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Simulation of peak tension loads in Subsea power cables during installation

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Abstract. At present, most of the insurance claims in the offshore wind industry are due to cable failures where a large percentage occurs during the installation of the array and export cables. As the reliability of the cables depends on the location and installation method, it is important to map the risks involved, which can compromise the cable's integrity in individual projects. This paper presents sensitivity analyses conducted on crucial parameters in the cable laying process, with an objective of successful installation of subsea power cables without any damages to the cable. The analyses focus on the peak tension loads with reference to key parameters as cable self-weight and laying geometry, as well as the cable deployment position on the installation vessel. Finite element analyses were conducted with both static forces and dynamic forces for irregular vessel motions, by the aid of the well-tested software OrcaFlex.

1. Introduction

A current matter of discussion 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 [1]. The impact of these cables failing is significant. Regarding finances, the cost for locating and replacing a section of damaged subsea cable can vary from £0.6-1.2 million [2]. Additionally, comes the loss in revenue as the damaged cable no longer transmits 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 installation phase of the cable, there are many factors present that challenge the integrity of the cable. In order 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 to a large degree influenced by its cable protection system and the 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). The laying parameters including minimum bend radius, minimum layback and maximum lay tension, needs to be part of the cable's limits and the limitations shall be maintained during the whole process [3, 4].

Tension forces on subsea cables during laying operations have been a topic amongst researchers for many years [5-14]. The maximum tension force must be calculated and analysed in advance and during laying to avoid less favourable operation situations. Investigating the crucial parameters that inflict top tension on the cable could obtain knowledge on how to complete the cable-lay operation without damaging the cable protective system and thereby cause failure of the cable.

2. The power cable grid and structure

Offshore wind farms may include different layouts, but in general a wind farm 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 [15]. In larger offshore parks the wind turbines are connected to an offshore platform (substation), which has the purpose of transforming the energy by increasing the voltage, before export cables transports the energy further. For export cables, it is mostly common to see HVAC (High Voltage Alternating Current) three-phase cables. HVDC (High Voltage Direct Current) 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 AC to DC [16].

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 dominating the cable network within offshore wind farms as the power generation is generated with alternative current [16].

A cable is basically an assembly consisting of a power core(s) with individual/common screen and sheath, assembly fillings, armour, and an 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 a convertor is needed, cable route, installation method and cable protection method. The majority of high voltage cables are individually designed for each single project [3].
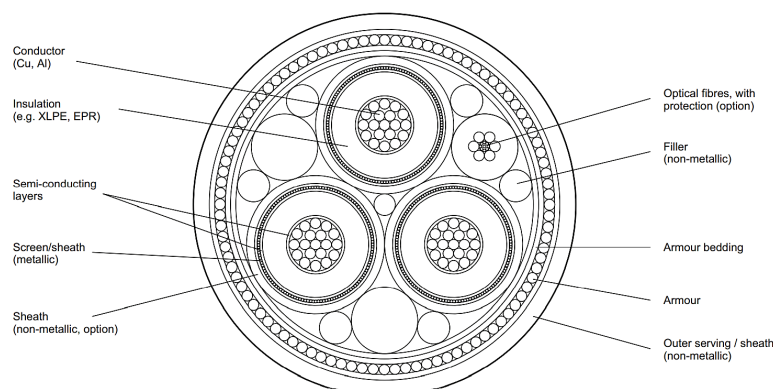
Figure 1. Typical 3-phase AC subsea power cable cross-section [3].

The armour of a cable has the task of providing the majority of the cable's own protection against the environmental 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 [16]. 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 is needed, i.e., in locations where there is a high risk of crush damage and hostile seabed interventions [15].

On top of the armour wires is another protective layer, the outer serving. This layer presents first-hand protection of the cable during all handling. 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 on 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 cable laying vessel (CLV). While the extruded servings, on the other hand, are more slippery [16].

The majority of the subsea cable failures originate 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 [3]. 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 occur at the damaged location, causing degradation of the cable [17].

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 [18]. Axial tension (beyond cable limits) can cause failures such as elongation, compression (bird-caging / buckling), strain and bonding failure between conductor and insulation.

3. Cable laying operations

The laying operation of a subsea power cable 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 include vessel speed, layback length, bend radius, departure angle and the tensioner's speed / pressure. These variables are affected by water depth, wave forces, current forces on the cable, and vessel motion in six degrees of freedom.[3] 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 vessel speed and tensioner pay-out velocity need 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 damaged. On the other side, too low tension might cause the cable to compress at Touch Down Point (TDP), bend excessively or fall uncontrollably to the seafloor [16, 17]. The tensioner's pull and pay-out speed can be controlled on the CLV. While an ROV (Remotely Operated Vehicle) can monitor the cable as it is being placed on the seafloor. The ROVs are equipped with cameras and positioning devices, 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 [16].
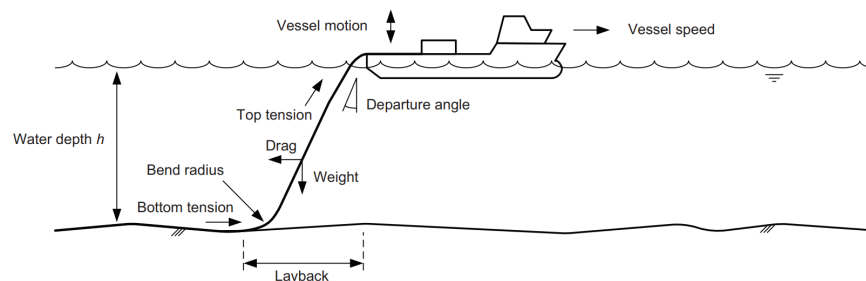
Figure 2. Main parameters in a cable laying process [3].

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 [16]. The main methods for deployment of a subsea cable include: S-lay with a chute/stinger and J-lay over the side of the vessel or 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 or larger than the MBR (Minimum Bend Radius) of the cable. With the J-lay method, the cable is deployed almost vertically down to the seabed, allowing it to have shorter layback lengths. The largest difference between these methods are the bending shapes of the cable as its being deployed, from the placement of the tensioner to the seabed. S-lay will have a bend over the chute and a bend at TDP (giving the S shape). J-lay will have no bending of the cable at the top after the tensioner and only a bend at TDP (forming a J-shape) [19].

Figure 3. Deployment methods: S-lay and J-lay [19].

4. Catenary equations

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, disregard of current and wave forces, continuous homogenous material and zero elastic elongation [20].

In order to find the necessary tension of the cable, the following equation (5) 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 cable's own weight, the gravity force and the horizontal force at the bottom from the anchoring of the cable. Eliminating the horizontal force while the cable is hanging straight down, giving the 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 a horizontal tension force is added at the top [21]. The main parameters of the catenary equations are illustrated in Figure 4 below.

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)
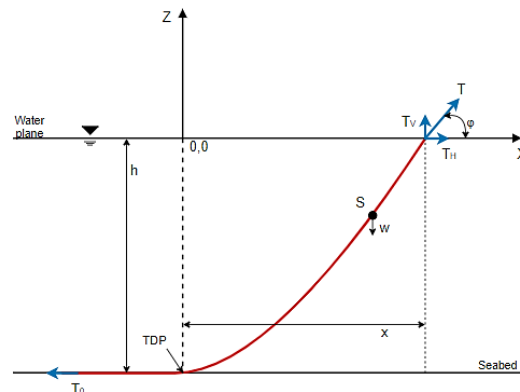φ [-]: orientation of cable element with the horizontal

Figure 4. Catenary parameters [20].

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, the following equation can be used according to given assumptions.[20]:

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

To measure the cable's layback length:

$$x = \frac{T_H}{w}\,arccosh\left[\frac{hw}{T_H} + 1\right] \tag{2}$$

The arc length of the cable can be derived from:

$$s = \frac{T_H}{w}\sinh\left(\frac{wx}{T_H}\right) \tag{3}$$

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

$$T = T_H + w(h + z) \qquad (4)$$

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 [16].

5. Modelling of cable lay scenarios

Static and dynamic models were created in the software OrcaFlex 11.0f. The full 3D non-linear time domain finite element program can calculate the dynamic response of a system based on several user defined conditions. During 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 [22]. The modelled scenarios in this paper are based on the corresponding author's master thesis [23].

5.1. Scenarios and sensitivity analysis

The main objective of the sensitivity analysis performed is to seek information about the restrictions of a subsea HVAC cable's armour and outer layer, considering tension load. Allowable tension must be within the range $x_{min} - x_{max}$ kN to avoid damaging the cable by exceeding its mechanical limitations. At the same time, the tension should be kept well under the selected tensioner's limits. The analyses seek to reveal some of the parameters that affect the increase and decrease of tension, with the emphasis on maximum tension in the cable. The focus is on an export cable installation scheme, which is further divided into three scenarios:
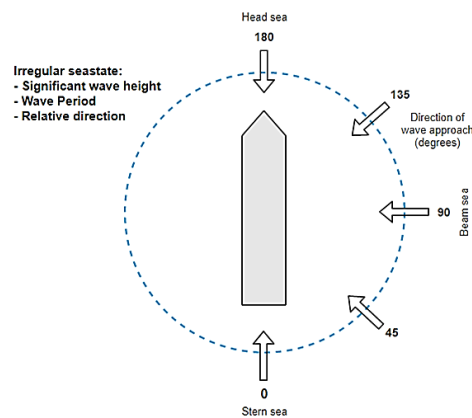
1. Cable lay with alternative cable weights; by analysis of three subsea HVAC cables configurations in static seas (no waves) by use of Orcaflex with comparison of the catenary equations.
2. Cable lay with alternative bending stiffness configurations with forced vessel motions.
3. Cable lay with irregular vessel motion (JONSWAP wave spectrum) with three alternating deployment positions: over stern starboard chute, midships through a moonpool and to the vessel's amidships external starboard side.

The sensitivity analysis is conducted as a series of analyses, where one parameter is altered at the time, with a minimum of three variations of the same parameter. A sensitivity test is normally used to identify which independent variables can have big individual influence on a dependent variable. This type of analysis is an important tool to incorporate in various steps of an installation analysis, including evaluation of operational method and analysis method. A cable installation analysis normally seeks to define the dynamic and static loads involved in the various phases of the operation, as well as to determine operable weather conditions. 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 [16]. Here, a sensitivity analysis can achieve higher validity of the installation analysis performed and operational method can be optimized by knowledge and identification of crucial parameters.

A matrix containing the key parameters was developed for each of the three scenarios (Table 1 and 2).

Table 1. Key parameters for scenario 1 & 2.

Key parameters	Scenario 1	Scenario 2
Vessel	(Head sea)	(Head sea)
- Relative heading [deg.]	180	180
Cable (Properties see section 5.3)		
- Weight [kg/m]	100	100
	120	-
	140	-
Axial stiffness [MN]	600	600
Bending stiffness (section 5.3)	Hysteresis	Hysteresis
	-	Non-linear
	-	Constant
- Deployment speed [m/s]	0	0
- Deployment position	Stern chute	Stern chute
Environment (Airy wave)		
-Water depth [m]	30	30
-Seabed friction Coeff. [-]	0,5	0,5
Layback distance [m]	10, 20, 30	15

Irregular seastate:
- Significant wave height
- Wave Period
- Relative direction

Head sea 180
135
Direction of wave approach (degrees)
Beam sea 90
45
0 Stern sea

Table 2. Key parameters for scenario 3.

Key parameters – Scenario 3					
Vessel	(Head sea)		(Beam sea)		(Stern sea)
- Relative heading [deg.]	180	135	090	045	000
- Deployment speed [kts]	0	0	0	0	0
Cable (Properties see section 5.3)					
- Deployment speed [m/s]	0	0	0	0	0
- Deployment position	Stern chute Moonpool M. Starboard	Stern chute Moonpool M. Starboard	Stern chute Moonpool M. Starboard	Stern chute Moonpool M. Starboard	Stern chute Moonpool M. Starboard
Environment (JONSWAP)					
-Current [ms⁻¹]	0	0	0	0	0
-Significant wave height [m]	3	3	3	3	3
-Wave period [s]	4,5,6…→13	4,5,6…→13	4,5,6…→13	4,5,6…→13	4,5,6…→13
-Water depth [m]	100	100	100	100	100
-Seabed friction Coeff. [-]	0,5	0,5	0,5	0,5	0,5
Layback distance [m]	25	25	25	25	25

5.2. Wave parameters and extreme value analysis

The dynamic simulations in this case are performed with irregular waves by 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 and describes 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 [21, 24].

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 [21]. With operability often being defined as a 3-hour operable sea state [24], performing simulations of this length 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 for 20 random seeds (equal seeds for each deployment method). From this sequence, the point in time where the highest waves occur is pointed out and 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 5.
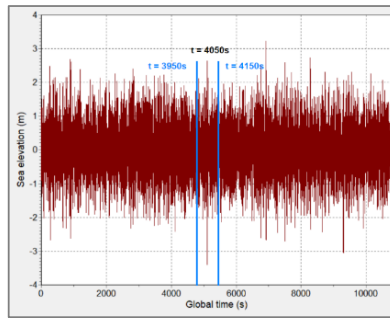
Figure 5. Characterising the Largest Rise and Fall From a 3h period.

5.3. Cable configurations

For the first scenario, three different weights for a HVAC export cable were utilized. Scenario 2 includes three different modelling methods for bending stiffness. While scenario 3 will include the lightest cable with a single bending stiffness configuration. Main specifications are listed in Table 3, see also Figure 6 regarding cable bending stiffness properties.

Table 3. Cable configuration specifications.

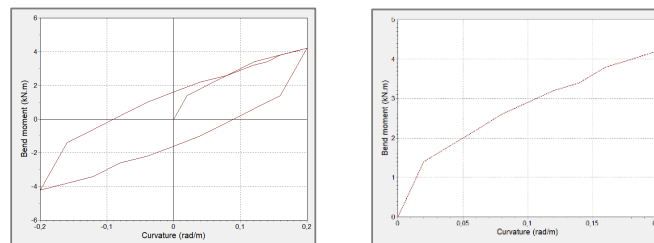| Property	Unit	Value		
		Scenario 1	**Scenario 2**	**Scenario 3**
Overall diameter	mm	243	243	243
Weight in air	kg/m	100, 120, 140	100	100
Axial stiffness (No rotation)	MN	635	635	635
Bending stiffness	kNm^2	Non-linear hysteresis	21.45 Non-linear Non-linear hysteresis	Non-linear hysteresis
Torsion stiffness (clockwise):	kNm^2	121	121	121

Figure 6. Left: Non-linear hysteresis bending stiffness, Right: Non-linear bending stiffness.

5.4. Orcaflex models

The simulations were performed with a modified OrcaFlex default vessel (vessel length 121m). 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 the same / different length. 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 are unique to each vessel. In order to properly assess the effects a sea state will have on a vessel's motion, this unique set of RAOs for the particular vessel should be applied. In this case the assumption was made that the default vessel could be used to reach the objectives of the sensitivity analyses. The scenarios are modelled with a stationary vessel and with no cable being paid out during the simulation. 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. 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.[25] The modelling of the vessel, cable and the three cable deployment methods can be seen in Figures 7 and 8.

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 3m above deck, 6m forwards of the chute and 4,3m to starboard from centreline. The chute has a radius of 5m.

The J-lay model with deployment over starboard side have the cable fixed to the vessel 54m from the vessel's transom, 3m above deck and 15m to starboard from centreline. The cable is held in place by supporters and a vertical tower (13m height) created by shapes. For the model with deployment through the moonpool, the setup is similar to that of the midship starboard model. Here the cable is moved from the starboard to the centre of the vessel. The moonpool was created using shapes (trapped water) with dimensions: 7.2 x 7.2 x 9.5 [m].
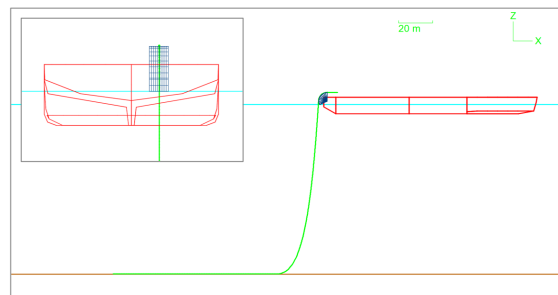
Figure 7. S-Lay model.
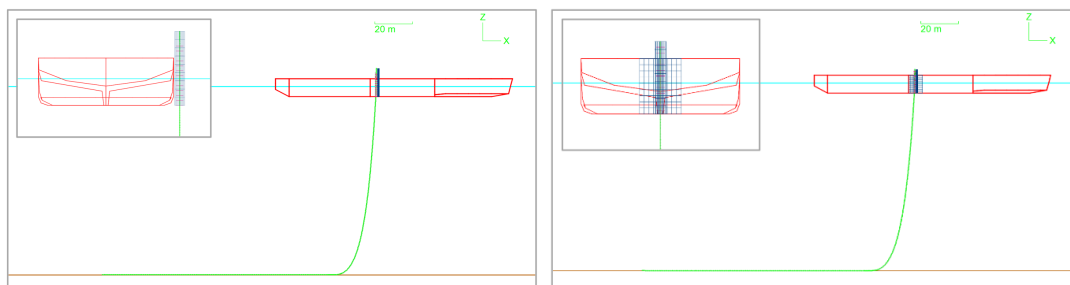
Figure 8. J-lay models: deployment over starboard side (left) and trough the moonpool (right).

5.5. Cable lay criteria

During cable lay 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 are maximum allowable tension, compression, Minimum Bend Radius (MBR) and Side Wall Pressure (SWP). Sidewall pressure can be considered as 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. The MBR 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. Common practice regarding compression is to avoid compression altogether as there is no accepted industry standard for determination of compression limits in subsea power cables. When considering limits for maximum axial tension, this may be set by either the limit of the tensioner or the breaking design limit of the cable (the combination of tension and curvature).[3, 16] For the sensitivity analysis the tension was measured at the cable by the chute exit point, and supporting tower entry point (which are both at same height above the vessel deck). By this reading of tension data, the capstan effect is neglected in this case.

6. Results and discussions

6.1. Scenario 1

The overall configuration and the effective tension along water depth, are compared in between results from simulation in OrcaFlex and the catenary equations. The results can be seen in Figure 9. It is observed that the graphs are in good agreement in static seas. The effective tension distribution be seen

to be linear through the water depth. While the maximum tension will increase with steeper steps as the layback length increases.
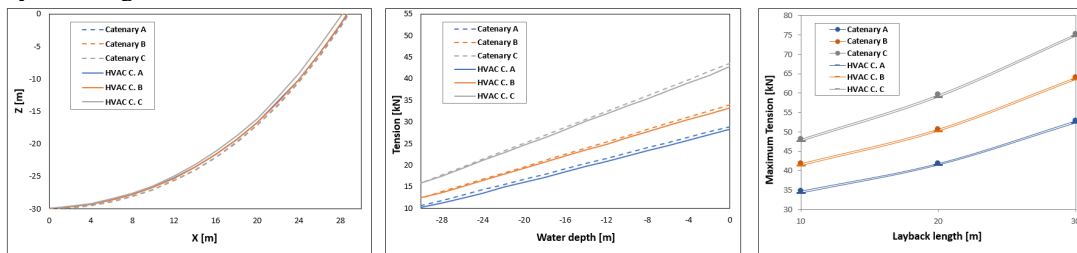

Figure 9. Illustrations from left: Cable configuration, Tension along arc and Tension across depth. HVAC cable A=100kg/m, HVAC cable B=120kg/m and HVAC cable C=140kg/m.

6.2. Scenario 2

Bending stiffness is defined as the ratio of the bending moment to bending curvature. 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 (Figure 6) due to internal stick-slip effects (caused by friction) and elastic-plastic material behaviour in the lead sheaths and the copper conductors.[26] Hysteresis effects in non-linear bend stiffness can provide a source of damping for the cable close to the touch down point. When a cable is modelled without bending hysteresis or i.e., Rayleigh damping, high frequency compression and tension waves can travel along the cable in the simulation, which can affect the values obtained for the tension.[22] The hysteresis 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.

A simple sensitivity analysis was conducted on the effects of bending stiffness, concerning minimum and maximum tension along the arc in the simulation period. Here the vessel was given superimposed motions with a -0.5m surge, 4m heave and 9s period.

The effects of these various bending stiffness configurations can be clearly shown (Figure 10) for minimum tension along the arc length. Constant bending stiffness and bending stiffness without hysteresis may be too conservative in regard to compression. However, for maximum tension along the arc at the same simulation period, the different configurations pose a less variance but nonetheless a difference in tension readings.
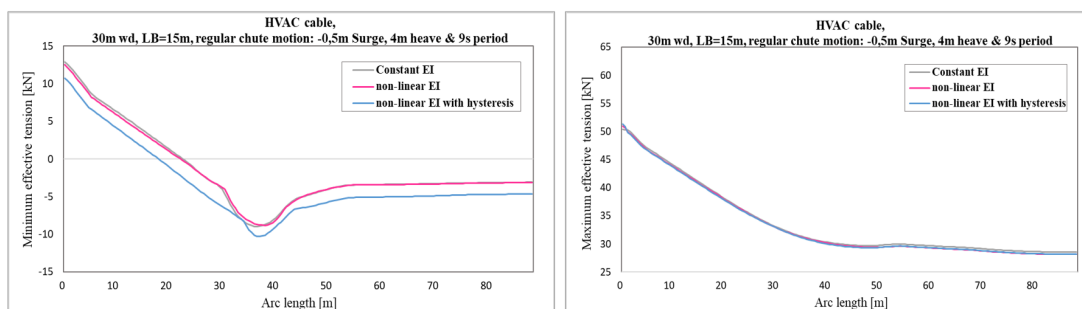
Figure 10. Left: Min. tension across arc length. Right: Max. tension across arc length. Measured from exit of chute and TDP is approx. at 54m (min. tension) and 62m (max tension).
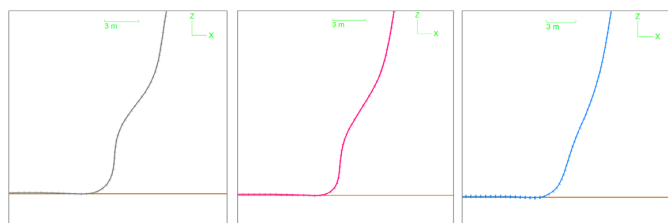
Figure 11. Bending behaviour of the cable in compression (at t=20,7s). From left: 1. Constant bending stiffness, 2. Non-Linear bending stiffness, 3. Non-linear bending stiffness with hysteresis.

With regards to minimum tension, the effects of the various bending stiffness configurations can be seen for compression in the cable at the TDP (Figure 11). Here, bending stiffness with hysteresis will dampen the bending of the cable at a larger degree compared to the other two configurations, creating a smoother bend.

6.3. Scenario 3

Most CLVs today have the chute or laying wheel at the stern of the vessel, while the J-lay method could be more frequently seen as offshore wind farms move to deeper waters. From the results (Tables 4 to 6), the S-lay method showed to be very sensitive to the wave induced vessel motions. 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 and roll motions of the vessel; in particular for deployment over the mid-starboard side. Deployment through the moonpool was clearly less affected by vessel motions, compared to the other methods. Even with its peak tension at a wave heading of 90 degrees, this method showed significant lower dynamic tension compared to the static tension.

Table 4. Max. tension loads – Deployment over stern chute.

	Wave Dir.	Tp [s] / Hs [m]	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Max tension [kN]	-	Static (no waves)	75									
	0	3.0	82	85	102	96	103	98	98	94	92	92
	45	3.0	78	83	98	110	135	105	109	106	100	97
	90	3.0	91	105	113	105	112	117	101	98	93	88
	135	3.0	76	81	94	101	117	103	102	107	99	90
	180	3.0	78	82	95	115	126	108	109	106	106	98

Table 5. Max. tension loads – Deployment over midships port side.

	Wave Dir.	Tp [s] / Hs [m]	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Max tension [kN]	-	Static (no waves)	79									
	0	3.0	83	84	81	83	83	83	84	82	82	82
	45	3.0	92	115	122	129	106	100	96	104	90	92
	90	3.0	97	111	115	147	155	164	135	139	128	134
	135	3.0	91	83	86	95	106	105	104	100	97	97
	180	3.0	87	101	101	88	102	97	86	95	91	110

Table 6. Max tension loads – Deployment through moonpool.

	Wave Dir.	Tp [s] / Hs [m]	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0
Max tension [kN]	-	Static (no waves)	74									
	0	3.0	76	76	80	79	80	78	78	78	78	78
	45	3.0	77	80	86	91	88	88	102	87	88	86
	90	3.0	86	100	110	108	116	104	132	111	104	97
	135	3.0	77	80	92	98	98	91	99	95	90	93
	180	3.0	78	83	82	91	95	94	98	94	92	92

7. Conclusion

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

A static analysis of different types of bending stiffnesses were carried out, for its importance when modelling the cable laying scenario. This showed that modelling with a constant value or with a non-linear bending stiffness would be more conservative than modelling with a non-linear bending stiffness with hysteresis, when considering compression. Regarding maximum tension, this caused only a minor difference in tension spread and maximum value. To validate simulation results, three cable configurations were investigated with catenary equations. The catenary shape and tension along water depth were examined in a static state and showed to be in good compliance. The three HVAC cables with varying weights were investigated further for their sensitivities for maximum tension with three different layback lengths. This illustrated that the design of the cable regarding its weight, will have a significant impact on tension loads, and this should be taken into consideration when designing a cable's armour. An overly conservative design will surely reduce the weather window available for installation.

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), along the mid-starboard side (J-lay) and through a moonpool (J-lay) were investigated for their 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 effects of roll and pitch on cable dynamics and thereby the maximum tension loads. The importance of the cable's deployment position may depend on the location of operation. 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 the vessel based on costs and operational uptime expected in a laying season.

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