,7
	0,7 < U.F >/= 0,9
	0,9 < U.F > 1,0
	U.F>/= 1,0

Table 14 maximum tension criteria - scenario 1

Three water depths (30-, 60-, 100m) were checked for their importance and influence on maximum tension for the three cables: HVAC cable A-C.

In order to assess the operational limits, four different layback lengths (0,5-, 1,0-, 1,5- & 2,0 x WD) were considered for each water depth (figure 38).

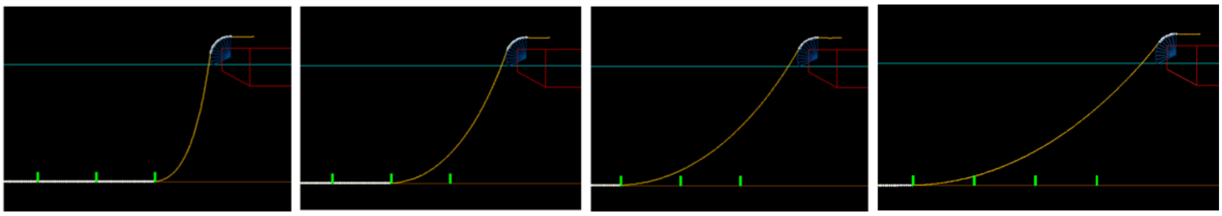

Figure 45 Illustration of different Layback lengths as varying parameter. Here in 30m depth with 0,5-, 1-, 1,5- and 2 x wd

From figure 39-41 below, we can clearly see the effects of cable weight through the different water depths. Increasing the depth under given layback distances, more of the cable is in free span and hence more tension is seen at the top of the catenary. Also, the spread of tension amongst the three cables (having different weights) can be seen to increase along with the water depth.

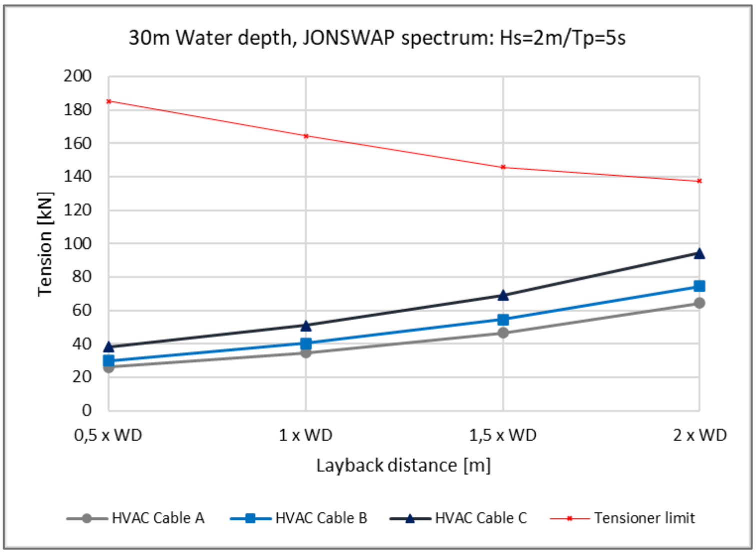

Figure 46 Cable configuration with varying layback lengths in 30m water depth

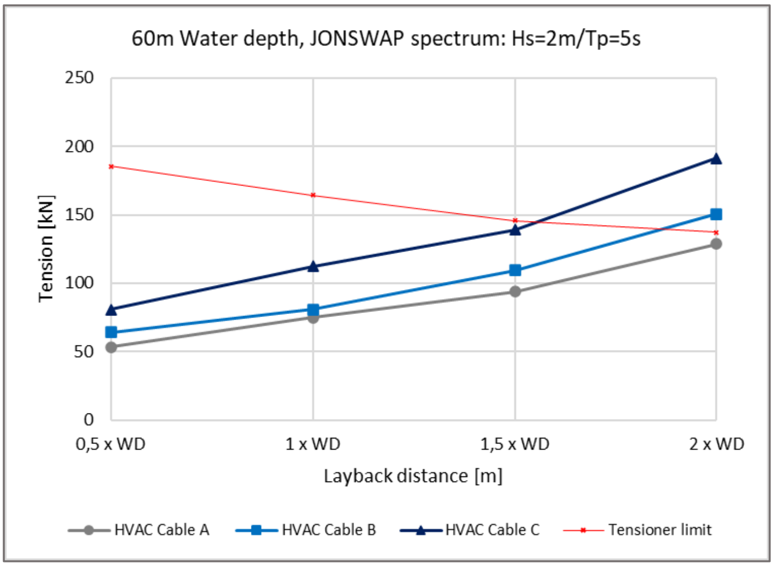

Figure 47 Cable configuration with varying layback lengths in 60m water depth

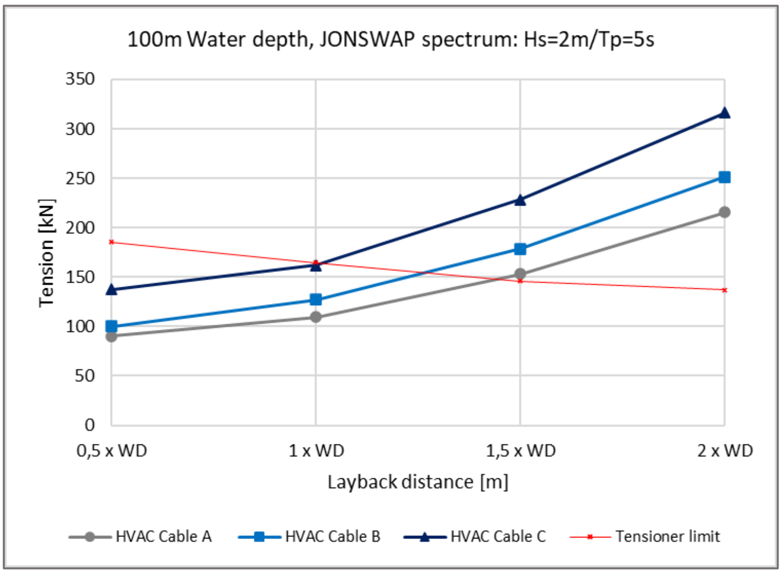

Figure 48 Cable configuration with varying layback lengths in 100m water depth

6.2 SIMULATION RESULTS – SCENARIO 2

This scenario investigates how different deployment methods will affect maximum tensions, given a set of various wave parameters in irregular sea with a water depth of 100m. Here only HVAC cable A is simulated.

Tension for S-lay and J-lay (moonpool & Starboard side) was here measured at the bottom of the keel (where the cable enters in water during J-lay). In static seas, the point on the cable which enters the water at approx. -5,5m in z-direction (equals to the draft of the vessel) was noted for all three methods and is used as a reference in comparison of tension loads. To set a limit for tension (given that all methods are equipped with the same tensioner), the capstan effect was calculated for S-Lay. A maximum tension of 164,35 kN was found for the exit at the chute (Top tension). Together with a safety factor (SF) of 0,9 (to compensate for the part of the cable neglected), the tension limit for all three method was set to 148 kN, as all methods are analysed with same layback distance. This was performed due to the many options of placement of a tensioner in the J-lay methods, and the goal here is purely a comparison of tension due to vessel motion with different deployment positions. It should be noted that a safety factor for operation was not added in this case. A Categorization of the levels of tension based on utilization factor can be found in table 43.

Tension limit categorization	
Maximum tension criteria: 148 kN	
	U.F </= 0,5
	0,5 < U.F </= 0,6
	0,6 < U.F </= 0,7
	0,7 < U.F </= 0,8
	0,8 < U.F </= 0,9
	0,9 < U.F >1,0
	U.F =/> 1,0

Table 15 tension limit critera – scenario 2

The other limiting criteria for safe operation were also monitored and noted. For limits found compromised, the following description can be added to the results in appendix E: C = compression limit and B = tension & bending relation limit. Below, figures 44-52, follows illustrations of the peak tension distribution found for the three different deployment methods in the various sea states. The full results can be found in appendix E. Note that the values given for the shorter wavelengths are not realistic as the shorter waves in the spectrum will break.

Peak tension distribution between wave & current headings for all deployment methods – Hs: 2m

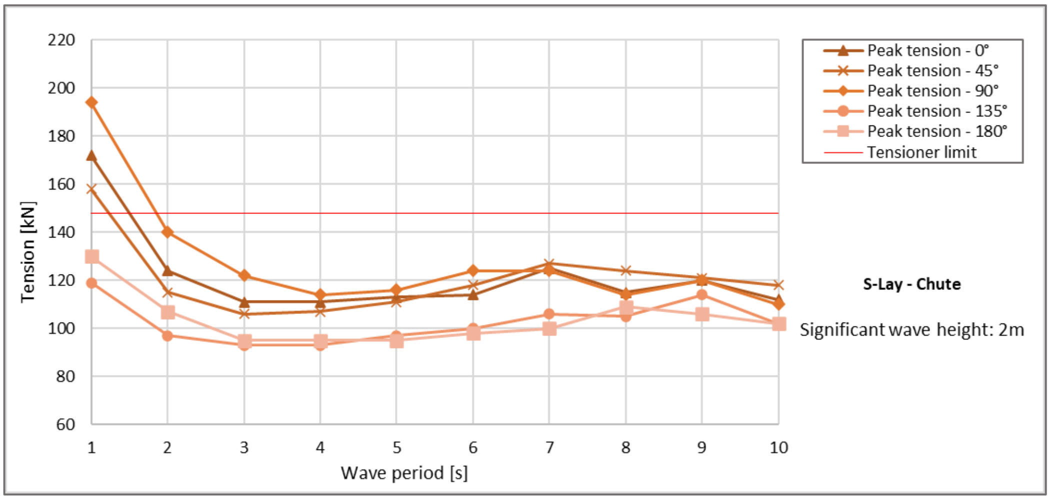

Figure 49 Dynamic simulation results - S-lay: Hs=2m

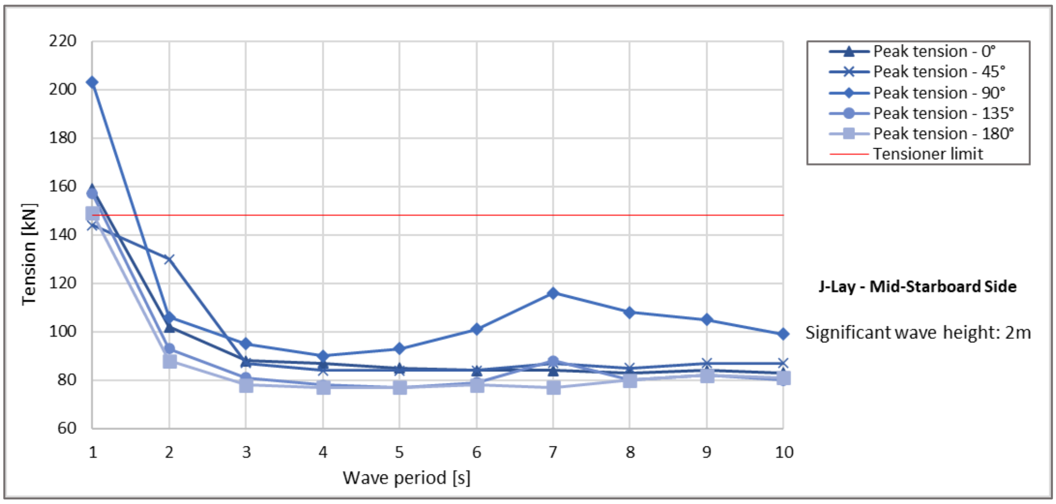

Figure 50 Dynamic simulation results - J-lay (Mid-Starboard side): Hs=2m

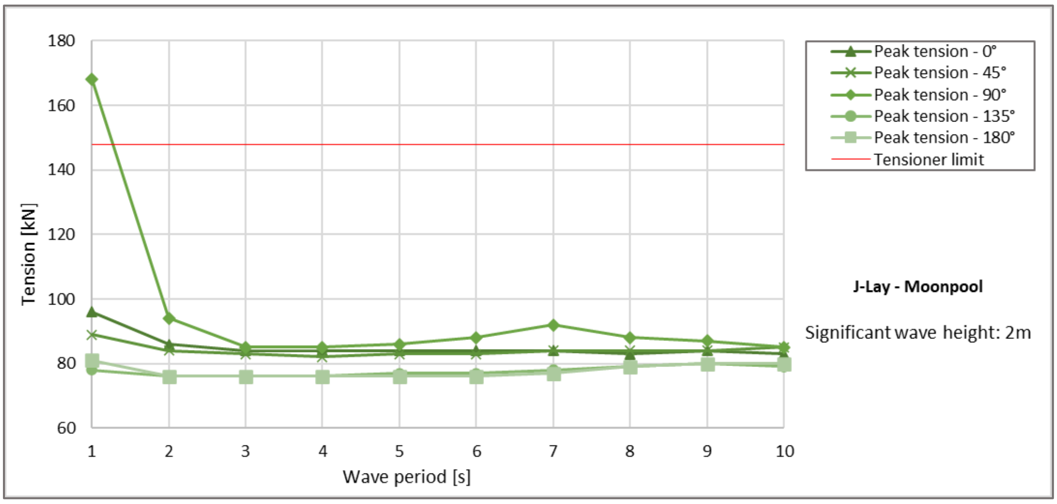

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Figure 51 Dynamic simulation results - J-lay (Moonpool): Hs=2m

Peak tension distribution between wave & current headings for all deployment methods – Hs: 3m

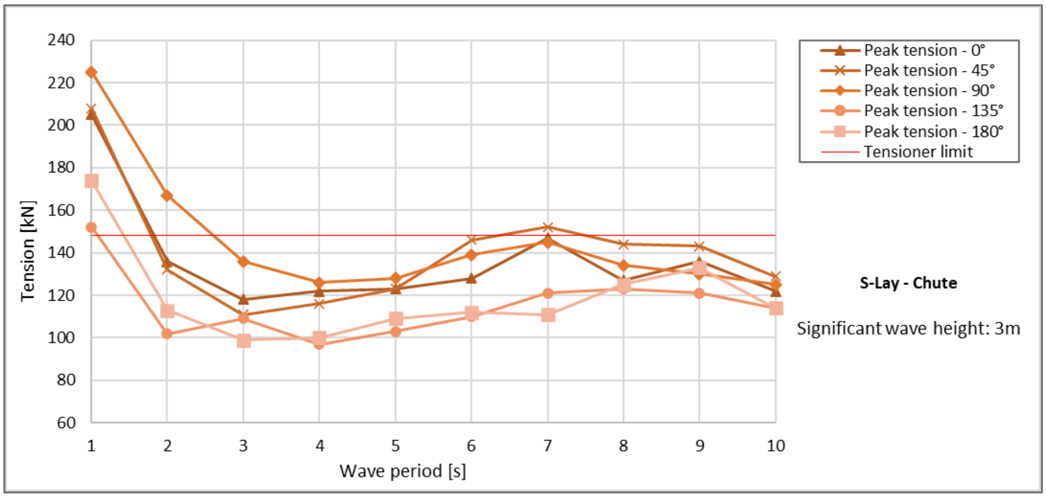

Figure 52 Dynamic simulation results - S-lay: Hs=3m

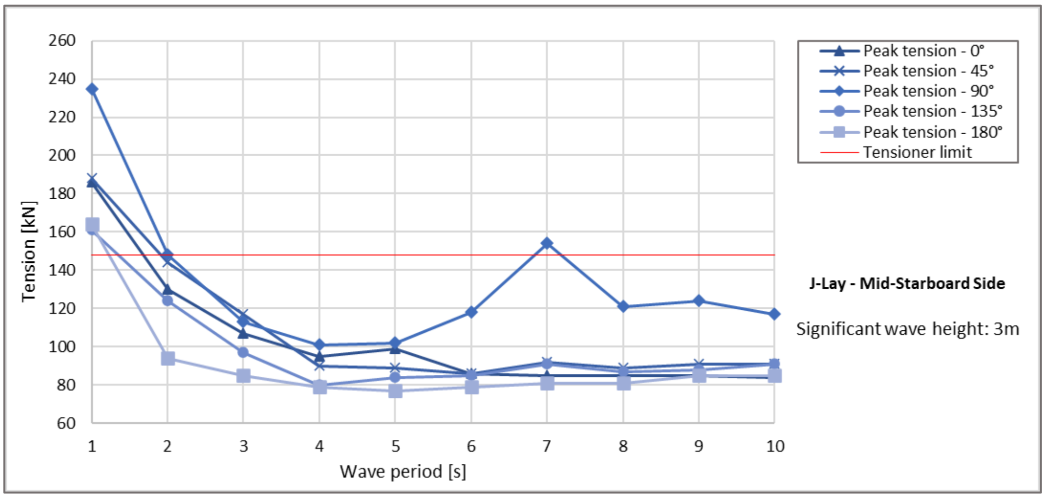

Figure 53 Dynamic simulation results - J-lay (Mid-Starboard side): Hs=3m

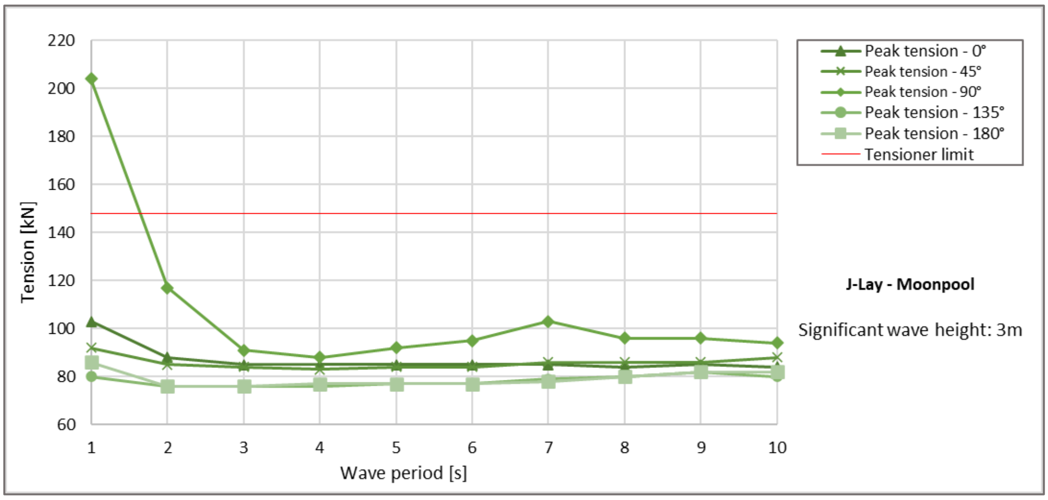

Figure 54 Dynamic simulation results - J-lay (Moonpool): Hs=3m

Peak tension distribution between wave & current headings for all deployment methods – Hs: 4m

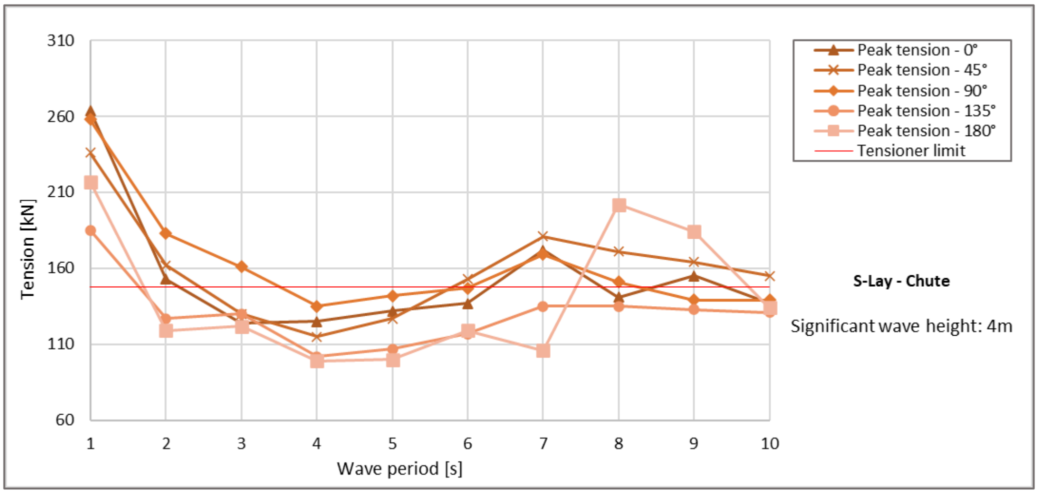

Figure 55 Dynamic simulation results - S-lay: Hs=4m

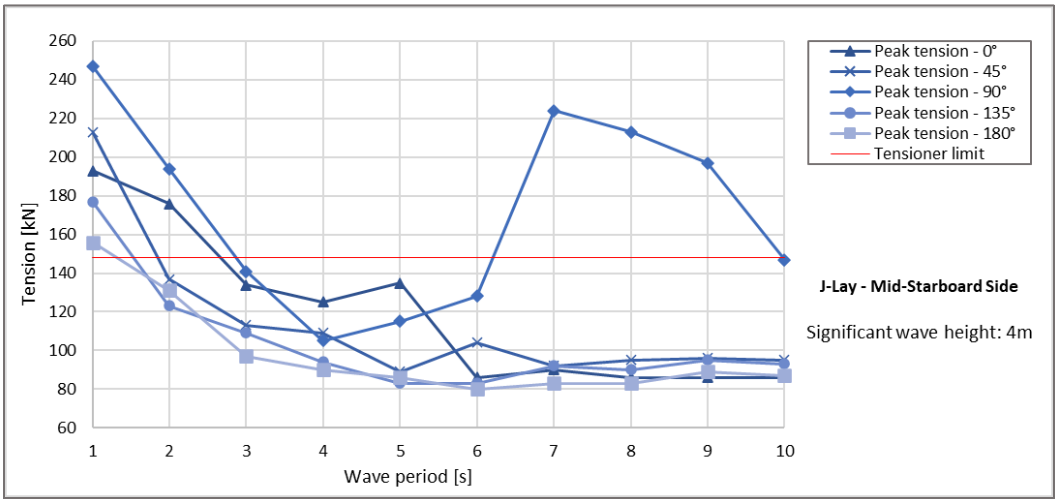

Figure 56 Dynamic simulation results - J-lay (Mid-Starboard side): Hs=4m

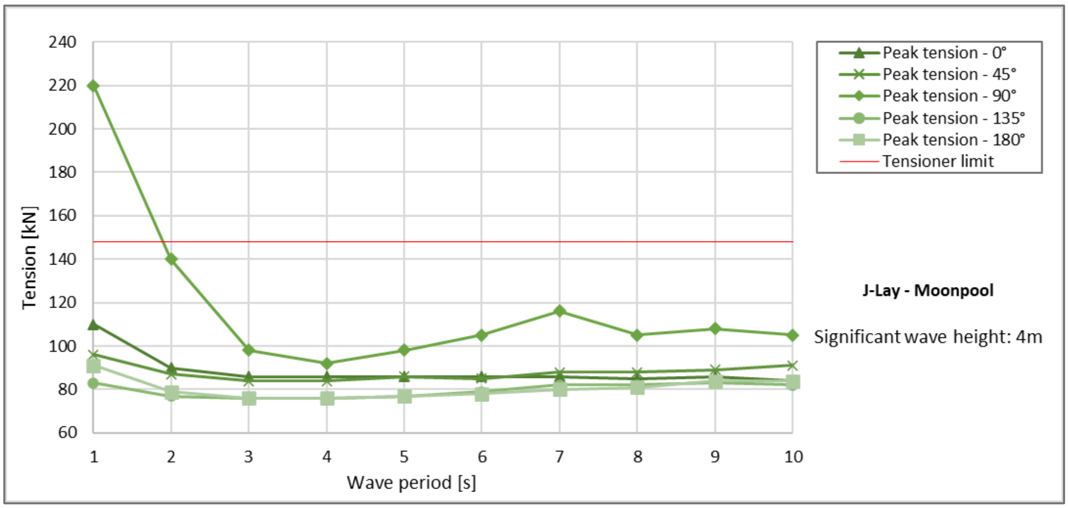

Figure 57 Dynamic simulation results - J-lay (Moonpool): Hs=4m

Concerning the breaking tension limit of the cable, this limit was hardly reached in this case. However for S-lay in 4m significant wave height with a heading of 180 degrees, as well as for J-lay in 4m significant wave height with heading of 90 degrees, this tension limit was reached (Table 18)

DEPLOYMENT METHOD:		Breaking tension limit [kN]					
	H_s [m]	0°	45°	90°	135°	180°	
S-Lay: Chute	2	-	-	-	-	-	Wave period [s]
	3	1	1	1	-	-	
	4	1	1	1	-	1, 8	
J-lay: Mid-Starboard side	2	-	-	1	-	-	
	3	-	-	1	-	-	
	4	-	1	1, 7, 8	-	-	
J-lay: Moonpool	2	-	-	-	-	-	
	3	-	-	1	-	-	
	4	-	-	1	-	-	

Table 16 Breaking tension limit for the different deployment methods

The compression limit was also monitored (table 19), which limits the operational window further. This was found domination in wave heading of 180 degrees for S-lay, 90 degrees for J-lay mid starboard and almost not present with deployment through the moonpool.

DEPLOYMENT METHOD:		Compression limit [kN]					
	H_s [m]	0°	45°	90°	135°	180°	
S-Lay: Chute	2	1	1	1	-	1	Wave period [s]
	3	1	1	1,2	9	1,5,7,8,9,10	
	4	1	1,2,7,8,9	1,2,7,8	1,7,8,9,10	1,2,6,7,8,9,10	
J-lay: Mid-Starboard side	2	1	1,2	1	1	1	
	3	1,2	1,2,3	1,2,7,8,9,10	1,2,3	1,2	
	4	1,2,3,4,5	1,2,3,4	1,2,3,6,7,8,9,10	1,2,3	1,2,3	
J-lay: Moonpool	2	-	-	1	-	-	
	3	-	-	1	-	-	
	4	-	-	1,2	-	-	

Table 17 Compression limit for the different deployment methods

CHAPTER 7 – DISCUSSION OF RESULTS

Through the sensitivity analyses conducted in this thesis, the goal was to examine the key limiting parameter of maximum top tension and its sensitivity for various cable configurations (scenario 1) and cable deployment methods (scenario 2).

At the same time, the goal was to present a method for conducting such analyses and illustrate its importance in a cable installation project to understand which parameters would be especially important to control and monitor. As well as to which parameters that will affect the design of the cable and cable laying method applied.

In modelling a cable system for dynamic studies there are a lot of aspects that can affect the accuracy of the simulation results. Besides the environment, such aspects can also be related to simplifications that need to be done due to software limitations or for simulation time reduction. The analyses were based on data from a past export cable installation project, however simplifications and alterations were made along the way as the sensitivity analyses focused mostly on the general dynamic behaviour of the subsea cables in irregular seas, and not on their actual values.

7.1 THE EFFECT OF CABLE SELF WEIGHT

To investigate the effect of the cable self-weight, the results from the quasi-static analysis gave an indicator of the variations in top tension, which could further be seen with the dynamic analysis in the time domain.

In achieving the balance between cable parameters such as the relation between bending, layback length and tension, the weight of the cable plays a significant role. The different cable configuration along the water depth showed that tension increases almost linearly. As the water depth increases, a more steeper tension curve can be seen, in particular with the heaviest cable which includes a double set of steel armour layers. Increasing the water depth from 30m to 100m, the layback length is needed to be heavily reduced.

Naturally the layback distance is illustrated as another key parameter in regards to cable weight, as the tension increases with length of the cable in free span. The cable departure angle increases with the layback length, which gives a lower chute contact angle and therefor less friction forces over the chute. This reduces top tension limit due to the capstan effect. By decreasing the layback length, the tension would remain within its limits. However, this would only be the case up to a certain water depth, given the tensioner's capacity.

It should be noted that these analyses incorporate three cables which have different stiffness properties. So, the effect of the cable self-weight is not investigated alone. The stiffness qualities of the cable will most likely have some significance to the tension in the cable. In particular regards to cable compression, as the cable with lower bending stiffness tends to experience larger and more frequent negative tension loads at touch down point. The cables also differ in outer diameter, which may to some degree have an influence on the drag forces acting upon the cables.

7.2 CABLE DEPLOYMENT POSITIONS

A simple analysis with a variety of sea states was performed to compare peak tension loads on the cable through deployment at different positions on the vessel.

Most cable laying vessels today have the chute or laying wheel at the stern of the vessel, while the J-lay method could be more frequently seen as OWFs moves to deeper waters. From the results, the S-lay method showed to be very sensitive to the wave induced vessel motions. Significant wave heights over 2m will in this case exceed the tension limit. It is mainly pitch and heave motions that contribute to the vertical motion of the chute at the stern, and the severity of these motions will vary from vessel to vessel as they all have different motion characteristics. Particular benefits can be obtained in case where the pitch can be reduced.

For the J-lay methods, both deployment methods were shown to be sensitive for heave motions of the vessel, in particular deployment over the mid-starboard side, with peak tension loads in a wave heading at 90 degrees and with a wave period of 7s (in correspondence to the OrcaFlex default vessel's heave period). With this sea state, the significant wave height over 2m would not be operable. This method also showed to be sensitive for roll motions. In a sea state of H_s=4m and with wave periods of 7 and 8s, the cable would reach its breaking limit. Still, this method is less sensitive to vessel motions compared to the S-lay method.

Deployment through the moonpool was clearly less effected by vessel motions, compared to the other methods. Even with its peak tension at H_s=4m and wave period of 7s, this method stayed well below the set tension limit. Depending on the level of conservatism of the safety factor to be set, these sea states could all be seen as operable.

However, the results obtained, are clearly affected by the RAO of the OrcaFlex default vessel. For a real life operation, this vessel would not be appropriate to determine operable conditions and the actual vessel Response Amplitude Operators (RAOs) must be modelled.

In irregular seas, waves height can be seen as both steeper and shorter in the spectrum. Superimposed waves may occur from different directions and by different sources. As a weather forecast can provide good estimates, it is rarely 100% accurate. For this reason, unexpected waves of great amplitude may occur which could be sufficient to damage the cable, displaying the need for a safety factor for safe operations.

Throughout the analysis, one can see that the success of a cable operation is highly dependent on the conditions of the sea state, and deployment method chosen. While every project is with different frames, it can be said that the choice of deployment method, would have a significant effect on the available weather window of operation. This could influence the competition between vessel owners, as the client will select vessel based on costs and operational uptime expected in a laying season.

CHAPTER 8 – CONCLUDING REMARKS

A review conducted on the historical failure data of subsea power cables in the offshore wind industry illustrated that the reliability of these cables highly depends on the specific project. With the cable instalment method, location, cable configuration and cable protection methods as key factors here. A HAZID analysis can be an important tool to implement in a cable installation project, both before and during the installation, to locate the hazards present which may jeopardize the cable's integrity. The HAZID analysis conducted in this thesis showed numerous hazardous events that could decrease the reliability of the installed subsea cables, including hazards present in project planning, during instalment and hazards posed by the environment.

Several sensitivity analyses concerning cable laying operations, were conducted within this thesis. Here, the objective was focused on investigating several parameters that might provide peak tension loads on a HVAC subsea export cable under instalment. The analyses were all performed by the aid of the software, OrcaFlex.

A small quasi-static analysis of different types of bending stiffnesses were analysed for its importance when modelling the cable laying scenario. This showed that modelling with a constant value or with a non-linear bending stiffness (without hysteresis) would be more conservative then modelling with a non-linear bending stiffness with hysteresis, when considering compression. Regarding maximum tension, this had only a minor difference in tension value.

The effect of different current velocities which encounters the cable and vessel in angles of 0°, 90° and 180° were tested with a quasi-static analysis, for three different cable configurations. Depending on the direction of the current, at high velocities, this will increase offset of the cable, TDP movement and an increase in maximum tension. Here the lighter and less stiff cables were more affected than the heaviest cable with double armouring.

To validate simulation results, three cable configurations were investigated with catenary equations. The catenary shape, tension along the arc and tension along water depth were examined both in a static state and while resting on a sinusoidal wave crest. This was compared to results obtained from the software. Besides some differences in catenary shapes when the cables are resting on the wave crest and experiencing the highest excitation of the vessel's chute, the results showed to be in good compliance.

The three HVAC cables with varying weight and stiffness properties were investigated further for its sensitivity for maximum tension in varying water depths (30m, 60m & 100m), and with four different layback lengths. For this analysis, dynamic forces in the time domain were applied along with a JONSAWP wave spectrum. This illustrated that the design of the cable in regards to its weight, will have a significant impact on tension loads.

A final sensitivity analysis was conducted on different cable deployment positions with irregular vessel motions in varying sea states in the time domain. Here deployment over a chute at the stern (S-lay), deployment along the mid-starboard side (J-lay) and deployment through a moonpool (J-lay) were investigated for its relations to peak tension loads. The results showed that deployment over the stern would make the cable vulnerable to vessel motions of roll, heave, and pitch. Deployment midships of the vessel's external starboard side reduces the effect of pitch, while deployment through the moonpool reduces both the effect of roll and pitch on cable dynamics and thereby maximum tension loads.

The sensitivity analyses conducted in this thesis, showed the importance of cable design when considering the cable's weight. The weight has a significant impact on tension loads, and this should be taken into consideration when designing a cables armour. An overly conservative design will surely reduce the weather window. The importance of the cable's deployment position may depend on the location of operation. While the trend in the offshore wind industry is to expand the OWFs to locations with deeper waters and more challenging environments, operability can be increased by altering the deployment position of the cable.

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APPENDIX A – HAZID study

HAZID ANALYSIS – SUBSEA POWER CABLE INSTALLATION

Based on anonymous discussions, a brainstorming session (4 individuals) and following references: (DNV-GL, 2016(a)); (Cigre, 2009(a)); (Cigre, 2009(b)); (Cigre, 2020); (Wang, Yan, Li, Zhang, Ouyang & Ni, 2020); (Vabenø, 2017); (El Wardani, 2012); (Worzyk, 2009).

HAZARD IDENTIFICATION: OWF – SUBSEA POWER CABLE INSTALLATION										
Category 1: Project method and planning										
Hazard number	**Hazardous event**	**Possible causes**	**Potential threats**	**Control/ barriers**	**Health & Safety**	**Cable & assets**	**Enviro -nment**	**Reput- ation**	**Project**	**Additional controls / Recommendations:**
1.1	Lack of work standards	Developing industry, lack of knowledge or experience	Substandard designs, delays	• Application of guidance from related areas					C3	Creation of dedicated guidance
1.2	Regulatory changes	Governmental changes	Delays and costs	• Management for change • Following developments • Clear agreed terms & conditions					B3	
1.3	Lack of site data / information	Inexperience, perceived cost saving	Excessive risk, potential delays and cost overruns, cable damage (during/after installation)	• Conservative planning • site assessments		C3			C3	
1.4	Poor survey results	Inexperience, perceived cost saving	Excessive risk, potential delays and cost overruns, cable damage (during/after installation)	• Well-planned, targeted surveys • Adequate budget and survey scope • Work with experienced partners		C3			C3	
1.5	Poor cable route	Inexperience, perceived cost saving	Excessive risk, delays, cost overruns, cable damage (during/after installation)	• Proper route engineering		C3		B2	C3	
1.6	No crossing agreement	Inexperience, lack of site knowledge	Increased risks, liability, legal challenges	• Minimise cable crossings • Agree on cable crossing design				B2	C3	
1.7	Mismatch between cable parameters and cable route	Unknown cable specifications, inexperience, negligence	Redesign, modifications, delays, cost overruns, cable damage	• Understand cable specifications • Adequate design for installation and operation		C3		B2	C3	
1.8	Overly conservative cable parameters	Conservatism	costly design	• Communication between cable manufacturer, installer and offshore unit designer					C3	
1.9	Cable manufacturing flaw	Impurities, lack of QA, insufficient testing	Cable damage (during/after installation), delays, liabilities	• Experienced manufacturer • Clear specifications • Quality assurance during manufacturing, audits • Routine and factory acceptance testing		C3			C3	
1.10	Cable fault	Manufacturing defect, storage, transport, compromised cable during installation, marine environment, ageing asset	Loss of transmission, loss of income, repair cost	• Adequate design, • proper manufacturing, • Proper handling during installation • maintenance • Cable protection		C3			C3	
1.11	Lack of spare cable or joints	Inadequate planning, poor route engineering	Significant delay, costs	• Appropriate planning • Spare part storage • route engineering • Sharing of resources		B3		B2	C3	

1.12	Manning	Inadequate planning, Inadequate training, Low/insufficient manning;	delays, increase risk of accidents	• Redundancy; extra manning, manning with multiple skills • Experienced workers in charge of their field • sufficient training • practice with exp. Workers • practice multiple skills	B2	B2			B2	
1.13	Testing to higher standard than required	Conservatism	Failed test, delays	• Clear agreement between manufacturer and buyer					B2	
1.14	Start-up delays, supply chain delays	Inexperience, lack of planning	Cost overruns	• Order parts / equipment further in advance • Detailed planning • Work with experienced installation contractors					B2	
Category 2: Operational hazards										
Hazard number	**Hazardous event**	**Possible causes**	**Potential threats**	**Control/ barriers**	**Health & Safety**	**Cable & assets**	**Enviro -nment**	**Reput-ation**	**Project**	**Additional controls / Recommendations:**
2.1	Contamination	Marine or landfall incidents, spillages of oil or chemicals, disturbance of contaminated areas	Habitat impact	• Avoid contaminated areas • Use safe work procedures • Regular maintenance • Build awareness			C2	C2		
2.2	Landfall habitat disturbance	Drilling, trenching, cable pull-in, backfilling, access of barges and machinery	Habitat loss in intertidal area, distress of birds, impact on feeding and breeding behaviour	• Choose alternative cable route /landfall • Choose lower impact periods of the year • Choose low-impact construction techniques			C3			
2.3	Seabed habitat disturbance	Cable burial, cable protection methods	Disturbance of seabed habitat	• Choose lower impact periods of the year • Choice of burial process and equipment • Choice of cable protection method			C3			
2.4	Construction noise, landfall area	Installation equipment and process	Disturbance of birds	• Choose lower impact periods of the year • Select low noise equipment • Minimise noise during installation process			C2	C2		
2.5	Construction noise, offshore	Installation equipment and process	Disturbance of marine life	• Choose lower impact periods of the year • Minimise noise during installation process			C2	C2		
2.6	Introduction of new materials	Rock placement for cable protection	Impact on ecosystem	• Assess risks • Use of local or alternative materials			C2			
2.7	Thermal radiation	Electrical cable losses	Increase of soil/seabed temperature	• Appropriate electrical and thermal design • Adequate burial depth (Germany)			C2			
2.8	Magnetic fields	Single-core DC cables laid at a distance to each other	Possible effect on fish orientation, cable damage by fish bite	• Suitable cable design and layout • Specific attention to fish migration pathways		B2	C2			
2.9	Contractor non-performance	Inexperience, lack of planning	Delays, cost overruns, knock-on effects for other projects	• Contractor references and qualification assessment					C2	

				• Audits • Clear contractual terms & conditions						
2.10	Cable route access	Inadequate agreements, change of policies or regulation	Delays	• Planning • Proactive communication with stakeholders					C2	
2.11	Unsuitable installation or burial tool	Lack of site information, poor design	Delays, cost overruns	• Extensive geophysical / geotechnical investigations • Selection of suitable equipment • Planning with contingencies					C2	
2.12	Equipment breakdown	Overload, lack of maintenance	Delays, cable damage	• Selection of suitable equipment • Regular maintenance		C2			C3	
2.13	Unscheduled vessel maintenance	Lack of maintenance	Delays	• Classed vessel, performance track record • Preventive maintenance					C3	
2.14	Cable loops formed on seabed	Uncontrolled cable payout, insufficient tension	Early failure of cable	• Controlled installation process • Post installation survey • Rectification		C3			C3	
2.15	Cable damaged during installation	Inexperience, inadequate equipment or processes, time pressure	Delays, cost overruns	• Fit for purpose equipment • Agreed handling limits, instructions • Procedures, training				B2	C3	
2.16	Specified burial depth not reached	Hard soil, inappropriate tool	Less protection of cable	• Selection of suitable burial method and tools		C3			C3	
2.17	Excessive burial	Mobile sediments	Overheating of cable	• Appropriate choice of cable design and route • Remedial works		C2				
2.18	Overloading cable	Wrong design assumptions, poor handling of equipment, poor monitoring, weather change	Premature failure of cable	• Design for site-specific conditions • Operational monitoring • Weather forecast		C3			C2	
2.19	Investigation following an incident	Substandard work Practices	Delays	• Safety culture					C3	
2.20	Dropped object	Unsecured freight	Cable damage	• Analysis and cable routing • Burial / protection of cable		C3			C3	
2.21	Work in proximity of the cable	Repairs, new installations	Cable damage	• Accurate charting • Proximity agreements • Stakeholder communication		C3			C3	
2.22	Termination fault	Poor workmanship	Loss of transmission capacity, loss of income	• Use of skilled workforce • Post-installation testing • In-service monitoring		C3			C3	
2.23	Cable free spans	Seabed movement, uneven seabed, to high residential tension	Cable exposure, mechanical stress, VIV, fatigue	• Detailed analysis of site conditions • Appropriate protection design • Inspections • Remedial work		C3			C3	
2.24	Cable crossing	Existing pipelines	Cable suspensions, VIV in cable suspension, cable abrasion, cable damage	• Cable protection		B3				Plan cable route to cross as few cables as possible
2.25	Recovery of deeply buried cable	Requirement to repair faulty cable	Delays, cost	• Burial to required depth only • Consideration of sand waves					C3	
Category 3: Natural and environmental										

Hazard number	Hazardous event	Possible causes	Potential threats	Control/ barriers	Health & Safety	Cable & assets	Enviro -nment	Reput- ation	Project	Additional controls / Recommendations:
3.1	Weather unsuitable for performing operations	Shift in weather conditions	Delays	• Suitable vessel and equipment, long-term charter • Good weather forecasting • Planning with contingencies					C3	
3.2	Strong/ high waves	Shift in weather conditions	Cable damage by over tensioning, compression, unwanted cable formations (loop, snaking…)	• Weather forecast studies • Limit installation to suitable sea state		C3			B3	Optimal tension; about 20*cable dry weight, tension below 2-300 kg may cause snaking and loops
			Fatigue of lead sheath and consequently water ingress during jointing or prolonged standby for weather change	• Weather forecast studies • Limit installation to suitable sea state • Limit ship movement and duration exceeding allowable parameters		C3			B3	Observe the movement/angle change in cable, cut cable if damaged. Use testing results, experience and historic data to set the limit of what a cable can handle.
			injury/ fatality of personnel during transportations and use of tug boats	• Weather forecast studies • Limit transfer and tug boat operations to time with suitable sea state	C3					
			Loss workboat's stability	• Weather forecast studies • Limit installation to suitable sea state. • Limit ship movement and duration exceeding allowable parameters.	C3	C3			C3	
3.3	Resonance	Encounter frequencies of the waves gets close to the vessel's natural frequency in given motion of freedom	Peak vessel motions which can lead to overloading and damaging the cable or equipment, loss of vessel stability	• Alter course or vessel speed	C3	C3			C3	
		shedding frequency of current vortices gets close to the natural frequency of the cable	cable damage, cable fatigue	• Proper protection of the cable		C3			B3	
	Freezing temperatures (<0°C)	Cold climate, weather change	Icing on vessel and equipment, damage to cable, weakening of cable structure			B3			B3	
3.4	Strong current	-	Current impact moves cable TD out of path, TD not on planned route	• Gather current data for location • Use of ROV • Adjust vessel direction		B2			B2	
			Cable breakage; Current impact moves cable floating on buoyancy elements off track	• Limit cable movements; tug boats holding cable back and assure MBR		B2			B2	
3.5	Storm, rain, adverse weather	-	Low visibility, possibility of vessel collision	• Proper weather forecast • Limit installation to suitable weather	B3	B3			B3	
			Bad sea state: increased risk of injury/ fatality of personnel during transportations and use of tug boats	• Weather forecast studies • Limit transfer • Limit tug boat operations to time with suitable sea state	B4	B4			B4	
3.6	Lightning	-	Lightning in CLV, injury/fatality of personnel	• Lightning arrestors	B4	B4			B4	
3.7	Erosion, unstable seabed, mudslide, sand waves	Mobile sediments, currents, waves	Cable suspensions, VIV in cable suspension	• Route survey • cable protection		B4				Avoid unstable areas if possible
3.8	Rocks, boulders	-	Cable suspensions, VIV in cable suspension	• Limit cable-rock interaction • route survey • route preparation • cable protection		B4				

3.9	Sediments, muddy seabed	-	Loss of sight for ROV; loss of control	• Wait for seabed to settle					B3	
3.10	Unexpected soil conditions	Inadequate survey specification or results	Delays, re-engineering of cable route	• Extensive geophysical / geotechnical investigations • Planning with contingencies					B3	
3.11	Scour at offshore unit	Seabed movement	Cable exposed, Cable suspensions, VIV in cable suspension	• Detailed analysis of site conditions • Proper cable protection • Inspections		B4				
3.12	Natural catastrophe	-	Cable exposure, cable fault	• Detailed analysis of site conditions • Reliable design • Site monitoring		B4				

Category 4: Human factor & Third-party

Hazard number	Hazardous event	Possible causes	Potential threats	Control/ barriers	Health & Safety	Cable & assets	Enviro -nment	Reput-ation	Project	Additional controls / Recommendations:
4.1	Fishing equipment	Fishing in restricted area	Cable damage	• Analysis and cable routing • Burial / protection of cable • Cable awareness charts • Exclusion zones • Vessel movement monitoring • Fishermen liaison • Notice to Mariners		B4				
4.2	Anchor impact (drop, drag)	Vessel traffic, emergency situation	Cable damage	• Analysis and cable routing • Appropriate burial / protection of cable • Cable awareness charts • Vessel movement monitoring		B4				Cross shipping-lanes at shortest distance, avoid crossing if possible, inform about cable location
4.3	Dredging incident	Dredging in proximity of cable	Cable damage	• Cable route selection • Accurate charting		B3				
4.4	Cable impact by diverse structures	Structures placed, dumped at seabed	Cable damage	• Thorough route survey • cable protection		B3				Create distance between cable and known structures, stay clear safety zones of gas and oil installations
4.5	Local population	-	Conflict with local population; disturbance of daily life/ local events	• Planning and cooperating with local community					B3	Cooperate to avoid disturbance of yearly events/festivals
4.6	Operator error	Inexperience, lack of training, mistakes	Inproper handling of equipment, cable damage	• Awareness • communication • training		B3			B3	
4.7	Loss of communication to vessel, offshore unit or shore	Equipment fault, loss of power	Escalation potential	• Equipment backup • Equipment maintenance	B2	B2			B2	

Category 5: CLV equipment

Hazard number	Hazardous event	Possible causes	Potential threats	Control/ barriers	Health & Safety	Cable & assets	Enviro -nment	Reput-ation	Project	Additional controls / Recommendations:
5.1	handling equipment	overstressing handling equipment, forces due to unintended manoeuvers and rope positions (loss of steering and rope control), forces associated	Malfunction, danger for personnel, cable damage	• Sufficient training of personnel • safety procedures/ routines • adequate protective equipment	B3	B3			B3	

		with emergency quick release and parting the ropes (intentionally or unintentionally).								
5.2	Turntable	Poor maintenance, overload	Malfunction	• redundancy		B3			B3	Have mechanics on board
		Improper handling	Danger of personnel injury/ fatality	Sufficient training of personnel • safety procedures/ routines • adequate protective equipment	B3	B3			B2	Have mechanics on board
5.3	Tensioners	Improper handling	Danger of personnel injury/ fatality	• Sufficient training of personnel • safety procedures/ routines • adequate protective equipment	B3	B3			B2	Medical assistance on board
		Poor maintenance, overload	Malfunction, cable damage, Overload; not capable of holding cable, uncontrolled cable pay-out	• redundancy • Design with sufficient SF		B3			B3	Have mechanics on board
		high pressure in tensioners	High friction between layers in cable , pull the "skin" off the cable, cable damage	• Proper handling • Understanding of cable specifications • Weather forecast • Load monitoring • Adequate safety distances	B2	B4			B3	More than one tensioner, even out pressure by applying load to longer sections of cable, design with SF
		Too low pressure in tensioners	Local loss of grip on cable	• Proper handling • Understanding of cable specifications • Weather forecast • Load monitoring • Adequate safety distances	B2	B4			B3	
5.4	Stern wheel	Malfunction, improper handling	Danger of personnel injury	• Sufficient training • safety procedures/ routines	B2	B3			B3	Medical assistance on board
5.5	Cranes	Malfunction, improper handling	Failure during lifting, not able to hold load, load falling	• Sufficient training • safety procedures/ routines	B2	B3			B2	Certification by a competent person approximately every 2nd year
5.6	ROV	Malfunction, out of range, poor view	Loss of operation/monitoring	• Regularly testing and inspection of equipment • Assess operation method		B2			B2	Have mechanics on board
5.7	DP-system, thrusters	Malfunction; loss of power	drifting, loss of tension in cable, increased tension in cable, cable damage, collision	• DP2, tugboats and anchors, GPS, echo	B2	B4			B4	Two separate DP systems
5.8	Tugboats	Malfunction; loss of power	Drifiting, collision, loss of support for CLV	• Redundancy					B2	
5.9	Anchors	Loss of grip, snap	Loss of anchor	• Redundancy					B3	
5.10	Jointing equipment/ procedure	Welding, hot-work, gas, improper procedures	Cable damage, damage to personnel, faulty joint, water leakage	• Sufficient training/skills • safety procedures/ routines • adequate safety equipment • NDT (x-ray) before installing cable at sea		B4			B4	
5.11	Chinese finger	slippage of cable	loose cable at seabed	• Methods for retrieving cable		B3			B4	
5.12	Buoyancy elements	Collapse of elements	cable sinking if many elements fail	• Redundancy in buoyancy elements		B3			B4	Examine cause of element failure to determine if it is a natural cause or sabotage
Category 6: Health and safety										
Hazard number	**Hazardous event**	**Possible causes**	**Potential threats**	**Control/ barriers**	**Health & Safety**	**Cable & assets**	**Enviro -nment**	**Reput-ation**	**Project**	**Additional controls / Recommendations:**

6.1	Man overboard	Weather unsuitable for performing operations, substandard work procedures, accident	Injury, fatality	• Training • Adherence to work procedures • Emergency procedures • All personnel must be secured when working in area of risk, use of safety vest	B4				B2	
6.2	Falling objects	Accident, improper handling of equipment/tools	Injury/fatality due to personnel falling or objects/tools falling from height >2m onboard vessel	• All personnel and tools must be secured when working in heights according to regulations	B3				B2	
		Accident, improper handling of equipment/tools, failure of equipment	Objects/tools falling overboard of vessel and damage existing structure at seabed	• All tools/equipment must be secured when working in areas of risk		B2	B2			
6.3	Physical working environment	-	Bad ergonomics, injury, fatality of personnel	• Use of right equipment, lifting mechanisms, working height,	B2					
		Improper safety gear	High noise under normal working conditions over long time	• Hearing protection, earplug, noise cancelling equipment	B2					
6.4	Shift patterns	Delays, heavy seas, improper planning	Irregular working hours, long hours, nights, little rest	• Fixed working schedules • follow regulations for working hours and shift-work	B2					
6.5	Transportation incident (roads, harbour)	Poor weather conditions, poor vehicle maintenance, tiredness	Injury, fatality	• Reduce transportation distances • Use safe work methods • Training	B4					
6.6	Vessel operation in rough sea state	Change of weather	Injury, man overboard, escalation due to moving cargo	• Select capable vessel • Adequate seafastening • Define acceptable weather conditions • Accurate weather forecasting • Follow procedures	B4	B4			B4	
6.7	Vessel collision with other vessel or Offshore unit	Inappropriate procedure/design, weather unsuitable for performing operations, loss of power, lack of navigation aids, human error	Injury, man overboard, fatality	• Suitable design and procedures • Vessel maintenance • Training	B4	B4			B4	
6.8	Inexperienced vessel crew	Limited resources, lack of training	Injury, fatality	• Training • Joint working of senior and junior resources	B3				B2	
6.9	Slips, trips, falls	Slippery or uneven surface, weather unsuitable for performing operations	Injury	• Adequate surface design and maintenance • Use of safe work methods	B2					
6.10	Transfer between vessel and offshore unit	Personnel required on offshore unit	Injury, man overboard, fatality	• Design for minimum number of person transfers • Reduce or eliminate equipment transfers • Work within acceptable weather conditions • Use of PPE	B3					
6.11	Diving operation	Divers required for cable installation or maintenance	Injury, fatality	• Eliminate diving operations • Reduce number of diving operations • Use safe work methods • Emergency plan and facilities	B3					
6.12	Work at height incident	Poor design, substandard work procedures, lack of training	Injury, fatality	• Safe design • Use safe work methods • Work within acceptable weather conditions • Use of PPE	B3					

				• Training						
6.13	Night-time working incident	Poor work planning, insufficient lighting	Injury, fatality	• Preference for daytime working • Good work planning • Adequate lighting	B3					
6.15	High voltage testing incident	Poor design, deviation from procedure	Injury, fatality	• Design for testability • Sound method statement • Qualified personnel	B4				B2	
6.16	Unexploded ordnance (UXO)	Inadequate preinstallation surveys, inadequate distances	Injury, fatality	• Perform adequate surveys • Choose appropriate cable route • Use clearing services if required • Use safe work methods	B4				B2	

Table 18 HAZID study

APPENDIX B – Cable cross-sections and technical specifications

CABLE CROSS-SECTIONS AND TECHNICAL SPECIFICATIONS FOR:

- SUBSEA HVAC EXPORT CABLE A
- SUBSEA HVAC EXPORT CABLE B
- SUBSEA HVAC EXPORT CABLE C

HVAC export cable A

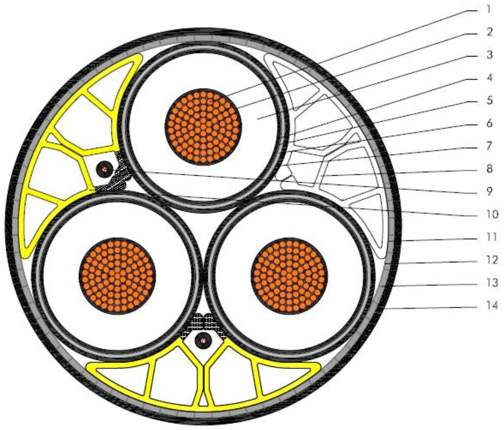

Figure 58 Cross-section – HVAC cable A

ITEM	DESCRIPTION	NOM. THICKNESS (MM)	NOM. DIAMETER(MM)
1	CU CONDUCTOR, WATER BLOCKING COMPOUND	-	-
2	CONDUCTOR SCREEN, SEMICONDUCTING XLPE	-	-
3	INSULATION, XLPE	-	-
4	INSULATION SCREEN, SEMICONDUCTING XLPE	-	-
5	SEMICONDUCTING WATER SWELLABLE TAPE	-	-
6	LEAD SHEATH	-	-
7	SEMICONDUCTING PE SHEATH	-	-
8	FILLER ELEMENT, PE FILLER	-	-
9	FIVRE OPTIC CABLE, 2 OFF	-	-
10	FILLER ELEMENT, PE FILLER SEMICONDUCTING LIP	-	-
11	BINDER TAPE	-	-
12	BEDDING TAPE	-	-
13	ARMOUR, FLAT STEEL GRADE 65, EMBEDDED IN BITUMEN	10.3X3	-
14	OUTER SERVING, PP YARN TWO LAYERS	-	243±3

MASS IN AIR, APPROX.	99 kg/m
SUBMERGED WEIGHT, APPROX.	61 kg/m
MINIMUM BENDING RADIUS (ZERO TENSION)	2.7 m
MAXIMUM PULLING TENSION (ZERO BENDING)	350 kN
AXIAL STIFFNESS (NO ROTATION)	635 MN
BENDING STIFFNESS	See figure xx
TORSION STIFFNESS (COUNTER CLOCKWISE, CLOCKWISE)	(150, 121) kNm^2

Table 19 Cable specifications – HVAC cable A

NO ROTATION	
TENSION [kN]	RADIUS [m]
0.0	2.70
50.0	2.79
100.0	2.90
150.0	3.54
200.0	4.68
250.0	7.05
300.0	12.64
350.0	22.00
400.0	29.90
450.0	500.00

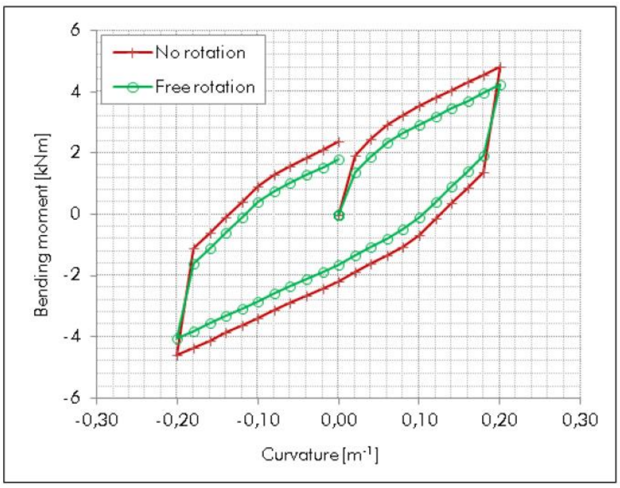

Table 20 Bending moment versus curvature – HVAC cable A

HVAC export cable B

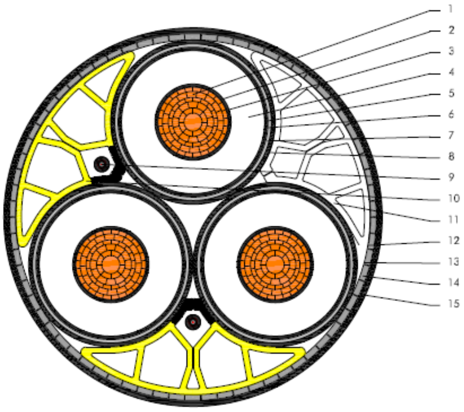

Figure 59 Cross-section: HVAC cable B

ITEM	DESCRIPTION	NOM. THICKNESS (MM)	NOM. DIAMETER(MM)
1	CU PROFILED CONDUCTOR, WATER BLOCKING COMPOUND	-	-
2	SEMICONDUCTING WATER SWELLABLE TAPE	-	-
3	CONDUCTOR SCREEN, SEMICONDUCTING XLPE	-	-
4	INSULATION, XLPE	-	-
5	INSULATION SCREEN, SEMICONDUCTING XLPE	-	-
6	SEMICONDUCTING WATER SWELLABLE TAPE	-	-
7	LEAD SHEATH	-	-
8	SEMICONDUCTING PE SHEATH	-	-
9	FIBRE OPTIC CABLE, 2 OFF	-	-
10	FILLER ELEMENT, PE FILLER SEMICONDUCTING LIP	-	-
11	FILLER ELEMENT, PE FILLER	-	-
12	BINDER TAPE	-	-
13	BEDDING TAPE	-	-
14	ARMOUR, FLAT STEEL GRADE 65, EMBEDDED IN BITUMEN	10.3X3	-
15	OUTER SERVING, PP YARN TWO LAYERS		251±3

MASS IN AIR, APPROX.	113 kg/m
SUBMERGED WEIGHT, APPROX.	72 kg/m
MINIMUM BENDING RADIUS (ZERO TENSION)	2.8 m
MAXIMUM PULLING TENSION (ZERO BENDING)	700 kN
AXIAL STIFFNESS (NO ROTATION)	727 MN
BENDING STIFFNESS	See figure xx
TORSRION STIFFNESS (COUNTER CLOCKWISE, CLOCKWISE)	(180 , 107) kNm2

Table 21 Cable specifications – HVAC cable B

NO ROTATION			
TENSION [kN]	RADIUS [m]	TENSION [kN]	RADIUS [m]
0.0	2.77	550.0	10.74
50.0	2.97	600.0	18.50
100.0	3.15	650.0	22.92
150.0	3.34	700.0	25.25
200.0	3.57	750.0	28.54
250.0	3.80	800.0	32.73
300.0	4.05	850.0	36.10
350.0	4.43	900.0	40.96
400.0	4.96	950.0	48.24
450.0	5.55	1000.0	71.53
500.0	6.93	1050.0	500.0

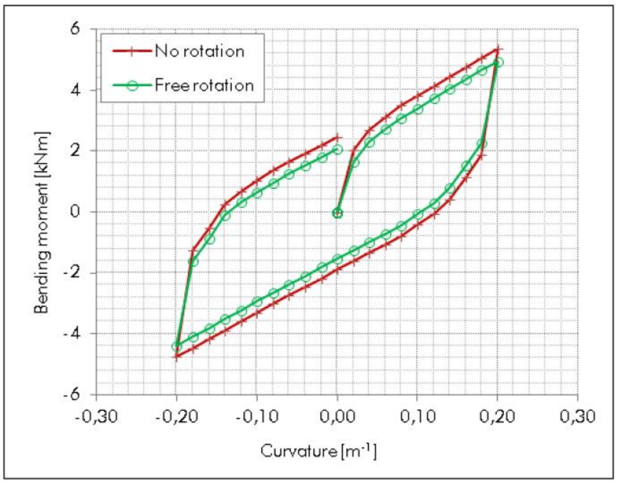

Table 22 bending moment versus curvature – HVAC cable B

HVAC export cable C

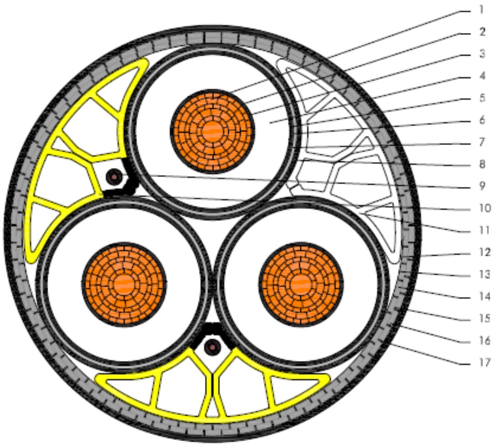

Figure 60 Cross-section: HVAC cable C

ITEM	DESCRIPTION	NOM. THICKNESS (MM)	NOM. DIAMETER(MM)
1	CU PROFILED CONDUCTOR, WATER BLOCKING COMPOUND	-	-
2	SEMICONDUCTING WATER SWELLABLE TAPE	-	-
3	CONDUCTOR SCREEN, SEMICONDUCTING XLPE	-	-
4	INSULATION, XLPE	-	-
5	INSULATION SCREEN, SEMICONDUCTING XLPE	-	-
6	SEMICONDUCTING WATER SWELLABLE TAPE	-	-
7	LEAD SHEATH	-	-
8	SEMICONDUCTING PE SHEATH	-	-
9	FIBRE OPTIC CABLE, 2 OFF	-	-
10	FILLER ELEMENT, PE FILLER SEMICONDUCTING LIP	-	-
11	FILLER ELEMENT, PE FILLER	-	-
12	BINDER TAPE	-	-
13	BEDDING TAPE	-	-
14	ARMOUR, FLAT STEEL GRADE 65, EMBEDDED IN BITUMEN	10.3X3	-
15	TAPE	-	-
16	ARMOUR, FLAT STEEL GRADE 65, EMBEDDED IN BITUMEN	10.3X3	-
17	OUTER SERVING, PP YARN TWO LAYERS	-	263±3

MASS IN AIR, APPROX.	138 kg/m
SUBMERGED WEIGHT, APPROX.	92 kg/m
MINIMUM BENDING RADIUS (ZERO TENSION)	3.3 m
MAXIMUM PULLING TENSION (ZERO BENDING)	1350 kN
AXIAL STIFFNESS (NO ROTATION)*	1122 MN
BENDING STIFFNESS	See figure XX
TORSION STIFFNESS (COUNTER CLOCKWISE, CLOCKWISE)	(308 , 398) kNm^2

Table 23 Cable specifications – HVAC cable C

NO ROTATION & FREE ROTATION -> IDENTICAL			
TENSION [kN]	RADIUS [m]	TENSION [kN]	RADIUS [m]
0.0	3.27	700.0	14.09
50.0	3.45	750.0	22.92
100.0	3.58	800.0	25.01
150.0	3.74	850.0	27.03
200.0	4.04	900.0	29.38
250.0	4.27	950.0	32.14
300.0	4.53	1000.0	35.06
350.0	4.82	1050.0	38.23
400.0	5.15	1100.0	42.52
450.0	5.49	1150.0	49.36
500.0	5.85	1200.0	58.82
550.0	6.27	1250.0	77.23
600.0	6.74	1300.0	115.91
650.0	7.33	1350.0	500.0

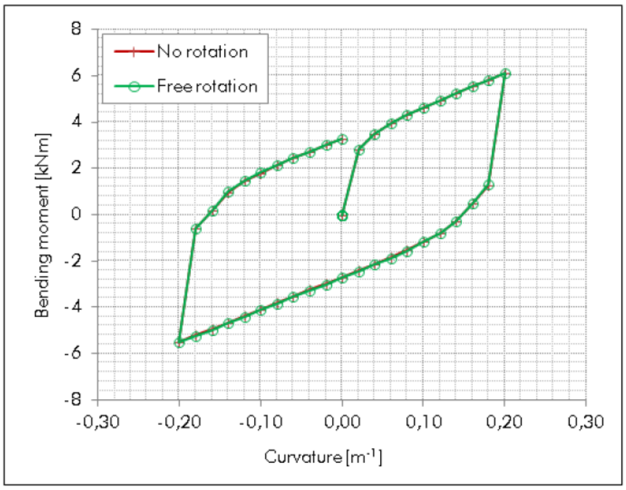

Table 24 Bending moment versus curvature – HVAC cable C

APPENDIX C – OrcaFlex default vessel: Displacement RAOs

CLV displacement RAOs (OrcaFlex default vessel):

→ For headings: 0°, 45°, 90°, 135° & 180°

Displacement RAOs – Direction 0°:

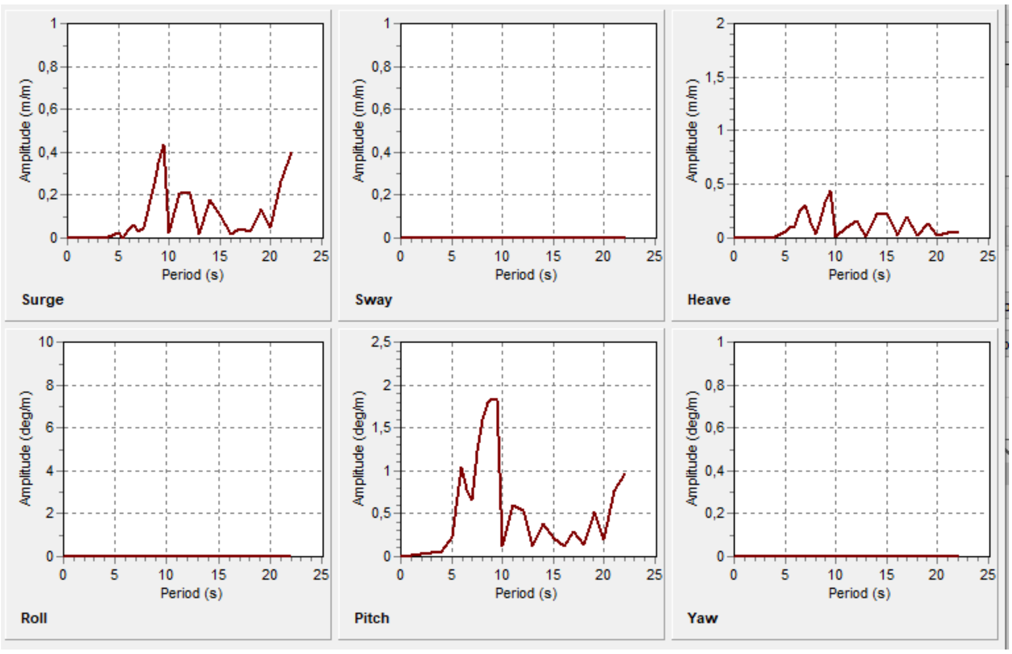

Figure 61 Discplacement RAO - 0°

Displacement RAOs – direction 45°:

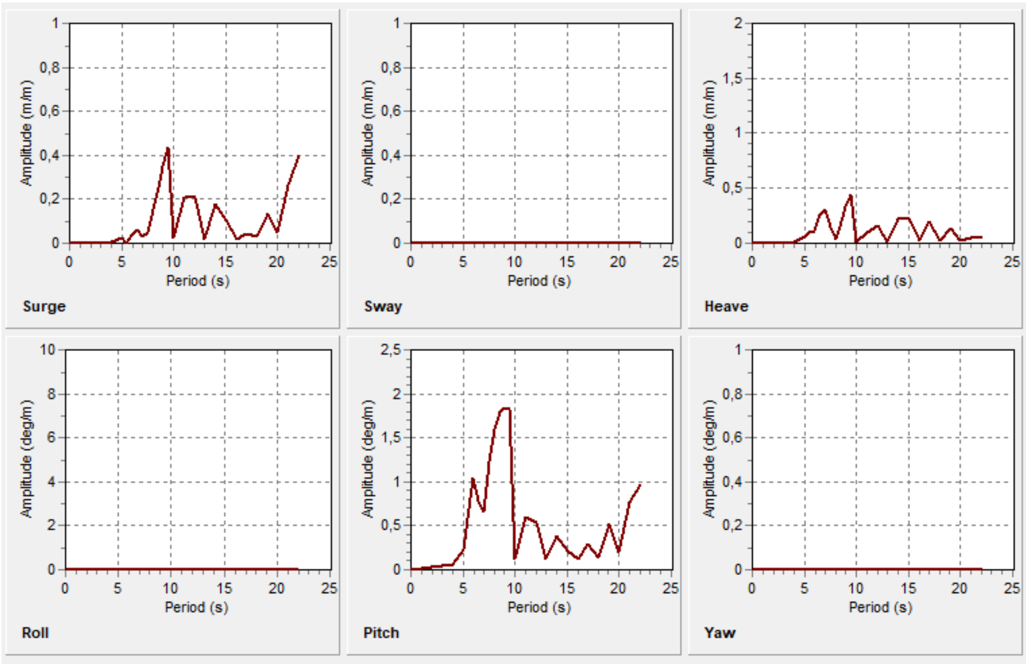

Figure 62 Discplacement RAO - 45°

Displacement RAOs – direction 90°:

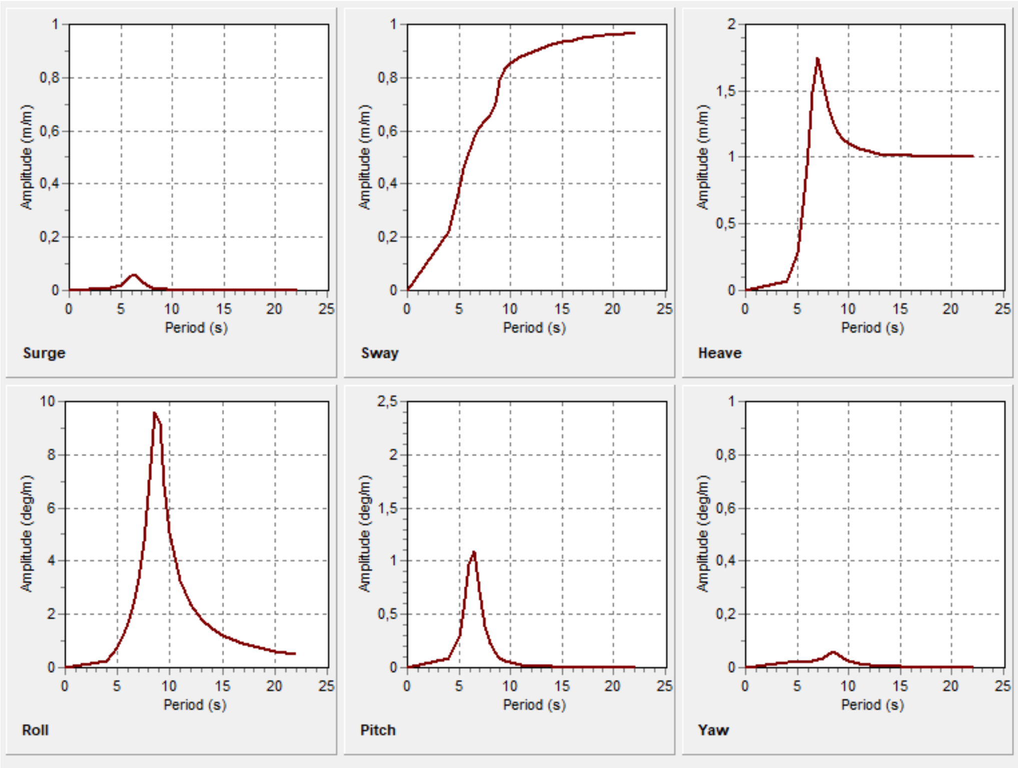

Figure 63 Discplacement RAO - 90°

Displacement RAOs – Direction 135°:

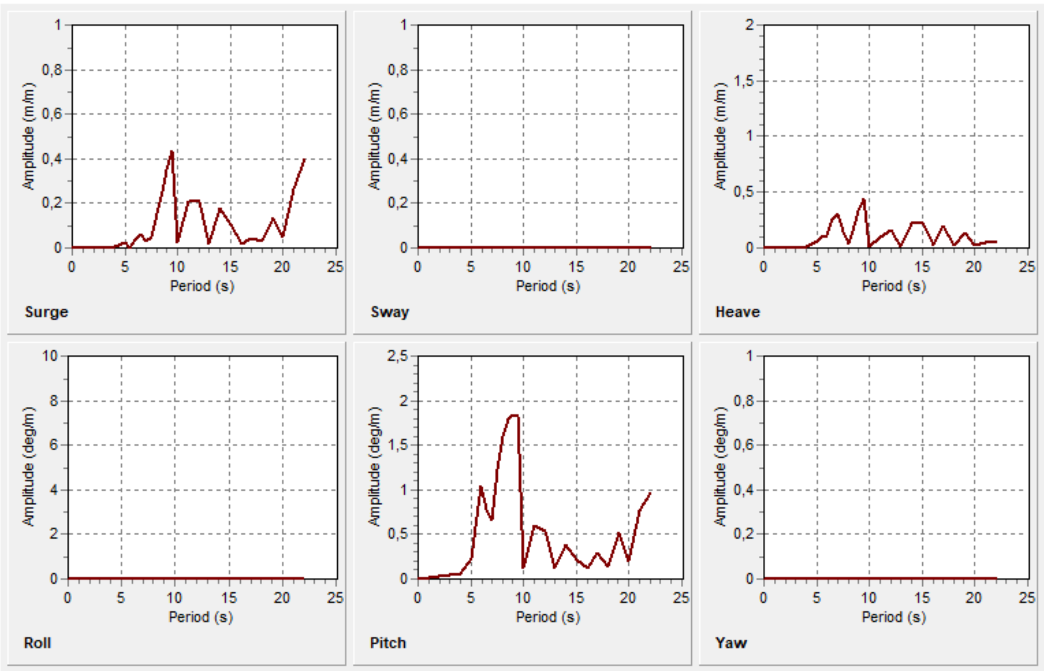

Figure 64 Discplacement RAO - 135°

Displacement RAOs – Direction 180°:

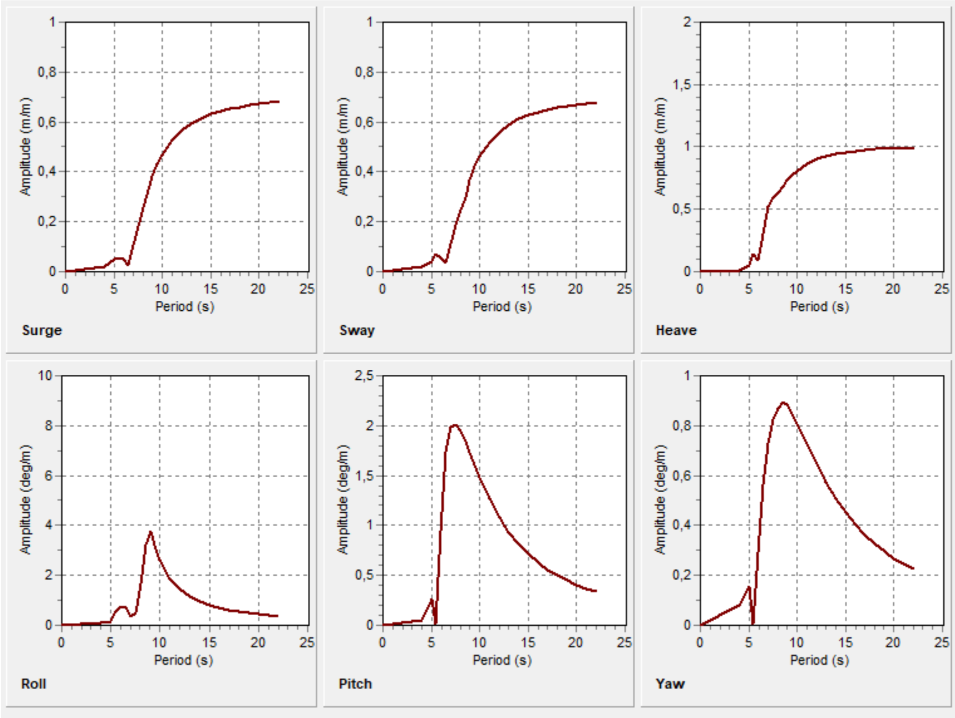

Figure 65 Discplacement RAO - 180°

APPENDIX D – Quasi-static analysis: Effect of currents

Quasi-static analysis

- Effects of currents
  - Current velocities: 0,5, 1,0 & 1,5 [m/s]
  - Current direction: 0, 90 & 180 [Deg.]
  - Three different cable configurations: HVAC export cables A, B & C
  - Zero wave loads
  - Water depth: 30m
  - Deployment method: S-lay - chute

QUASI-STATIC SIMULATION RESULTS – EFFECT OF CURRENT

Following parameters were investigated in the analysis:

- Maximum tension
- Touchdown tension
- Sidewall pressure
- Minimum bending radius
- Cable displacement

* Chute contact angle: LB 1,5 x wd = 57,30°. Giving following limit for top tension according to the Capstan effect: LB 1,5=145,77kN

CABLE CONFIGURATION: HVAC CABLE A
Static top tension (no current): 44,1 kN

Current direction [°]	Current speed [m/s]:	Layback max [m]:	Layback Min [m]:	TDP Offset Max [m]: (X-axis)	Offset Max [m]: (Y-axis)	Tension Max [kN]:	U.F	MBR [m]:	U.F	SWP [kN/m]:	U.F
Limits						146*	1,00	See appx. B	1,00	42,7	1,00
0	0,5	45,1	45	$2{,}56*10^{-3}$	0,10	44,32	0,30	5,07	0,55	8,74	0,21
90	0,5	45	45	0,02	0,40	43,71	0,30	5,09	0,55	8,59	0,20
180	0,5	45	44,9	$1{,}67*10^{-3}$	0,10	43,68	0,30	5,09	0,55	8,58	0,20
0	1	46	45	$2{,}56*10^{-3}$	0,10	46,33	0,32	5,07	0,55	9,14	0,21
90	1	45,5	45	0,39	1,74	47,18	0,32	5,05	0,55	9,34	0,22
180	1	45	44,5	$1{,}67*10^{-3}$	0,10	43,68	0,30	5,09	0,55	8,58	0,20
0	1,5	47,5	45	$2{,}56*10^{-3}$	0,10	48,98	0,34	5,05	0,55	9,7	0,23
90	1,5	48,1	45	1,73	4,10	46,64	0,32	4,94	0,57	9,44	0,22
180	1,5	45	43,5	$1{,}67*10^{-3}$	0,10	43,68	0,30	5,09	0,55	8,58	0,20

CABLE CONFIGURATION: HVAC CABLE B
Static top tension (no current): 51,4 kN

Current direction [°]	Current speed [m/s]:	Layback max [m]:	Layback Min [m]:	TDP Offset Max [m]: (X-axis)	Offset Max [m]: (Y-axis)	Tension Max [kN]:	U.F	MBR [m]:	U.F	SWP [kN/m]:	U.F
Limits						*	1,00	See appx. B	1,00	81,1	1,00
0	0,5	45,5	45	$2{,}14*10^{-3}$	0,09	51,65	0,35	5,1	0,62	10,13	0,13
90	0,5	45	45	0,06	0,41	51,04	0,35	5,08	0,62	10,05	0,12
180	0,5	45	45	$2{,}98*10^{-3}$	0,09	50,98	0,35	5,08	0,62	10,04	0,12
0	1	46	45	$3{,}19*10^{-3}$	0,09	53,55	0,37	5,09	0,62	10,52	0,13
90	1	45,5	45	0,40	1,68	51,41	0,35	5,06	0,62	10,16	0,13
180	1	45	44,4	$2{,}1*10^{-3}$	0,09	50,98	0,35	5,09	0,62	10,02	0,12
0	1,5	47	45	$4{,}59*10^{-3}$	0,09	56,67	0,39	5,08	0,62	11,16	0,13
90	1,5	47,6	45	1,86	4,09	58,52	0,40	5,06	0,62	11,57	0,13
180	1,5	45	43	$2{,}19*10^{-3}$	0,09	50,98	0,35	5,08	0,62	10,04	0,12

CABLE CONFIGURATION: HVAC CABLE C
Static top tension (no current): 64,5 kN

Current direction [°]	Current speed [m/s]:	Layback max [m]:	Layback Min [m]:	TDP Offset Max [m]: (X-axis)	Offset Max [m]: (Y-axis)	Tension Max [kN]:	U.F	MBR [m]:	U.F	SWP [kN/m]:	U.F
Limits						*	1,00	See appx. B	1,00	89	1,00
0	0,5	45,5	45	$1{,}52*10^{-3}$	0,08	65,84	0,45	5,15	0,70	12,78	0,14
90	0,5	45	45	0,04	0,4	65,37	0,45	5,10	0,70	12,82	0,14
180	0,5	45	45	$1{,}47*10^{-3}$	0,08	65,35	0,45	5,10	0,70	12,81	0,14
0	1	46	45	$2{,}26*10^{-3}$	0,08	68,21	0,47	5,09	0,70	13,40	0,15
90	1	45,5	45	0,09	1,29	67,45	0,46	5,08	0,71	12,93	0,15
180	1	45	44,5	$1{,}47*10^{-3}$	0,08	65,23	0,45	5,10	0,70	12,79	0,14
0	1,5	47	45	$3{,}37*10^{-3}$	0,08	71,54	0,49	5,06	0,71	14,14	0,16
90	1,5	47	45	1,17	3,13	74,65	0,51	5,00	0,72	13,49	0,15
180	1,5	45	43,5	$1{,}46*10^{-3}$	0,08	64,35	0,44	5,10	0,70	12,62	0,14

Table 25 Quasi static simulation results – effect of currents

APPENDIX E – Dynamic simulation result: Scenario 1 & 2

Dynamic simulation results

- Scenario 1
  - Wave load (JONSWAP)
  - Three different cable configurations: HVAC cable A-C
  - Water depths: 30, 60, 100 (m)
  - Four different layback lengths (0,5 x wd, 1,0 x wd, 1,5 x wd & 2,0 x wd)
- Scenario 2
  - Wave load (JONSWAP)
  - Three different cable deployment methods: S-lay (chute), J-lay (Mid-starboard side & moonpool)
  - Current velocity: 1m/s
  - Five different wave heading; 0°, 45°, 90°, 135° & 180°
  - Significant wave heights: 2, 3 & 4 (m)
  - Wave periods: 1-10 (s)
  - Water depth: 100m

DYNAMIC SIMULATION RESULTS – SCENARIO 1

Following parameters were investigated in the analysis:

- Layback changes
- Maximum tension [kN]
- Touchdown tension
- Sidewall pressure
- Minimum bending radius

Maximum tension criteria of tensioner [kN]:	
	U.F </= 0,5
	0,5 < U.F >/= 0,7
	0,7 < U.F >/= 0,9
	0,9 < U.F > 1,0
	U.F>/= 1,0

Table 26 tension criteria, scenario 1

* Chute contact angle: LB 0,5 x wd=80,21°, LB 1 x wd=68,76, LB 1,5 x wd= 57,30 & LB 2 x wd= 51,57. Giving following limits for top tension according to the Capstan effect [kN]: LB 0,5=185,31, LB 1=164,35, LB 1,5=145,77 & LB 2=137,28

CABLE CONFIGURATION: HVAC CABLE A

Set Layback [m]	Water depth [m]:	Layback max [m]:	Layback Min [m]:	Compression [kN]	TopTension Max [kN]:	U.F	Tensioner [kN]:	MBR [m]:	U.F	MBR TDP [m]:	SWP [kN/m]:	U.F
Limits					*	1,00	80,0	See appx. B	1,00	See appx. B	42,7	1,00
0,5 x wd	30	16,0	14,0	-	25,90	0,14	11,18	5,08	0,18	6,58	5,10	0,12
1 x wd	30	31,0	29,5	-	34,73	0,21	16,91	5,08	0,18	15,71	6,84	0,16
1,5 x wd	30	46,5	43,5	-	46,63	0,32	25,60	5,07	0,18	29,7	9,20	0,22
2 x wd	30	61,5	58,5	-	64,15	0,47	37,38	5,08	0,25	50,74	12,63	0,30
0,5 x wd	60	32,5	29,0	-	53,37	0,29	23,04	5,06	0,26	11,52	10,55	0,25
1 x wd	60	62,0	57,0	-	74,78	0,46	36,40	5,04	0,26	29,32	14,84	0,35
1,5 x wd	60	93,0	87,0	-	93,73	0,64	51,44	5,09	0,25	57,58	18,42	0,43
2 x wd	60	122	118	-	128,47	0,94	74,87	5,09	0,56	100,27	25,24	0,59
0,5 x wd	100	51,5	48,5	-	90,16	0,49	38,92	5,08	0,25	18,30	17,75	0,42
1 x wd	100	101,0	98,0	-	109,38	0,67	53,24	5,09	0,56	49,96	21,49	0,50
1,5 x wd	100	102	96	-	152,89	1,05	83,91	5,10	0,91	100,65	29,97	0,70
2 x wd	100	103	97	-	215,65	1,57	125,67	5,10	1,28	173,45	42,28	0,99

CABLE CONFIGURATION: HVAC CABLE B

Set Layback [m]	Water depth [m]:	Layback max [m]:	Layback Min [m]:	Compression [kN]	TopTension Max [kN]:	U.F	Tensioner [kN]:	MBR chute min [m]:	U.F	MBR TDP min [m]:	SWP [kN/m]:	U.F
Limits					*	1,00	80,0	See appx. B	1,00	See appx. B	81,1	1,00
0,5 x wd	30	16,0	14,5	-	29,92	0,16	12,92	5,06	0,30	7,05	5,91	0,07
1 x wd	30	31,0	29,0	-	40,35	0,25	19,64	5,07	0,29	18,52	7,96	0,10
1,5 x wd	30	46,5	43,5	-	54,40	0,37	29,86	5,07	0,39	30,21	10,73	0,13
2 x wd	30	61,5	58,5	-	74,51	0,54	43,42	5,08	0,39	51,14	14,67	0,18
0,5 x wd	60	32,5	29,5	-	64,22	0,35	27,72	5,09	0,38	10,88	12,62	0,16
1 x wd	60	62,0	57,0	-	80,91	0,49	39,38	5,09	0,38	28,23	15,90	0,20
1,5 x wd	60	93,0	87,0	-	109,35	0,75	60,01	5,10	0,47	58,98	21,48	0,26
2 x wd	60	122	118	-	150,71	1,10	87,83	5,09	0,57	101,26	29,61	0,37
0,5 x wd	100	51,0	48,5	-	100,30	0,54	43,30	5,09	0,48	17,83	19,71	0,24
1 x wd	100	102	98	-	127,13	0,77	61,88	5,09	0,48	50,69	24,98	0,31
1,5 x wd	100	102	96	-	178,82	1,23	98,14	5,10	0,57	99,82	35,06	0,43
2 x wd	100	103	97	-	251,53	1,83	146,58	5,10	0,74	175,86	49,32	0,61

CABLE CONFIGURATION: HVAC CABLE C

Set Layback [m]	Water depth [m]:	Layback max [m]:	Layback Min [m]:	Compression [kN]	TopTension Max [kN]:	U.F	Tensioner [kN]:	MBR min [m]:	U.F	MBR TDP min [m]:	SWP [kN/m]:	U.F
Limits					*	1,00	80,0	See appx. B	1,00	See appx. B	89,0	1,00
0,5 x wd	30	15,5	14,5	-	38,30	0,21	16,54	5,05	0,54	6,42	7,58	0,09
1 x wd	30	31,0	29,0	-	50,88	0,31	24,77	5,06	0,59	15,84	10,06	0,11
1,5 x wd	30	46,5	43,5	-	69,14	0,47	37,95	5,08	0,58	30,82	13,61	0,15
2 x wd	30	61,5	58,5	-	94,38	0,69	55,00	5,09	0,58	51,19	18,54	0,21
0,5 x wd	60	32,5	29,5	-	80,69	0,44	34,84	5,08	0,58	11,63	15,88	0,18
1 x wd	60	63,0	58,0	-	112,20	0,68	54,61	5,11	0,63	30,65	21,96	0,25
1,5 x wd	60	92,0	88,0	-	139,00	0,95	76,29	5,11	0,63	60,24	27,15	0,31
2 x wd	60	122,0	118,0	-	191,33	1,39	111,50	5,07	0,75	107,7	37,74	0,42
0,5 x wd	100	101,0	98,5	-	137,58	0,74	59,40	5,08	0,64	18,65	27,08	0,30
1 x wd	100	101	98	-	161,95	0,99	78,83	5,09	0,74	51,75	31,82	0,36
1,5 x wd	100	102	96	-	228,54	1,57	125,43	5,10	0,81	100,40	44,81	0,50
2 x wd	100	103	97	-	316,22	2,30	184,28	5,10	0,94	173,52	62,00	0,70

Table 27 Dynamic simulation results – scenario 1

DYNAMIC SIMULATION RESULTS – SCENARIO 2

Following parameters were investigated in the analysis:

- Layback changes
- Maximum tension [kN]
- Touchdown tension
- Sidewall pressure
- Minimum bending radius

Top tension categorization	
Maximum tension criteria: 148 kN	
	U.F </= 0,5
	0,5 < U.F </= 0,6
	0,6 < U.F </= 0,7
	0,7 < U.F </= 0,8
	0,8 < U.F </= 0,9
	0,9 < U.F >1,0
	U.F =/> 1,0

Table 28 tension limit - scenario 2

For other limits found compromised, following description can be added to the results: C= compression limit, B= tension & bending relation limit (breaking limit)

DYNAMIC SIMULATION RESULTS

Deployment method: S-Lay with chute

→ For wave and current encounters in direction 0°, 45°, 90°, 135°, 180°

Maximum tension - 0°			
Wave period [s]			
10			
9			
8			
7			
6			
5			
4			
3			
2			
1	*C	*C, B	*C, B
	2	3	4
	Significant wave height Hs [m]		

Maximum tension - 45°			
Wave period [s]			
10			
9			*C
8			*C
7			*C
6			
5			
4			
3			
2			*C
1	*C	*C, B	*C, B
	2	3	4
	Significant wave height Hs [m]		

Maximum tension - 90°			
Wave period [s]			
10			
9			
8			*C
7			*C
6			
5			
4			
3			
2		*C	*C
1	*C	*C, B	*C, B
	2	3	4
	Significant wave height Hs [m]		

Maximum tension - 135°			
Wave period [s]			
10			*C
9		*C	*C
8			*C
7			*C
6			
5			
4			
3			
2			
1			*C
	2	3	4
	Significant wave height Hs [m]		

Maximum tension - 180°			
Wave period [s]			
10		*C	*C
9		*C	*C
8		*C	*C, B
7		*C	*C
6			*C
5		*C	
4			
3			
2			*C
1	*C	*C	*C, B
	2	3	4
	Significant wave height Hs [m]		

Table 29 Dynamic results - scenario 2 - S-lay

DYNAMIC SIMULATION RESULTS

Deployment method: J-Lay - Mid-Starboard side

→ For wave and current encounters in direction 0°, 45°, 90°, 135°, 180°

Maximum tension - 0°

Wave period [s]	2	3	4
10			
9			
8			
7			
6			
5			*C
4			*C
3			*C
2		*C	*C
1	*C	*C	*C
	Significant wave height Hs [m]		

Maximum tension - 45°

Wave period [s]	2	3	4
10			
9			
8			
7			
6			
5			
4			*C
3		*C	*C
2	*C	*C	*C
1	*C	*C	*C, B
	Significant wave height Hs [m]		

Maximum tension - 90°

Wave period [s]	2	3	4
10		*C	*C
9		*C	*C
8		*C	*C, B
7		*C	*C, B
6			*C
5			
4			
3			*C
2		*C	*C
1	*C, B	*C, B	*C, B
	Significant wave height Hs [m]		

Maximum tension - 135°

Wave period [s]	2	3	4
10			
9			
8			
7			
6			
5			
4			
3		*C	*C
2		*C	*C
1	*C	*C	*C
	Significant wave height Hs [m]		

Maximum tension - 180°

Wave period [s]	2	3	4
10			
9			
8			
7			
6			
5			
4			
3			*C
2		*C	*C
1	*C	*C	*C
	Significant wave height Hs [m]		

Table 30 dynamic simulation results - scenario 2 - J-lay mid-starboard side

DYNAMIC SIMULATION RESULTS

Deployment method – J-Lay: Moonpool

→ For wave and current encounters in direction 0°, 45°, 90°, 135°, 180°

Maximum tension - 0°				
Wave period [s]	10			
	9			
	8			
	7			
	6			
	5			
	4			
	3			
	2			
	1			
		2	3	4
		Significant wave height Hs [m]		

Maximum tension - 45°				
Wave period [s]	10			
	9			
	8			
	7			
	6			
	5			
	4			
	3			
	2			
	1			
		2	3	4
		Significant wave height Hs [m]		

Maximum tension - 90°				
Wave period [s]	10			
	9			
	8			
	7			
	6			
	5			
	4			
	3			
	2			*C
	1	*C	*C, B	*C, B
		2	3	4
		Significant wave height Hs [m]		

Maximum tension - 135°				
Wave period [s]	10			
	9			
	8			
	7			
	6			
	5			
	4			
	3			
	2			
	1			
		2	3	4
		Significant wave height Hs [m]		

Maximum tension - 180°				
Wave period [s]	10			
	9			
	8			
	7			
	6			
	5			
	4			
	3			
	2			
	1			
		2	3	4
		Significant wave height Hs [m]		

Table 31 dynamic simulation results - scenario 2 - j-lay moonpool