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Abstract

Underwater cables have been connecting continents since the 1860s. Over time, the process of laying cables at sea has developed into a state-of-the-art operation. Now these operations are becoming more technologically advanced and it is possible to lay large diameter electric cables over large distances. One method is to lay cables in two or more lengths to have them jointed together mid-sea. A particular challenge will occur in case an unplanned splicing will be necessary. In this thesis, we will explore the design criteria for such cables and the procedures and challenges of installation. Furthermore, the effects of how dynamic motions of the vessel and sea influence the situation in deep water will be explored.

The OrcaFlex software will be used to simulate and analyze the effects of waves on vessel motion, and how this may affect the cable during a jointing operation of two cables at different water depths. The effects of current forces on the cable are to be analyzed and how the cable reacts to both current and wave forces. This analysis method can assist in determining the weather criteria for a jointing operation to prevent excessive bending, compression or fatigue damage in the cable.

When installing a cable in an area with currents, one needs to take into account the direction of the currents relative to the cable, as tension and bending of the cable are highly affected by the direction and strength of the current.

From the OrcaFlex analysis, one can see that vessel motion due to waves are more critical to the cable with respect to fatigue damage in shallow water (100 m) than in deep water (1200 m). The residual bottom tension in the cable at the touch down point is, however, more sensitive to the vessel motion at deep water than in shallow water.

In areas with waves and currents, a current approaching the cable at 0 degrees will decrease the critical parameters. The bottom tension is less affected by the vessel motion and the cable will experience less bending cycles over the laying wheel. With a large current approaching at 180 degrees (i.e. toward the vessel), the bending of the cable increases and hence the cable may experience fatigue damage sooner. The bottom tension in the cable will become more sensitive to vessel motions in this situation and the risk of loops developing will increase as tension decreases.

By changing the location of the laying wheel, one can improve the situation. Placing the wheel closer to the center of the stern will reduce the effect of vessel motion on cable tension. The cyclic bending of the cable is, however, less affected by changing the laying wheel location.

A HAZID carried out for cable installation, shows that there are many risks and hazardous events that may occur during the operation in connection to the cables integrity. Handling these risks early may reduce both their probability of occurring and the related consequences.

One finding in the analysis is that there are different requirements for laying cable and jointing operations. The suitable sea states for jointing are more limited than for laying. When vessel and cable are standing still, all bending occurs at the same place in the cable, resulting in increased risk of fatigue damage, hence it is necessary with a calmer sea state for this kind of operation.

Future work might emphasis on developing quick connectors to quickly join cable ends offshore. Reference is here made to the offshore oil and gas industry’s underwater connectors.

Acknowledgements

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I would also like to thank Lars A. Solberg in Nexans Norway AS for sharing with me his incredible firsthand knowledge about power cables and subsea cable installation, and for taking the time to travel to Halden and show me the cable laying vessel C/S Nexans Skagerrak. His help and patience with all my questions have been key to this thesis.

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And finally, I want to give special thanks to my family and friends for their great support, never-ending encouragement and for believing in me along the way. Without them, this would not have been possible.

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Louise Våbenø

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List of Abbreviations

AC	Alternating Current
ALARP	As Low As Reasonable Practicable
CLV	Cable-Lay Vessel
COG	Centre of Gravity
DC	Direct Current
EHV	Extra High Voltage
HAZID	Hazard Identification
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
KP	Km Post
MBR	Minimum Bending Radius
MI	Mass Impregnated
NDT	Non-Destructive Testing
NSL	North Sea Link
PE	Polyethylene
PLB	Post Lay Burial
PP	Polypropylene
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
SWL	Still Water Level
TD	Touch Down
TUV	Tactical Underwater Vehicle
UHV	Ultra-High Voltage
VIV	Vortex Induced Vibration
WP	Way Point
XLPE	Cross-linked Polyethylene

List of symbols

Symbol	**Description**
D	Cable diameter
d	Water depth
H	Horizontal bottom tension
L	Layback length
L_s	Suspension length
R_{min}	Smallest bending radius
s	Catenary cable length
T	Top tension
$T_{allowable}$	Allowable top tension
T_{Cr}	Critical low tension
V	Vertical force
w_{air}	Cable weight in air
w	Cable weight in water

1 Introduction

1.1 Background

Modern society, with growing industrial production and improving living standards, consumes more power. This has led to an increased demand for electricity. At the same time, we are becoming aware of the damage the fossil fuel power production is inflicting on the environment. The knowledge is spreading and research in the field is leading to new methods to extract renewable energy. In recent years, we have experienced an increase in use of wind and solar power all over Europe. In order to maximize production and utilize as much as possible of the energy, there needs to be a more efficient way of exchanging electricity between countries.

Norway has a power generation that is very flexible and emits low levels of CO_2. European countries should cooperate amongst each other in order to achieve shared CO_2 reduction goals. A reduction or an increase in the Norwegian power production has little to none effect on worldwide emissions of greenhouse gases. By connection Norway's power grid to the European continent, this would change. Then changes in the Norwegian power production and consumption could have an impact on the global CO_2 emission target. This way renewable energy production is able to compete with polluting power plants in Europe. Over time, this can lead to reduced need for fossil power plants and possibly a technological shift in electricity management.

New power connections between the countries grids need to be established in order to create a *Pan-European Transmission Network*. By using high voltage subsea cables this is achievable. Many cables are already installed, but also new cables are at the planning stage. The laying of cables is key to combining electrical resources from many countries.

Norwegian Power Production

Norway, on average, produce more energy than is consumed. In the years between 1974 till 2012 the average export of energy was 4,3 TWh (Statnett SF).

98 % of Norway's energy production is renewable and environmentally friendly. The huge amount of water resources makes it possible to store energy in reservoirs, and make use of this potential energy when needed. Hydroelectric power puts Norway in a unique position. With an increase in exchange capacity between Norway and the continental Europe, it can import more energy when the prices are low abroad and export more when the prices abroad are high. This way Norway can have an effect on the CO_2 emission in Europe and may influence the future power production.

At the moment Norway have five subsea cable connections. Four connections to Denmark (Skagerrak 1-4) and one to the Netherlands (NorNed) with the capacity of 1700 MW and 700 MW respectively (Statnett SF). As seen in Figure 1**Error! Reference source not found.**, two new cables, one to Germany and one to the United Kingdom, will be installed and set into operation within the next 4 years. This will increase the transmission capacity by 2800 MW, 1400 MW from each (Statnett SF).

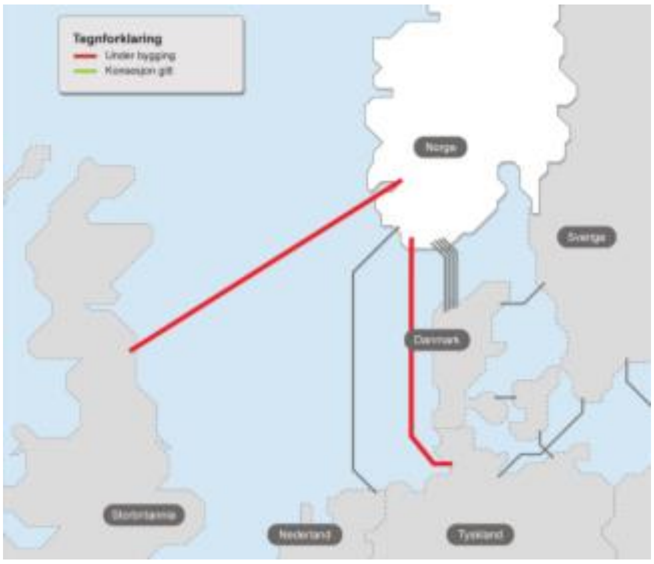


Figure 1: Subsea power cable connections to Norway (Statnett SF)

North Sea Link

A license for a new cable interconnection between Norway and England was approved in 2013, after a previous request from 2001 was denied. New calculations showed that the cable connection would have been more financially advantageous than estimates from preceding studies (Statnett SF, 2013). This new connection, called North Sea Link (NSL), will open for import and export of energy between Norway and England. It will contribute to UK's continuing large-scale development of clean wind and solar power, and eventually it may phase out the fossil fuel production.

The United Kingdom has suitable conditions for high wind power production. On windy days, with high production and low energy prices, Norway can buy inexpensive energy to use instead of the stored potential hydropower. The continued storing of energy will reduce the need for fossil fuel power later on. Excessive energy generated by wind can also be used to pump water back up into water reservoirs, making the hydro power plants function as a battery for countries outside Norway. This stored energy may be used for production later when the wind is calm and the energy prices increase. At days of no wind, Norway can sell energy back to the United Kingdom. In this way, the wind power is utilized as much as possible. The cables will also increase the security of supply in Norway and can reduce energy prices in periods or seasons with less rain. The supply and prices may stabilize and become more predictable over the years.

Statnett and National Grid both own 50 % of the cables that are planned to go from Kvilldal in Norway and to Blyth in England. The cable route is divided into three parts, Lot 1, Lot 2 and Lot 3 with a total distance of 725 km (Tunheim, 2016). The cables for Lot 1 is both produced and laid by Nexans Norway AS, while Lot 2 and Lot 3, towards England, are laid by the Prysmian Group.

Lot 1 starts in Kvilldal and goes over to Hylen in Suldal. From Hylen it is going out through the fjords and about 150 km out in the North Sea towards Blyth (Statnett SF, 2013), as seen in Figure 2. The features of the cable route through the fjords has challenging parts, with water depths varying between deep water (550m in Boknafjorden (Kartverket)) and shallow water and narrow curves in the fjord. With a vessel that can hold a load of 7000 tons (Nexans Norway AS), the cable need to be jointed together about every 140 km to reach over the whole distance. The best suitable location for the cable to be jointed may depend on a combination of the features of the cable route and the sea state.

Figure 2: Cable route Lot 1 of NSL cable; From Kvilldal in Norway towards Blyth in England.

Icelandic Power Production

Iceland has huge resources in renewable energy. Except for the diesel generators that are used on the small islands of Grimsey and Flatey and for emergency power on the main island, Iceland's power production is all renewable. 75.5 % of the energy comes from hydropower and the remaining 24.5 % are generated from geothermal power (Orkustofnun). An interconnector is planned to be installed between Iceland and Scotland (Landsvirkjun). This new power cable, over 1000 km long, will open for export of excess energy from Iceland.

Danish Power Production

With over 6000 wind turbines (Energistyrelsen), Denmark gets about 40 % of its energy from wind power yearly. The renewable energy production is constantly increasing and causing a reduction in the non-renewable production. On a windy day, the wind power production exceeds the electricity demand and power is exported to Norway, Germany and Sweden. At times with high wind power production the price of electricity has become free, and in extreme situations the price is negative, resulting in the end user being paid to use the electricity (Nilsen, 2013). Due to congestion management in the power grid, these extreme situations do not always affect Norwegian and Swedish energy prices. To avoid these kinds of situations and utilize as much as possible of the energy one needs to have the possibility of higher power transmission between countries.

Although the percentage of renewable electricity output is increasing every year for many countries like Denmark, Germany and United Kingdom, as seen in Figure 3, there are still a need for backup power whenever the renewable power production is low. As seen in Figure 4, the electricity production from sources like oil, coal and gas are still high, and could be reduces further if part of the backup power has the possibility to come from renewable sources in Norway and Iceland.

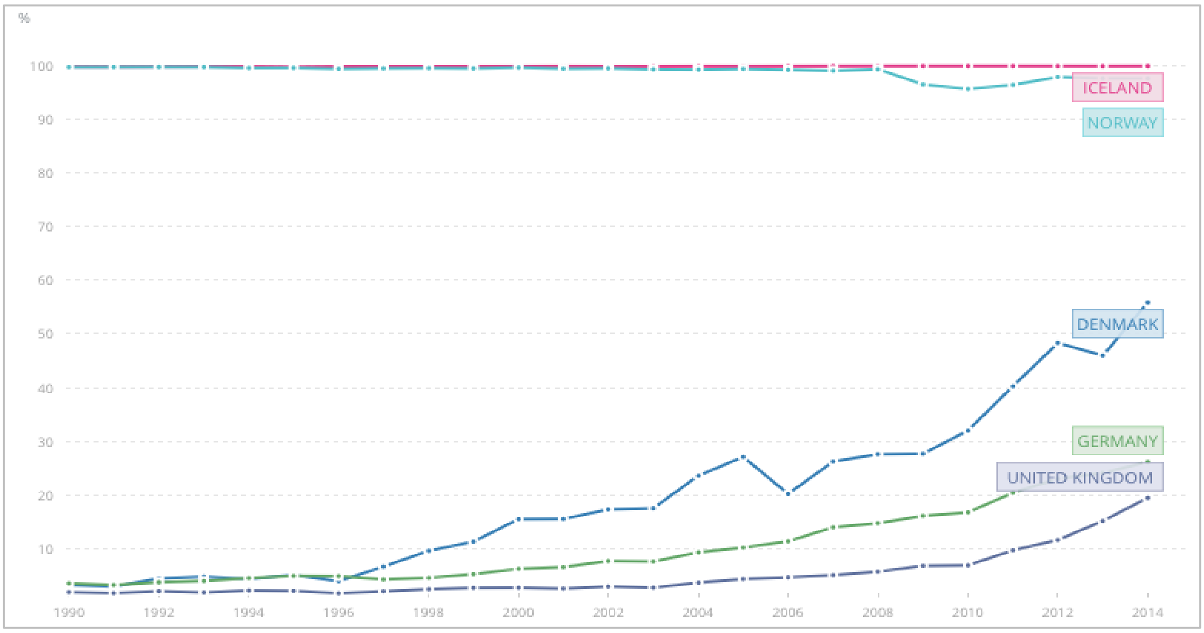


Figure 3: Renewable electricity output (% of total electricity output) (The World Bank)

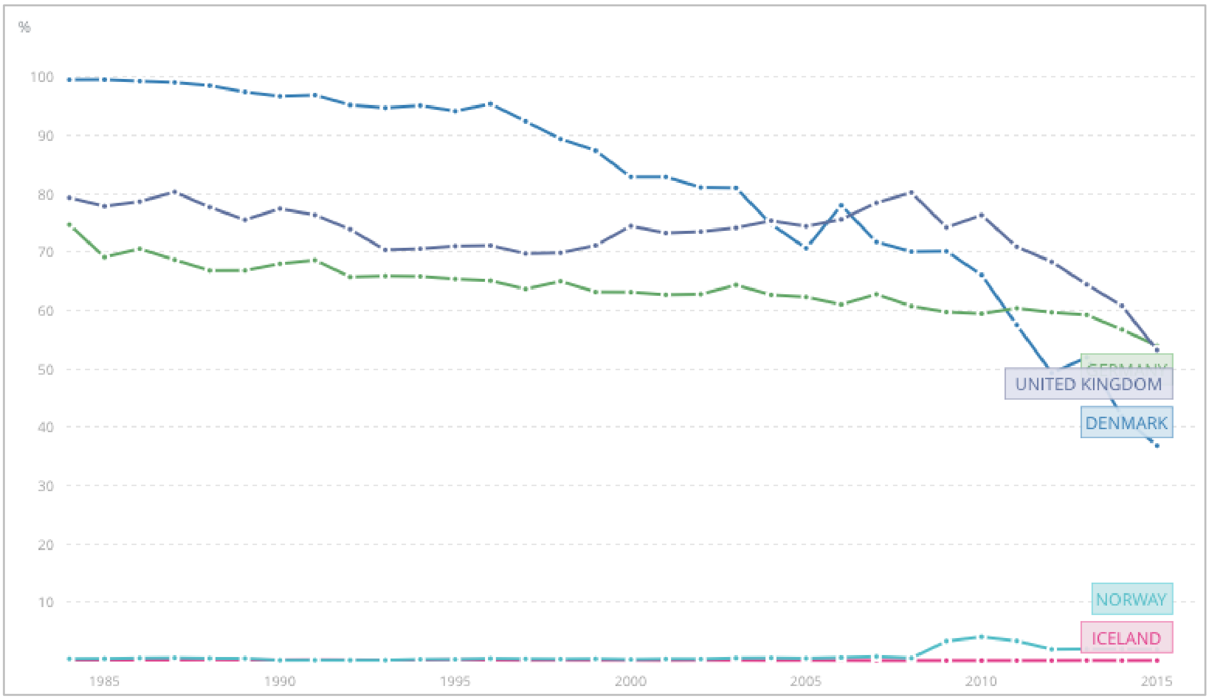


Figure 4: Electricity production from oil, gas and coal sources (% of total) (The World Bank).

1.2 Motivation and objectives

Each new power cable connection is unique, and must be planned in detail. Although experience gained from other similar projects can contribute with valuable knowledge, new projects may have issues that have not yet been experienced. Potential problems may arise in deeper water, on less convenient seabed surface or in rougher sea states.

The distance of interconnections is becoming longer and many cables need to be installed in segments. The segments are then joined together mid-sea in an operation that usually takes between 8 and 12 days to complete with high voltage cables. Throughout the whole jointing operation, the vessel and the cable must keep the same position and heading, with no chance of changing location. The main objectives of this master thesis are to:

- Study how the electric interconnections are installed and operated.
- Analyze how the sea state and current affects the vessel motions and hence how the vessel motions affect the cable.
- Analyze how installation-time during jointing of cables and weather condition limits the installation of long distance cables at deep water.
- Prepare a HAZID of cable installation at sea.
- Identify limiting factors and establish criteria for installation.

1.3 Structure of the thesis

This report is organized in seven chapters, where the *First chapter* gives a background for the thesis and introduce the main objectives of this report.

The theory of electric power systems and high voltage transmission is presented in *chapter two*, followed by a presentation of the physical structure and the main components of a high voltage power cable in *chapter three*.

Fourth chapter consists of theory on cable installation at sea, including the cable laying vessel and special equipment required for the operation.

Chapter five presents the theory of a HAZID analysis.

Chapter six consists of theory of cable installation analysis and the analysis method used in this thesis for both static and dynamic analysis.

Chapter seven present a discussion of the results that are obtained from the analysis, and *chapter eight* presents conclusions.

2 The Electric Power System

The electrical power network is built up by electricity at different stages; generation, transportation, distribution and usage. The electricity is generated at various types of power plants, where the source may be renewable or fossil-based. After production, the electric power is transported through the transmission network before entering the distribution network. At the end of the distribution network are consumers like factories, schools and homes, as seen in Figure 5.

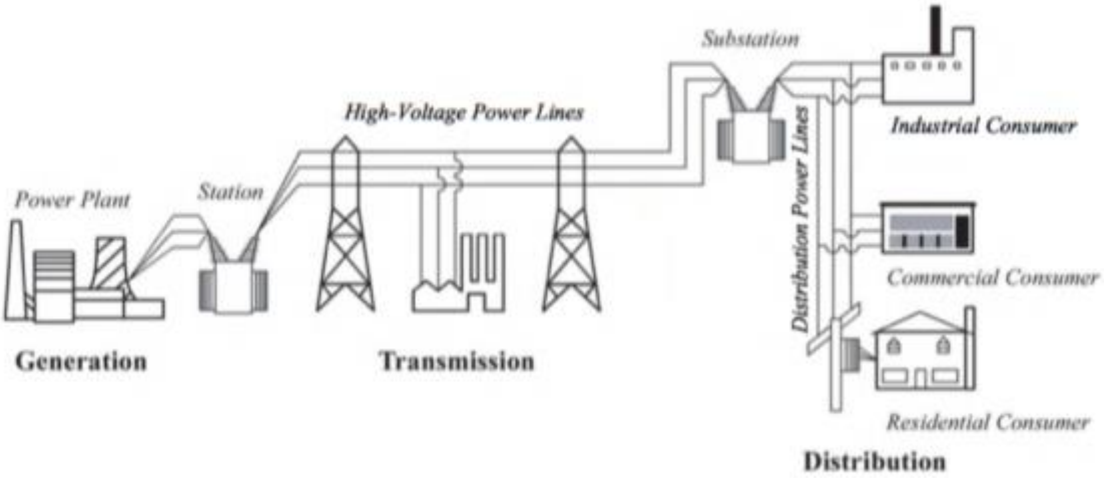


Figure 5: An overview of the electric power system (Blume, 2007)

The system operates in real time, which means that the electricity is produced when consumers use it. There are very few ways of storing the energy that has been generated, and it typically needs to be used right away. When you turn on a switch there are instantaneously power to be used and you get light in the room. When more power is used, more must be produced. On a daily basis, power plants operate after statistical history and expected weather to plan how much they need to produce. Power generators that are running on material like water, coal or gas, can control its production and increase and decrease when needed. Power from solar photovoltaic (PV) systems or windmills are harder to control as they are dependent on the sunlight and wind at that exact moment. It is thus harder to predict its future production for the next day.

To stabilize and equilibrate the power supply, many units are linked together. When the demand and supply do not coincide due to sudden changes, like an increase in demand or drop in generation, changes must be made quickly. Some units have the ability to change its production faster than others, but might not be the preferred source or an economic choice for generating power over longer periods of time. With many sources and consumers linked to the same grid, these changes can be made easier and faster without or with fewer complications.

The power units, which can be located far away from each other, are connected by a high voltage grid of transmissions lines to efficiently transfer large quantities of power to wherever it is needed. Reaching the distribution network, the power is stepped down to a lower voltage. Different consumers require different voltage, and some require further step down of voltage before use.

2.1 Electric power

Since the first discovery of electricity by Benjamin Franklin in the 1750's, the electrical system has advanced. Thomas Edison started the first electrical powered streetlights (Pearl Street, New York) from a locally placed power plant. He quickly discovered that by longer distances the power was lost. This resulted in many small power stations, where all customers lived within a short distance. As the demand increased and the need for larger power stations occurred, they also needed a better way of transporting the electricity without too high power losses. When George Westinghouse developed the transformer (Blume, 2007), it did not take many years before it changes from a local DC-powered system to a AC-powered system with distant power plants. The new transformer allowed the power to be stepped up in voltage, reducing the losses during transmission, and then stepped down at the receiving end. This is how the power distribution still works all over the world.

Electric power is a combination of electric current and voltage. With either one of them absent, no work will be done. The voltage is what makes thing happen; it pushes the electrons from one point to another, and is known as the potential energy source. The electrons in the conductor is the current that flows through due to the voltage work. The current flow is defined as going from positive pole to the negative pole, although the electrons are moving in opposite direction, from negative to positive pole (Blume, 2007). The electrons leave the voltage source and enters the load, which can be an electrical instrument, before it returns to the voltage source.

Power, as watt, used over time creates energy. As a measure of the energy used, the amount of power used is multiplied by the time it is used, and gives us watt-hours (*Wh*). This means that 1000 Wh, or 1 kWh, could be 10 W used for 100 hours as well as 100 W used for 10 hours.

There are two ways of transporting electrical power; by direct current (DC) or by alternating current (AC) transmission.

2.1.1 DC power

In a direct current (DC) system, the current moves at a constant pace through the conductor. This is due to the constant voltage in the circuit, as seen in Figure 6 a). It is a simple solution that requires that the electrons move in a circle. Batteries works as a DC system (Blume, 2007), where the battery is the voltage source, pushing the electrons through the load, before they return to the batteries. When all the electrons have gone through the circle, the battery is “empty”.

The DC systems do not have the possibility of increasing or decreasing the voltage, and thus need to operate at a voltage level the equipment can handle or need. Too high voltage can damage the equipment and with too low voltage, it will not work properly. Using DC for distribution is hence not possible as the voltage need to be stepped down before usage. DC power need to be transformed to AC before feeding it to the grid.

2.1.2 AC power

Alternating current (AC) systems work with an alternating voltage, as seen in Figure 6 b). This means that the current electrons are pushed and pulled back and forth, as the voltage goes in cycles from positive to negative. The rate at which the voltage alternates is called the frequency, and is described as cycles per second, hertz. For it to function properly, the whole system needs to operate at the same frequency.

AC power is generated with a rotating magnetic field next to a wire coil, forcing the electrons in the wire to switch directions every half period. The speed of the rotation determines the frequency. The number of wire coils used determine the number of phases. With three coils three-phase AC is produced, and is used in most power plants today (Ardelean and Minnebo, 2015).

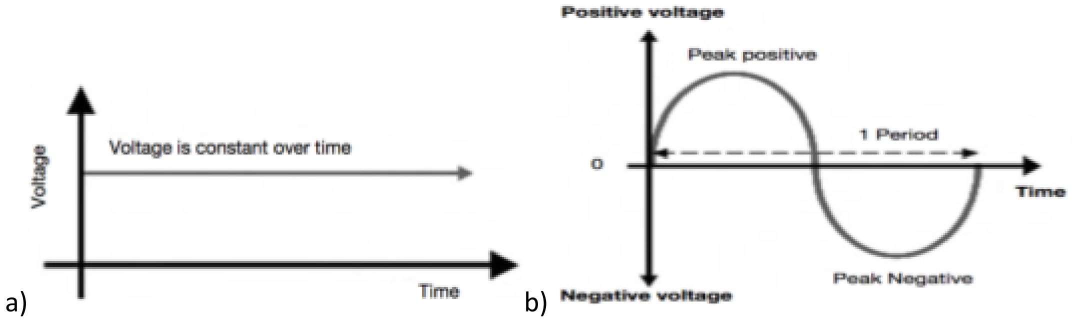


Figure 6: a) DC; constant voltage and b) AC; alternating voltage (Blume, 2007).

2.2 High Voltage Power Transmission

According to the power equation *P=I*V,* increasing the voltage will increase the power. To transfer large quantities of electric power, the voltage is stepped up and increased to a much higher level. High voltage (HV) is defined as higher than 100 kV, as seen in Table 1 below. Further reference to HV in this chapter include Extra High Voltage (EHV) and Ultra-High Voltage (UHV), unless other is stated.

Table 1: Transmission Voltage Classes (Kalair et al., 2016).

Voltage Class	Voltage [kV]
Low Voltage	< 1
Medium Voltage	1 – 69
High Voltage	100 – 138
Extra High Voltage	220 – 800
Ultra-High Voltage	> 800

2.2.1 HVAC versus HVDC

When the need to transfer large quantities of power across an ocean arises, the question is whether to go for a high voltage alternating current (HVAC) or high voltage direct current (HVDC) system. The choice depends on which is more economical or what is technical feasible. It can also be limited due to environmental restrictions, like long distance and water depth at the crossing. The total cost depends on the material used, number of cables and installation cost, the equipment needed and the power lost in the cable during transmission.

The power losses in an AC cable are affected by the skin-effect (Ardelean and Minnebo, 2015). While DC takes advantage and flow through the whole conductor cross-section, the AC draws itself towards the conductor surface. As illustrated in Figure 7, the middle of the conductor is not contributing to the transmission. The effective cross section is reduced and resistance increased. To get the same amount of power the HVAC connection needs three cables whereas a HVDC connection only needs one. This will increase the material used and production and/or installation time substantially.

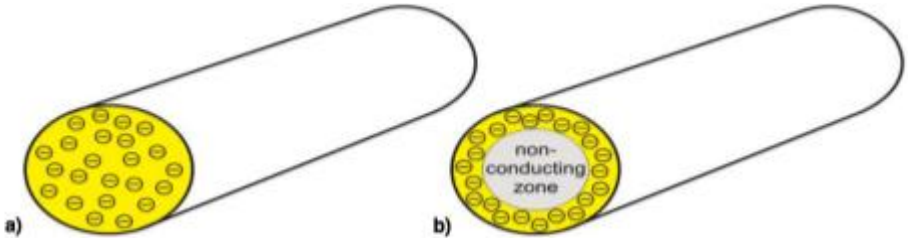


Figure 7: a) DC-conductor, b) AC-conductor with skin-effect (Ardelean and Minnebo, 2015).

A large limitation for HVAC cables is the power loss due to the heat produced. This loss increases with length and the critical distance is met when the loss becomes so large that the entire current is lost (Negra et al., 2006).

A comparison of power loss in HVAC versus HVDC (May et al., 2017) shows, Figure 8, how the loss in an HVAC system increases greatly with length, while the loss in the HVDC system is fairly stable. Table 2 below shows the power loss in each component of the systems, transformers (T1, T2), cables and converter stations (CS1, CS2), where the input power to both systems were 117 MW. The loss from the converter stations in the HVDC system is higher than the loss in the transformers in the HVAC system, but the difference is very small compared to the loss in the HVAC cable alone. As the cable length increases, the power loss percentage in the HVAC cable increase with length. If the trend continues in the same direction, at some length the loss will consume the entire current going through, leaving nothing left. The loss in the HVDC cable has a marginally increase with length, resulting in the possibility of nearly unlimited cable lengths.

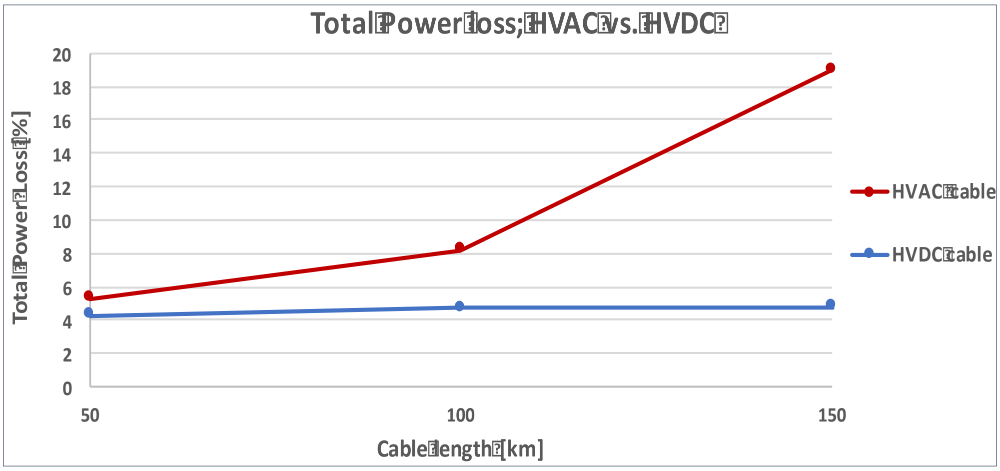


Figure 8: Total power loss in a HVAC and a HVDC system (May et al., 2017)

Table 2: Power loss in HVAC vs HVDC systems (May et al., 2017).

Cable length [km]	HVAC				HVDC			
	T1	Cable	T2	Total loss	CS1	Cable	CS2	Total loss
50	1,60 %	2,21 %	1,49 %	5,30 %	1,77 %	0,59 %	1,93 %	4,29 %
100	1,61 %	5,31 %	1,25 %	8,17 %	1,79 %	1,04 %	1,90 %	4,73 %
150	1,62 %	16,28 %	1,10 %	19,00 %	1,78 %	1,10 %	1,89 %	4,77 %

The HVAC cable requires a frequency equal to the frequency at both ends, which means that both the sending and receiving grid of the cable need to operate at the same frequency. This could be out to an island or across a fjord within the same country, or between two neighboring countries operating at the same frequency.

When connecting between to grids, which operate at different frequencies, the power need to be transformed two times. First from AC to DC, and then back to AC. If using a HVAC cable, this transformation would need to happen before entering the new grid with another frequency. Both transformations can be done at one converter station in one end of the cable, also known as a back-to-back interconnection (Meah and Ula, 2007) without any transmission line in between. When using HVDC cable this is done one time in each end of the cable, when leaving the first AC-grid and before entering the second AC-grid at the other end, requiring two converter stations.

The costs of converter stations are high, but when including material cost and power losses, the HVDC cable becomes economically favorable already at 50 km, while the break-even price for overhead lines occur at a distance of 600 km (Kalair et al., 2016). The HVDC system is also known to be more stable and can change the direction of energy flow and power level fast.

2.2.2 Power Loss in HVDC cable

In a HVDC cable, the heat produced by power transmission results in power loss at the receiving end of the connection. The “power in” does not equal the “power out”, as power in the form of heat is transferred trough the layers of the cable and out to the ambient environment. The loss P_L, also known as ohmic losses, can be seen in relation to the current and the conductor resistance of the cable

$$P_L = I_C^2 * R'$$

where R' is the resistance in Ohm per length of cable (Worzyk, 2009). In the power equation

$$P = I_C * V$$

where I_C is the conductor current and V is the voltage, one can see that the input power stays the same if one both increases the voltage and decrease the current. This way one can reduce the power losses in the transmission. By increasing the voltage by a factor of 4, and reducing the current by a factor of 4, the power loss will be reduced by a factor of 16 as the current, I_C, is squared. This shows that with higher voltage we get less dissipative losses.

The temperature in the conductor change the resistance. As seen in the equation below, higher temperatures result in higher resistance

$$R' = R_{20°C}\left(1 + \alpha(\Theta_C - 20°C)\right)$$

where R_{20C} is the specific resistance at 20°C for the chosen conductor cross section, α is the thermal coefficient of the specific electric resistivity at 20°C and Θ_C is the temperature of the conductor. Assuming a cylindrical single core cable, the temperature-drop over layer n in the cable can be seen in relation to its thermal resistance T_n and the ohmic loss

$$\Delta\Theta_n = P_L * T_n$$

For simplification, the thermal resistance has to be calculated for each group of layers according to IEC 60287’s thermal model (IEC, 2006). The thermal properties of the semi-conducting layers are similar to the insulation and can therefore be calculated as one. For the insulation, T_1 is dependent on the specific thermal resistivity ρ_{T1} of the insulation material and the relation between its outer and inner diameter, D_o and D_i respectively, semi-conducting material included,

$$T_1 = \frac{\rho_{T1}}{2\pi} * \ln\left(\frac{D_o}{D_i}\right)$$

The next layer considered is between the metallic sheath and the armoring, and the thermal resistance T_2 can be found by

$$T_2 = \frac{\rho_{T2}}{2\pi} * \ln\left(1 + \frac{2t_2}{D_s}\right)$$

where t_2 is the thickness of the layer and D_S is the inner diameter of the layer, over the metallic sheath, and ρ_{T2} is the layer's thermal resistivity. The layer includes both the extruded PE sheath over the lead alloy and any bedding under the armor. Over the armor is the outer sheath, and its thermal resistance T_3 is found similarly to T_2

$$T_3 = \frac{\rho_{T2}}{2\pi} * \ln\left(1 + \frac{2t_3}{D'_a}\right)$$

where t_3 is the thickness of the sheath and D'_a is the inner diameter of the sheath, over the last layer of armor, and ρ_{T3} is its thermal resistivity. The metallic sheath and the armor are assumed to have $\rho_T = 0$, and thus $T_n = 0$, as their thermal resistance is very low relative to that of the other materials in the cable. This applies to both flat wire armoring and round wire armoring packed with bitumen.

If a cable is buried, the thermal resistance between the cable surface and the seabed must be accounted for. The term u, defined as $u=2L/D_e$, is dependent on the vertical burial depth L between the seabed and the center of the cable and the outer diameter of the cable, D_e. Assuming a homogeneous soil and a single buried cable the thermal resistance T_4 is

$$T_4 = \frac{\rho_{T4}}{2\pi} * \ln(2u)$$

where ρ_{T4} is the soils thermal resistivity. When $u>10$, which is the case for most buried cables, this is assumed to be a valid approximation. A more comprehensive calculation must be done for a shallower burial depth.

When having two identical cables buried within the vicinity of each other, assuming they are equally loaded and at the same depth, T_4 is found by

$$T_4 = \frac{\rho_{T4}}{2\pi}\left(\ln\left(u + \sqrt{u^2 - 1}\right) + \frac{1}{2}\ln\left(1 + \left(\frac{2L}{s_1}\right)^2\right)\right)$$

where s_1 is the distance between the cables, center to center. The last equation is only valid when $u<10$, otherwise $\left(u + \sqrt{u^2 - 1}\right)$ can be replaced with $2u$.

The entire temperature drop can now be calculated by

$$\Delta\Theta = P_L \sum\nolimits_n T_n = I_C^2 * R' \sum\nolimits_n T_n$$

The difference between the undisturbed surrounding soil temperature and the maximum conductor temperature is the maximum acceptable temperature difference *ΔΘ*. Considering that the temperature in the sea and its surroundings change over the months, a conservative approach should be applied, especially in a new area with less data.

Turning around the equation and calculating all the thermal resistances, the cables ampacity, which is the cables current carrying capability (Worzyk, 2009), is found by

$$I = \left[\frac{\Delta\Theta}{R'(T_1 + T_2 + T_3 + T_4)}\right]^{0.5}$$

By iteration, one can increase the ampacity and optimize the cable system. The thermal resistances only experience smaller changes by increasing the conductor size. Changing burial depths and spacing will also affect the result.

2.2.3 Transmission Configurations

The configuration of a HV system may be affected by the power level, the required stability and the reliability of the system and economy of the project. The main configurations for use in system with HVDC transmission cables are monopolar and bipolar.

Monopolar

A monopolar system (Alstom, 2010) requires converter(s), a single conductor and a return path. The converter unit(s), six-pulse, are placed in series or in parallel in both ends of the conductor. The return path can go through earth or sea or through a metallic return, as seen in Figure 9 a) and b). A metallic return can be used when the earth and sea conditions are not optimal. The ground can have high resistivity or be interrupted by other cables, pipes and constructions. Low salinity or fresh water may also influence the result. With a metallic return, the system usually has two conductors, one with high voltage and one with medium to low voltage.

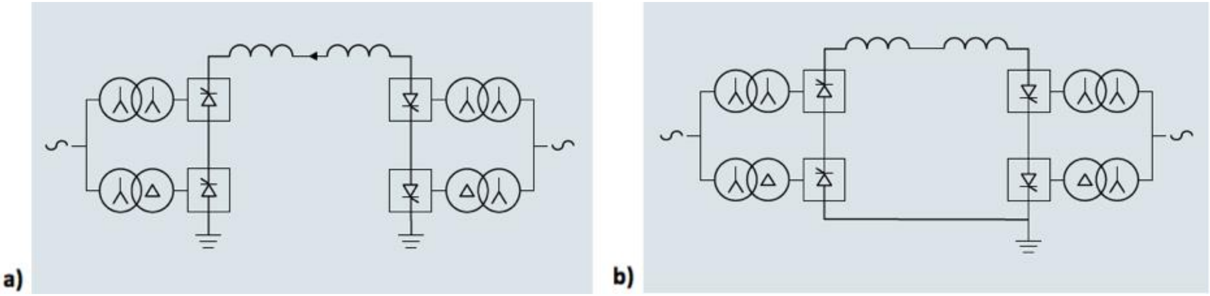


Figure 9: Monopolar Configurations for HVDC system with a) ground return and b) metallic return (Alstom, 2010).

As it only requires one high voltage cable, a monopolar system can be a cost-effective solution with less material and installation costs. The redundancy is however none. If the cable has down time, the whole system is down. The monopolar system, both with earth or metallic return, can be upgraded to a bipolar system at a later stage in a project.

Bipolar

A bipolar (Alstom, 2010) system is having two monopolar systems with ground return; converter(s), two conductors and a ground return as seen in Figure 10. The converter(s), twelve-pulse, are, like the monopolar configuration, placed in series or in parallel at both ends of the cables. In normal operation, the conductors operate as poles of opposite polarity; positive and negative, where the second one is ground for the power flow. This system can easily switch the power flow direction by switching the polarity of the cables.

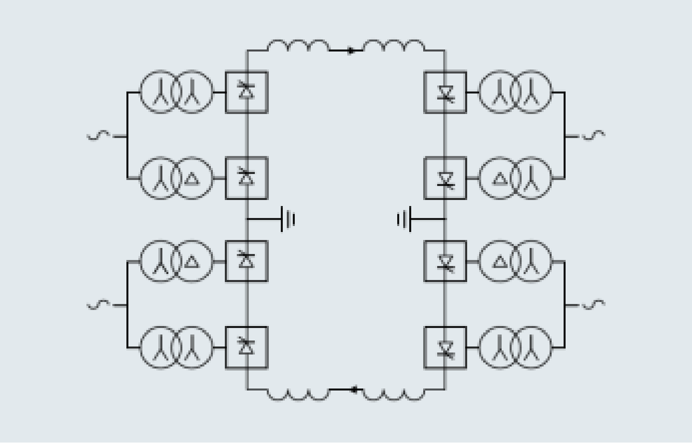


Figure 10: Bipolar configuration for HVDC system (Alstom, 2010).

Normal operation of a bipolar system can transmit double of a monopolar system working from the same basis. In case of an outage or maintenance of one cable, the system can run with only one conductor as a monopolar system with half the transmission capacity. Either ground or metallic will function as return, depending on the arrangements made.

In case of a fault resulting in reduced capacity in one cable, the cables can function as two independent monopolar systems with ground return operating at different currents. For higher redundancy of the system, a third conductor can be installed. This will function as the return when one cable is out of service and carry unbalanced currents during normal operation.

Homopolar

A homopolar system (Maharaja, 2012) (Figure 11) is very similar to a monopolar system, with the exception of two or more conductors. All the conductors have the same polarity, and as the monopolar, it is usually negative. The return is either by ground or metallic. The advantage of the system is whenever one cable is down; the other cable(s) can function independently of the other.

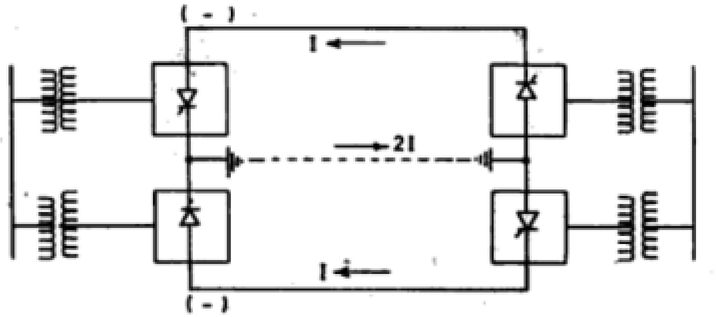


Figure 11: Homopolar configuration for HVDC system (Maharaja, 2012).

2.2.4 The Converter Station

When connecting two AC grids together using a HVDC transmission system, two converter stations are needed, located one in each end of the HVDC transmission line. The purpose of a converter station is to step up and down the voltage and to convert the power. The rectifier converts the AC into DC in the sending end of the system, while the inverter converts the DC back into AC at the receiving end, as seen in Figure 12.

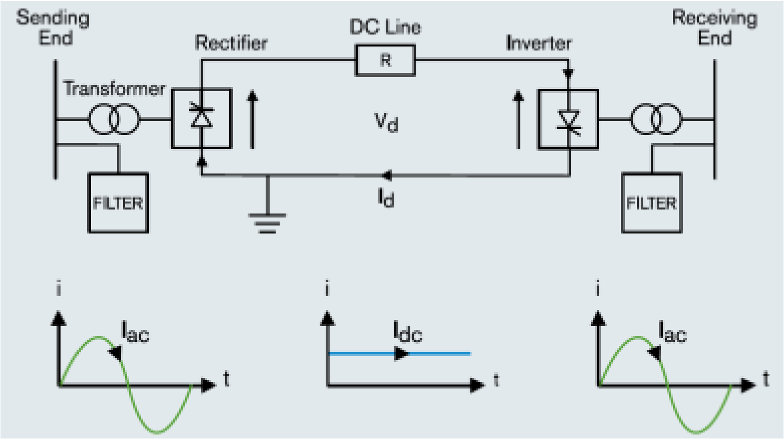


Figure 12: Simplified HVDC transmission system (Alstom, 2010).

Converter stations are specially built for each system, and will thus vary in both size and layout. Different requirements and technology used will affect the result. The main features are still the same and the stations are usually divided in two parts (Alstom, 2010); the AC switchyard and the "converter island". An alternative and simplified sketch of the converter station layout is seen in Figure 13.

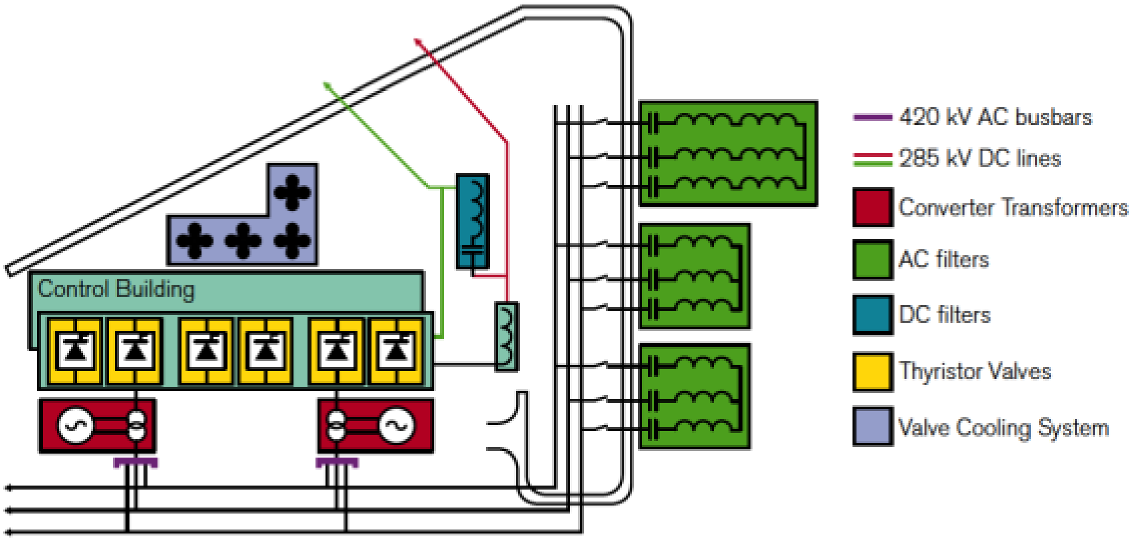


Figure 13: An alternative layout of a converter station (Alstom, 2010).

The AC switchyard comprises of the AC harmonic filters, the high frequency filters and the busbar connections between the AC system and the HVDC converters. The arrangement and complexity of these connections are dependent on the requirements for reliability and redundancy, the AC voltage level and the number of converters. A connection with a double busbar can handle a fault in one without resulting in an outage of the entire station, but also requires more space and often more circuit breakers than a single busbar.

The filters connected to the AC busbar are turned on and off whenever they are needed. The AC harmonic filters are intended to limit the AC harmonic current impact and the absorbed reactive power. The high frequency filters are needed to prevent the high-frequency interference to propagate into the AC system. The interference has no effect on the operational safety of the AC system, but may interfere with signaling systems, e.g. Power Line Carrier signaling.

The converter transformers, the valve halls, the DC switchyard and the control and service building are all included in the “converter island”. Connecting the AC system and the thyristor valves together is the converter transformer. This interface need to be able to handle the frequency load and the AC harmonic current on its way from the converter to the filters.

Converters perform the transformation between AC and DC. A converter consists of six- or twelve-pulse bridges. Each bridge is made of 6 or 12 “valves” where one valve contains many thyristors connected in series. The thyristor valves generate an electromagnetic field, and thus the valves are located inside a special valve hall. The hall is purpose built with metal screen covering all walls, roof and floor, as a Faraday cage, and will also function as a barrier against pollution and outdoor conditions.

To reduce the DC current ripple and improve the performance in a transmission scheme, a DC smoothing reactor is required. This will also reduce the losses in the system. AC harmonic current may flow in to the DC line, and DC filters are used to confine the flow.

On the DC side of the converter, the switchyard mainly consists of disconnectors, earth switches and transducers. This is used for scheme reconfiguration and to assure safe maintenance operations. When two or more HVDC poles share a common conductor, the DC current can commutate between different transmission paths whilst on load by use of DC side switchgear. To measure the DC voltage and DC current different types of resistive and optical DC transducers are used.

Offices and control rooms are located inside the control and service building, together with cooling plant rooms, workshops and batteries. Much of the equipment at the station generate acoustic noise, roughly between 80 dB – 110 dB, and special considerations must be made considering insulation of the buildings and layout of the equipment to meet the noise limits.

3 High Voltage Cables

Producing cables are a very neat and time-consuming procedure. The procedure and layering depends on the type of cable to be produced. For high voltage, most cables are designed and tailor-made to fit each single project. As illustrated in Figure 14, the general layout consists of the conductor in the core of the cable. The insulation system is next, then a water barrier of lead and plastic, and armoring and an outer serving furthest out.

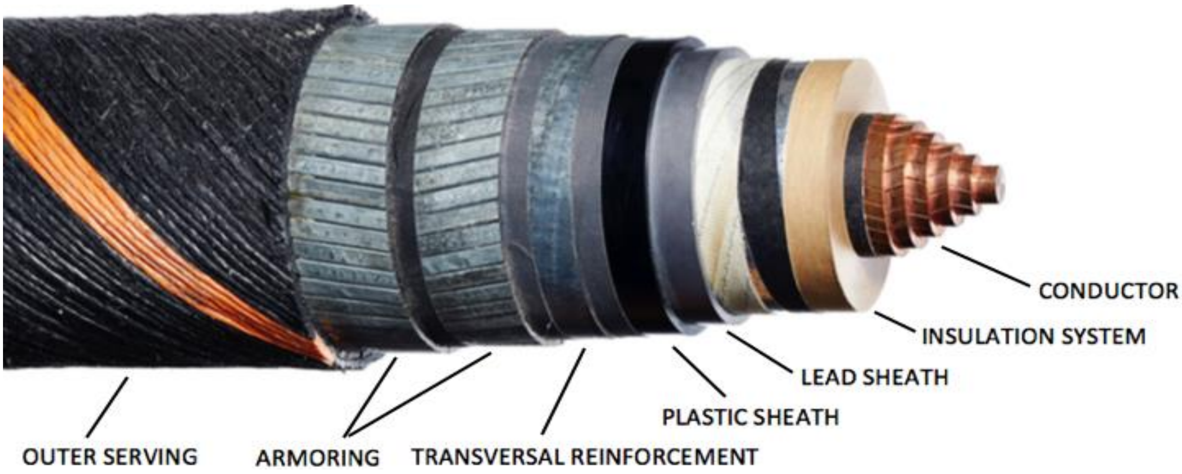


Figure 14: Submarine HVDC cable. (Nexans Norway AS)

3.1 Conductor

Conductors are made of copper or aluminum. In cases where weight is of critical concern, aluminum is more suitable as it has one third of the weight compared to copper. Copper, on the other hand, has much higher electrical conductive properties, and are therefore often preferred. The high conductivity results in a smaller cross section, and thus less insulation, armoring and other material needed. As the two conductor types can be jointed together (Nexans Norway AS), some projects have copper for one part and aluminum for the other part of the cable to get the best of both.

Non-Fluid-Filled Conductor

The conductor comes in many shapes. A solid circle conductor, as seen in Figure 15, is usually not used for higher cross sections than 400 mm^2 and are thus limited to voltage <150 kV (Worzyk, 2009). Conductors made of stranded round wires are well known and used over many years. The round shape causes small gaps in between the wires. To reduce these interstices, the conductor is compressed to get a filling factor of 92 %. This cold forming work however, reduces the electric conductivity in the material.

Stranded keystone shaped profile wires fit perfectly together resulting in a filling factor as high as 96 %. As it is done without any cold work, the conductivity is not hampered in any way. The conductor can handle large cross sections and high voltage and is therefore much used for HVDC cables.

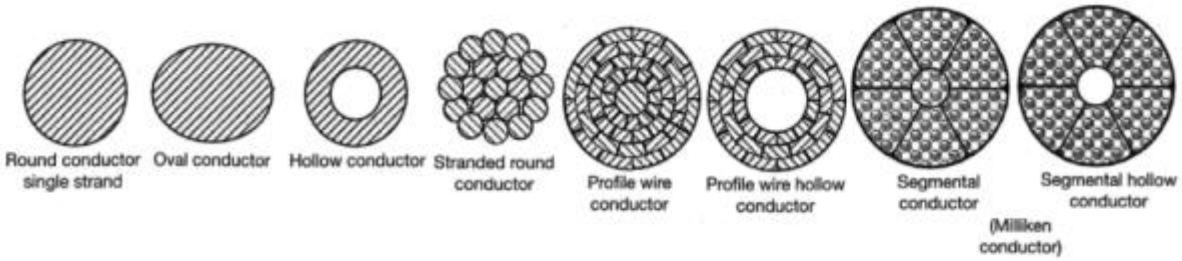


Figure 15: Cross section of conductors. (Worzyk, 2009)

The Milliken conductor is known for the segmental composition of the wire strands. It is much used for AC cables as the segments help reduce the skin effect. The conductor's current carrying capability is reduced by the skin effect. Conductors of 5-6 segments are common, though more segments will reduce the skin effect further. As the cost are quite high due to the extensive production procedures, it is mostly used for cross sections higher or equal to 1200 mm^2.

Fluid-Filled Conductor

Self-Contained Fluid-Filled (SCFF) are cables filled with low-viscosity oil in the core of the conductor and can be used for both AC and DC. The insulation is usually paper, often with different thicknesses and different dielectric strengths. In order to maintain a certain pressure required in the cable and ensure acceptable oil flow, the cable has a distance limit of approximately 30-60 km (Worzyk, 2009), and are therefore excluded for use for long distance interconnections. They are, however much used for shorter high voltage connections with high power transmission capacity. On the downside, in case of a leakage, the oil inside need to keep being pumped through the cable until the leakage is fixed, to prevent the water from getting inside the conductor. In sensitive environments, it is important to avoid such oil spills.

3.2 Insulation

To create a barrier between the surfaces, one must have an insulating material in-between. A clean and even insulation is necessary to protect against the extreme potential differences. At the same time, the insulation also has to be able to withstand temperature and aging, and be mechanically robust, in order to last throughout its planned lifetime.

The most common used insulation types are Cross-Linked Polyethylene (XLPE) and Mass-Impregnated paper (MI). For HVDC, the XLPE cable can operate at a maximum of 320 kV, which limits the capacity for power transmission, and is more suitable for smaller projects with less power needed. The MI cable is more favorable for extra high DC power transmission as the voltage can reach as high as 600 kV (2016) (Nexans Norway AS). Cables with 525 kV have been in use for many years.

Cross Linked Polyethylene

To erase any unevenness and create a smooth surface, a conductor screen, a semi-conductive compound, is applied over the conductor, approximately 1-2 mm thick. Polyethylene (PE) -based co-polymers, mixed with carbon black, make up the semi-conductive layer. Covering the conductor screen is the insulation. By applying heat and high pressure in combination with organic peroxides as additives, the hydrocarbon material, PE, is forming cross-linking between the molecules (Leader Cable Industry Berhad). High temperature can easily cause the not-chemically bonded molecules to deform. With this treatment, the material changes from being a thermoplastic to an elastic material when the molecules links to one another forming a three-dimensional network. When the temperature rise, the material will not melt, as the reaction is irreversible. Over the insulation is the insulation screen, which is a new layer of semi-conductive compound. The exact type of material depends on the voltage it is to be used with, and whether it is for AC or DC. For best result, all three layers are extruded on the cable conductor simultaneously in a triple-extrusion process. As discussed in Erfurths report (Erfurth, 2016), the life span and durability of the cables insulation and whether water will ingress and when, is an ongoing study.

Mass Impregnated Paper

The MI cable, also known as MIND cable for No-Drain to indicate no fluid-filled conductor, has been in use for many years. Currently, this kind of cable and insulation is the only one used for HVDC cables, as there are no other options available for the highest voltages. The available distance of reach becomes longer every year, and the cable can in theory be laid for infinite lengths. The set-up of the MI cable is much similar to the XLPE cable. To eliminate possible unevenness, semi-conducting carbon-black paper is wrapped around the conductor in a thin layer. For insulation, high-density paper (≈ 1.0 kg/dm^3) (Worzyk, 2009) is soaked in oil and then dried up. The paper is continuously tested before being shipped to the customer to assure the outmost quality in order to get the insulation properties needed. Neatness and cleanliness is of very high importance for this production. Paper strips of about 20 mm are helically wrapped around the conductor with a butt gap of 2 mm between the strips for every turn, to allow some movement of the strips during bending. The next paper strip is then placed over the last butt gap, covering it up. The higher the voltage is; the more layers of MI paper are needed. To protect the insulation, a new layer of semi-conducting paper is laid outside the paper insulation. All paper layers can be lapped on in one single run.

3.3 Water Protection

Outside the insulation is a layer of metallic sheath. A lead alloy sheath is more common, but copper or aluminum sheaths are also used. The sheath is to protect the insulation, both XLPE and MI, from moisture and water ingression to keep the dielectric strength. The metallic sheath will also function as a conductor for the capacitive currents and as an electrical screen (Nexans Norway AS), and has to be adjusted to allow for the short circuit current. The layer of semi-conductive sheath is applied to hinder a voltage difference between the layers.

The lead alloy can be extruded on to the cable with high accuracy and high reliability. A layer of PE is extruded outside the lead to act as corrosion protection. The layer will also work as protection for physical damage during manufacturing, transportation and installation, as the lead is very soft and can damage easily.

3.4 Armoring

For mechanical strength and protection of the cable, a layer of steel wire is helically applied. Each cable needs to be designed to withstand the static and dynamic tensional forces it is exposed to. At the same time, it also must endure the pressure and loads caused by tools during installation and possible dropped objects and snagging loads from fishing gear and anchors. The armor lay-length of the wire is the longitudinal distance on the cable between the start and finish point when the wire goes one time around the cable (Worzyk, 2009). This length will impact the mechanical properties of the cable.

With a short armor lay-length, the tensional forces are translated into a torsional force at a higher rate than a long armor lay-length, which can cause the cable to twist. A long lay-length results in less torsional forces, but also an increased bending stiffness, and thus the length need to be optimized for each case.

To add extra strength, another layer of wire can be applied. To reduce or eliminate the torsional stress, the two layers can be applied in opposite directions, canceling each other out. For deep water, this is in many cases necessary.

In between the wire layers is a thin layer of synthetic tape to reduce friction. For corrosion protection is the steel wires coated in zinc. A second protection is a layer of bitumen and two layers of black non-rotting Polypropylene (PP) yarn, to keep the bitumen from being washed out.

3.5 Three-core cable

To reduce the number of cables being laid, a 3-core cable can be used for HVAC. Each cable core is made separate with the insulation and metallic screen, then put together forming a triangle as shown in Figure 16. To create a full circle, the empty space is filled up with filler material to increase the mechanical properties of the cable. Other kinds of cable, like fiber optics, can also be placed in the empty space. The conductors, the filler material and the fiber optics are then twisted all at once, in one big operation, and held together by semi-conducting tape. The armoring and corrosion protection is then laid on the outside, creating one cable.

Figure 16: 3-core HVAC cable. (Nexans Norway AS)

3.6 Design for Tensional Strength

For the cable to last throughout its intended lifetime it has to be able to withstand all mechanical stresses in all the phases of its life. This include manufacturing, transportation and operation as well as installation. With a poor and weak design, the cable will have a higher risk of getting damaged and thus a higher risk of extra cost due to repair and downtime, or in worst case, abandonment.

During installation, the water depth is the main variable when calculating the required tensional strength. The static force due to the weight of the cable hanging down from the vessel to the seabed is calculated as

$$T_s = w * d$$

where w is the weight of the cable in water per meter and d is the maximum water depth. For simplification, the extra length between the laying wheel and water level is neglected as it contributes very little to the total tension. To avoid compression and critically small bending radius in the cable, the cable is always held in tension at touch down (TD) point. The additional horizontal tension translates to vertical tension at the top of the cable and causes the cable line to form a catenary shape. As the catenary length s is longer than a cable hanging straight down, the total tension become

$$T = \sqrt{T_0^2 + (ws)^2}$$

where T_0 is the horizontal tension at TD.

Calculating the dynamic contribution to the tension is a complex task, as the forces can be affected by many parameters, such as weather conditions and the response amplitude operator (RAO) of the vessel. Due to ocean waves, the cable is exposed to dynamic forces. The wave induced vessel motion causes the laying wheel or chute to move vertically. To account for these forces, the maximum vertical acceleration b_{max} of the wheel is found by

$$b_{max} = \frac{h}{2} * \left(\frac{2\pi}{P}\right)^2$$

assuming the movements are sinusoidal (Worzyk, 2009). Here h is the maximum vertical movement, from peak to peak, and P is its period, between the wave peaks. With m being the mass of the cable hanging from the vessel, the maximum tension in the cable can now be found as

$$T = T_s + (m * b_{max})$$

It is mainly pitch and heave motions that contribute to the vertical motion of the laying wheel, but how severe the motions are will vary from vessel to vessel as they all have different motion characteristics. In reality, waves do not often have a fully sinusoidal waveform. They can be both steeper and shorter. The dynamic forces can also be larger than anticipated by the sinus formula, due to superimposed waves from different directions and sources. The steeper waves result in a higher vertical acceleration in the laying wheel. A weather forecast is rarely 100% accurate, and one should always have in mind that only a few unexpected waves of great amplitude can be enough to damage the cable. For a conservative approach, one should use a value of $b_{max} = 6\ ms^{-2}$ *(Worzyk, 2009)*, especially if no documentation on the vessels vertical behavior is present.

The updated version of the Cigré test recommendation for submarine power cables known as Electra No. 171 (Cigré Working Group B1.43, 2015) presents equations for finding an estimate of the maximum tensile force occurring in the cable during installation. The tensile forces during the test have to be larger than any tensile forces experienced throughout the whole installation process. The equations are valid for both MI and XLPE cables of voltages higher than 30 kV AC or 60 kV DC. For a maximum water depth of 500 m the test tension is found as

$$T = 1.3 * w * d + H$$

with $H=0.2*w*d$ being the maximum bottom tension during installation, and always above $40*w$ [N]. To include the contribution from dynamical forces, a factor of *1.3* is added. By using this, the significant wave height is limited to $H_s \leq 2\ m$. For more severe weather, one should follow the procedure below for water depths beyond 500 m, where the movement of the laying wheel is included. The expected maximum tension is

$$T_E = w * d + H + D$$

where D is the dynamic tension, a combination between the drag force and the inertia acting on the cable.

$$D = \sqrt{D_I^2 + D_D^2}$$

Inertia force:

$$D_I = 1.1 * \frac{h}{2} * m * s * \omega^2$$

where, as stated previously, h is the maximum vertical displacement of the laying wheel, m is the cable mass per meter, s is the catenary shaped length of the cable, $\omega=2\pi/t$ is the circular frequency of the laying wheel movement. The added mass that will move with the cable is accounted for by a factor of *1.1*.

Drag force:

$$D_D = 500 * OD * R^{0.9} * (h\omega)^{1.8}$$

where *OD* is the outer diameter of the cable and the term *R*, *R=H/w,* is the bending radius close to TD. The term is composed after a thorough study, and to ensure a conservative result the constants *500, 0.9* and *1.8* were determined when using SI units. The worst allowed weather conditions and the planned installation vessel should be the basis for movement and period. The maximum expected wave height H_{max} is found by $H_{max}=H_s*1.9$ and should be the basis for estimating *h,* the vertical movement of the laying wheel.

The test tension is now found by adding a safety factor to the expected tension:

$$T = 1.1T_S + 1.3T_D$$

where $T_s=w*d+H$ is the static tension and $T_D=D$ is the dynamic tension.

Calculating the real combined effect of the forces is a complex procedure, as opposed to each source separately. For this reason, software tools are developed, and used by most engineering companies. When designing the cable armoring, one need to know which sea state to design for. The sea state is affected by the season in which the cable is to be installed and the weather statistics of the area. Number of suitable weather windows is affected by the sea state one choose to design for, which also affects the risk associated with cost due to termination of operation and duration of the installation.

4 HVDC Cable Installation

When installing a subsea cable there are many things to think through. The selected route and whether it is a single cable length going from A to B or a long-distance connection consisting of multiple cable sections being spliced together affect how it is done. The location and layout of the landing stations and where to start and finish the cable are different for each single project.

According to DNV-RP-J301 for shallow water (DNV GL AS, 2014), there are no limitations on how to install the cable. The method for laying a cable will vary depending on the surrounding conditions. Especially whether it is in the ocean or in a lake. The accessibility in a lake can be low and one should consider using other methods than in the ocean. Laying in a fjord can be limited due to narrow waters. One need to make sure there is a passage wide and deep enough for the vessel to get through. It is therefore important to have done a thorough survey of the route before selecting and starting the laying. Once the laying has started, it is harder and much more expensive to make any changes is the plan. The survey will identify obstacles and potential hazards such as unsuitable weather conditions and currents, seabed conditions, other cables and pipelines, ongoing oil and gas projects, and areas with special environmental concern.

The technology has evolved since the first cable was laid, and the equipment becomes more advanced than ever, gaining more control over the operation. Nevertheless, the procedure is still time-consuming and demanding. Some of its equipment, methods and uncertainties concerning cable installation will be discussed in this chapter.

4.1 Cable-Lay Vessel

A Cable-Lay Vessel (CLV) is a ship or barge specially built for the sole purpose of laying and repairing subsea cables. Accompanying the CLV are often smaller tug boats stored on the CLV deck when not in use or during transit. When planning an installation operation there are many things that need to be considered, like storage capacity, tension capacity and equipment needed to do a safe and successful installation. Some of these subjects are discussed in this chapter.

4.1.1 Vessel Positioning

Keeping the correct position at sea is of crucial importance for a successful cable lay. Waves and currents will always push on the vessel for it to move. Once the cable is being payed out, it will be pulling in the vessel. The tension in the cable from its own weight and the bottom tension will pull the vessel backwards. A wrong vessel position can cause the bottom tension to decrease to a minimum, or in worst case, result in compression forces and damage in the cable at TD.

Old cable barges can be assisted by powerful tugs to pull the barge. To slow down, the cable payout speed can be reduced while the tugs keep going to maintain the required tension in the cable. Manual anchor handling by anchor handling tugs are still used, mostly for cable laying barges with no propulsion of their own, but very rarely as it is a cumbersome method.

Most new CLV relay on a dynamical position (DP) system with powerful thrusters. By having multiple thrusters one can manage and keep the required position of the vessel at all time. The thrusters can be located both in the bow and stern as well as in the center underneath the vessel. The whole system may consist of different types of thrusters, all connected to the navigation and computer system, working together to stay at the desired location in the correct position. There are different types of thrusters with various qualities; tunnel thrusters, retractable thrusters, azimuth thrusters that can turn 360 degrees and variable pitch thrusters.

The vessel keep its location according to a global coordinate system (Solberg, 2017). To keep the TD point of the cable at its required position, it coordinates its local location to the global location of the vessel. The entire route of the cable is settled upon before the laying starts after a thorough route survey. The route is sketched up by using way points (WP), where each WP is a coordinate location. To keep track of where one is on the cable route, every km is denoted as a km-post (KP). The vessels DP system follow these coordinates at all time to make sure the cables TD is at the correct location. Being 1-2 meter off track is usually acceptable, especially where the seabed is flat and without any hinders. On a rocky seabed, the accuracy of the cable-lay becomes more critical to avoid laying the cable over sharp rocks, and rather in between them.

4.1.2 Cable Storage

The cables are stored on large reels or in tanks. The same storage options on shore can be used on the vessel during installation. The storage methods have different qualities and the type of cable and armoring may influence the decision. A vertical reel (Solberg, 2016) gives the advantage of simple installation where break can be applied directly to the reel flange. It is however, hard to control at deep water due to the high tension in the cable. The high center of gravity (COG), as seen in Figure 17 a), will also result in limited capacity to maintain the stability of the vessel, and is more common for smaller projects that does not require large load capacity.

A horizontal reel will lower the COG and increase the capacity. Some tension can be taken by the reel to aid the external tensioners. The packing of the cable, vertically around the core of the reel, can be tricky if not done right. For the cable to stay in place and prevent disorder, it needs to be held in tension at all times.

A simple solution of coiling the cable into a fixed tank is an option, but the coil itself cannot handle any tension, and must be controlled by external tensioners. If having a cross armored cable, a turntable is a great option as it handles the cable more gently, but also here, the tension must be taken by external tensioners, resulting in an expensive installation.

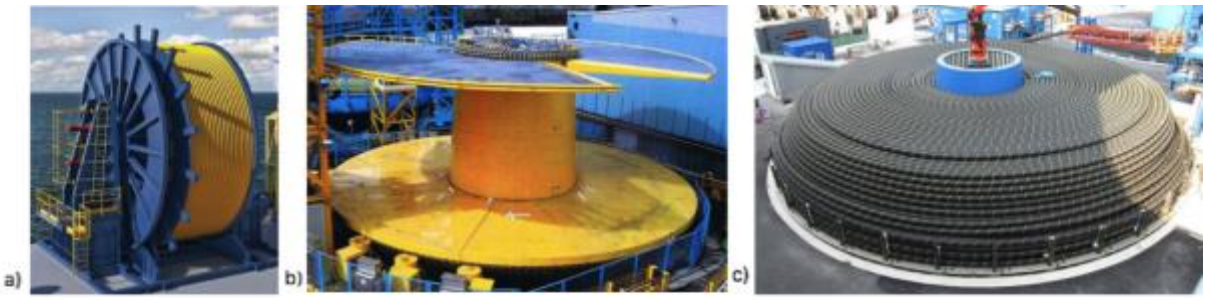


Figure 17: Storage of submarine power cables, a) Vertical reel (Subsea World News), b) Horizontal reel (Solberg, 2016), c) Turntable (Haun, 2014).

The cable length a vessel can carry depends on both the weight and dimensions of the cable and the load capacity of the vessel. To reduce time and costs, the cable storage should carry maximum allowed capacity. This will reduce the trips back and forth and the number of cable joints along the whole distance.

4.1.3 Vessel Stability

Full control over a vessel's stability is crucial in any operation at sea. The stability of the CLV and how much ballast is needed has to be calculated before loading. When loading the vessel, all cable load is applied at one location. With no ballast, the keel can experience some deflection due to the high concentrated load at the center of the vessel. The vessel has a fixed cable load it can accept, but the coil height and the COG of this load will change as the volume of the cable change. The accepted load capacity divided by the cable weight per meter gives the total cable length to be loaded on the vessel. For simplification, the cable is assumed to be square when calculating the total volume (Solberg, 2017). The coil height is then found by

$$L_{cable} = \frac{C_{load}}{w_{cable,air}}$$

$$V_{cable} = OD_{cable}{}^{2} * L_{cable}$$

$$H_{coil} = \left(\frac{V_{cable}}{(R^2 - r^2)\pi}\right) * 0.95$$

where:
L_{cable} is the total length of the cable
C_{load} is the load capacity of the vessel
W_{air} is the weight per meter of cable in air
V_{cable} is the volume of the whole cable length
OD_{cable} is the outer diameter of the cable
H_{coil} is the coil height
R and r is the outer and inner diameter of the vessels turntable

The coil height is assumed to sink by 5 % (Solberg, 2016). Although the calculation is not exact, experience shows that it is a good approximation, and is therefore in use by cable laying companies.

For the lay to go smooth, the stability of the cable coil needs to be assured. As the table turn the cable will experience some acceleration. The cables are placed in the gap between the two cables underneath, creating a triangle, as seen in Figure 18. Due to this, the rings of cables will be interlocking.

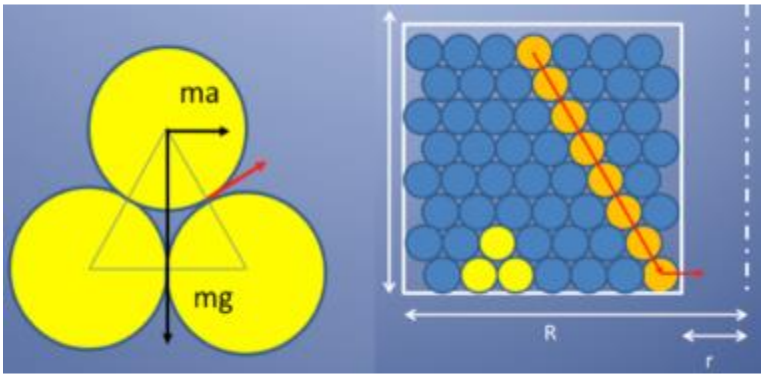


Figure 18: Cable placement on a turntable. (Solberg, 2016)

4.1.4 Cable Tensioners

Once the pay out of cable has started, tension is rising and will start to pull on the cable and on the vessel. Previously this tension was held back by manual labor. As the water depth increased and the cable weight got heavier, this became impossible. A CLV is now equipped with tensioners with different capacities for different purposes.

Caterpillar Tensioner

A caterpillar holds the cable by use of belts. The tensioner can have two, three or four belts, depending on the tension capacity it needs to have, that are pressed against the cable on opposite sides, as seen in Figure 19 a). It can be used for tension and speed control during both load in and pay out of the cable. The capacity depends on the number of belts and the pressure applied by each belt seen in the equation below (Solberg, 2016):

$$T_{max} = n * \mu * P * l$$

Where:
n = number of belts
μ = friction factor, typically 0.2
P = clamping force per meter length
l = length of contact on the belt, normally < 2.5 m
Max speed is typically 20 m/min

This equipment is simple and easily installed. Nonetheless, this is not always the standard, and thus have few standard components.

Figure 19: Cable tensioners; a) Caterpillar (4 All Ports), b) Linear Engine (Photo: Louise Våbenø), c) Capstan (Solberg, 2016).

Linear Cable Engine

Wheels in two straight lines built up to a linear cable engine can be considered, as seen in Figure 19 b). This equipment can have both higher speed, about 100 m/min, and quicker response than the caterpillar, but they both can be very sensitive to locally low friction. Each wheel is driven by a separate motor, and each wheel pair can handle about 700-800 kg in tension (Solberg, 2016).

Capstan

The capstan is usually the main tensioner on the vessel if present and a vital equipment during pay out. It is a costly and large design that requires some space on the vessel. As seen in Figure 19 c), the cable goes in circles, normally three times, around the capstans drum and is then straighten out as it goes over the laying wheel and into the water. The first turn takes 80 % of the load; the second turn takes 15 % of the load, while the last turn takes approximately 5 % of the load (Solberg, 2016). The capacity depends on how many times the cable goes around the drum, but can typically hold about 40 ton and have a maximum speed of 50 m/min. The technique is simple but has a slow response. It is not affected much by low friction locally and is a very safe equipment as there is no chance of slippage.

Capstan Formula (Solberg, 2016):

$$T_{max} = T_0 * e^{\mu\alpha}$$

Where:
T_0 = tension into the system
μ = friction factor
α = 6π (due to three times the circle)

Line Pressure Formula:

$$P = \frac{T_{max}}{r_{capstan}}$$

4.2 Loading and Landing of Cable

Once the seabed and route survey is finished and the cable is ready for installation, the CLV is heading for the factory to start loadout. The cable, being stored at shore, is fed through an onshore caterpillar and then further in over the stern laying wheel on the vessel, as seen in Figure 20. The cable end is connected to a "pull in head", also known as a "Chinese finger", and hooked to a winch on board the vessel. On the CLV the cable goes through the linear machine and the caterpillar, but not the capstan, as the tension is not at its highest at this point. The use of capstan causes the cable to bend and unbend. Although it is within the safe limit, it is not wanted if not necessary. The caterpillar on shore starts up first to give the cable some slack, then the crew on board can start the linear machine and the cable gets pulled in and over the to the turntable, which starts slowly to rotate as the cable is loaded on. The vessel runs at fixed speed, while the onshore caterpillar adjusts to keep the catenary in a middle position, not too tight and not with too much slack. One standard loading session of a cable can take as much as 1-2 weeks to finish.

Figure 20: Cable loading to CLV (photo: Louise Våbenø).

4.2.1 First-End Pull-in

Depending on the seabed conditions close to shore and the need for protection of the cable, the pull-in can be done in different ways. The cable can be pulled in over beach-like conditions, connected to the landing station, and will then follow the slope of the seabed out into the ocean. In an area with less smooth ground, large rocks and hard ground, one should make other arrangements. This can be fixed my making a trench and have the cable pulled in through a pipe, as seen in Figure 21. One can also drill and have the cable pulled in to shore through a micro tunnel at a deeper water depth where the seabed is better suited. This way the cable is better protected against later activities near shore. In many cases, the water depth is too shallow near shore and the pull-in has to be done by a smaller shallow draft vessel, leaving the main vessel further out in deeper water.

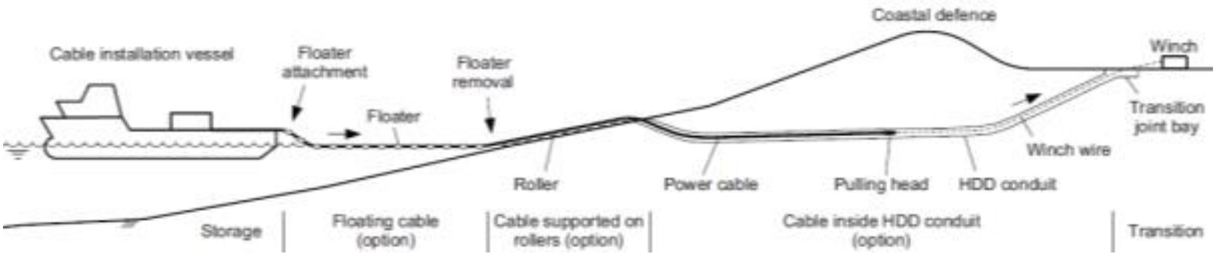


Figure 21: Cable pull-in. (DNV GL AS, 2014)

When the laying of the cable starts, the end of the cable, fixed to a Chinese finger, is connected to the capstan before going back over the laying wheel. The water depth at the location determines how close the CLV gets to shore, and the distance from the vessel to the connection point at shore, sometimes as far as 3000m, is measured and the cable is payed out the measured length. To keep the cable from sinking, it is floated out on buoyancy elements that are placed underneath the cable as it is being payed out. Each element consists of two pillow-shaped parts, connected at the long end. When the weight of the cable is laid in between the pillows, they get pushed towards each other, locking itself to the cable. The end of the cable is pulled out by a tug, leading it towards shore. When reaching shore, the cable is hooked on to a winch-wire, getting ready to be pulled through a micro tunnel in the ground. The tunnel is in many cases at the maximum depth at the beach and leads to a station at shore. To disconnect the buoyancy pillows, the cable is lead over an over-boarding bow on a small barge. The pillows are there removed one by one, as the cable is going down into the water. The pillows, all being connected to each other by a rope, are collected by the main vessel for later use. When the cable has reached the landing station, the cable is laid down at the seabed as the barge is moving closer to the CLV. With all the buoyancy elements removed, the cable laying can continue out on the route.

At places where the micro tunnel comes out at a depth deep enough for the vessel to come up close, there are no need for buoyancy elements. The cable can then directly be pulled through the tunnel without the use of tugs. This is also the case when connecting a cable to a platform offshore. The cable is then lowered to the seafloor, and pulled through the J-tube up to the top of the platform.

4.2.2 Second-End Pull-In

Second-end pull-in is done at the end of a cable lay, where the whole distance is covered by one cable length with no splices. The procedure is much like the first end, except that here, the cable need to be cut and released from the vessel. The CLV lay the cable as close to shore as possible. The distance left is measured and the cable is cut to fit the length. Getting the right length of cable is very important, as a too short cable results in jointing on a new piece. This causes both time delay and cost increase as well as an increased risk of failure in the cable due to the jointing.

When getting close to shore, the buoyancy pillows is attached to the cable, keeping it floating at water level. It is further laid in a large half-circle as the CLV takes a U-turn. When reaching the end, the cable is connected to a tug that will steer the cable in the right direction. The cable is now completely disconnected from the CLV and the rest of the job can be done using tugs, with the CLV standing at a safe distance for observation. Other tugs will keep the cable from bending too much by pulling in the cable and keeping the half-circle large enough. When reaching the spot for the cable pull-in, a barge with an over-boarding bow is connected to the cable to remove the pillows and let the cable be pulled in through the tunnel or J-tube. To prevent the cable from sinking too fast and falling straight down and creating a loop at the seabed when removing the last pillows, the air in one half of the buoyancy element is let out. The cable can now be safely pulled in as the pillow slowly descends. When all the air is out of the pillow, it will disconnect from the cable and float back up to surface by the other half of the element, still filled with air.

4.3 Cable Lay

When installing a cable there are many individual motors and equipment that need to cooperate and work together to achieve the desired result. As seen in Figure 22, the laying operation is influenced by many factors. One of the largest concerns is to keep just about the right amount of tension in the cable. The vessel and the tensioners need to coordinate their speed so the payout speed of cable and the tension in the cable is correct. All the variables can affect the end-result in different ways. Too high tension can damage the cable when going above its design limit, and too low can cause longitudinal compression in the cable, damaging the layers inside and its conductive abilities. Too low tension at TD may also result in too small bending radius in the cable, damaging it, or cause the cable to loop instead of being laid in a straight line. Cables with one layer of steel wire armoring have a higher possibility of looping at the seabed due to unwanted torsional forces in the cable (Worzyk, 2009). The difference in tension from the vessel to TD transfer to torsional forces that can result in loops at the bottom. If not noticed, these loops can cause some serious damage to the cable where it needs to be cut and jointed together.

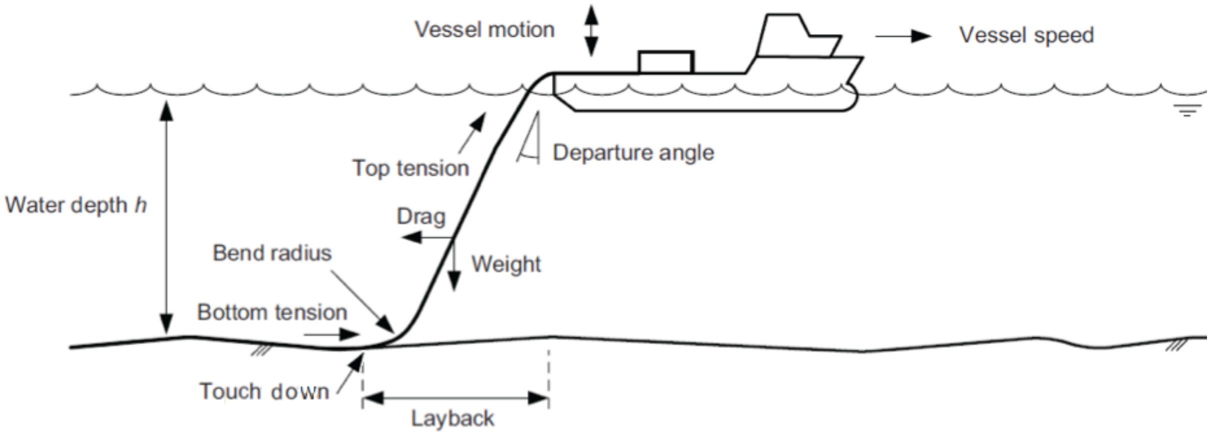


Figure 22: Factors influencing the laying procedure. (DNV GL AS, 2014)

Controlling the tension is done by monitoring all the variables. The departure angle of the cable when it leaves the laying wheel together with the water depth and layback length can be used to calculate the tension. This is applicable for shallow and intermediate water. In very deep water the departure angle change very little and goes more or less straight down giving no real indications of the situation on the seabed (Makai Ocean Engineering). A remotely operated vehicle (ROV) equipped with camera and positioning device can give very accurate data about the cables whereabouts, its layback length and position relative to the vessel and the planned cable route. When the surrounding conditions change, the vessel speed or the payout speed need to change with it. Speeding up the vessel for a short distance will increase the cable tension, while speeding up the cable payout reduces the tension.

Both the vessel and the cable are subjected to external forces due to the weather situation. The waves have a large impact on the vessel motions. The DP system can reduce the lateral movements like surge and sway, but the vessel will still experience heave motions. At the top of a wave the depth increases with the crest height of the wave, and at the bottom of the wave it is reduced by the wave trough. The vessels pitch motion caused by waves causes the laying wheel at the stern of the vessel to move up and down. This motion will both change the tension in the cable and change the departure angle when the cable leaves the laying wheel. These vessel motions combined with the speed of the vessel will change the tension in the cable all the time, which then changes the location of TD and the bend radius in the cable.

Strong drag forces hitting the cable result in erroneous results. Current going in vessel direction cause higher tension in the cable and current going against the vessel cause a lower tension in the cable as it is being “lifted”.

The seabed bathymetry also needs to be taken into calculations. Every time the water depth changes, and the flat seabed becomes a slope, the parameters change. To reduce the bottom tension at the TD one normally pays out more cable. When paying out more cable in a down-slope the top tension increase as it gets deeper. If one is not careful one may end up paying out too much. The same caution must be seen when going up-hill.

For better positioning and control of the cable at the seabed, a Captrack can be used (Nexans Norway AS). It is a tactical underwater vehicle (TUV) located on top of the cable near TD during the laying, and towed and operated from the vessel. It provides video and exact position of the cable near TD point. The tension in the cable and angle of the cable can be calculated and provide navigation input to the computers onboard the laying vessel. In addition, one can use a ROV for visual effect and better control of the situation.

4.3.1 Cable-lay Around Obstacles

When approaching an obstacle, the cable may have to be laid around it in a bend, as illustrated in Figure 23. The soil conditions and required bottom tension in the cable both have an impact on the radius it need to be laid in. Cables being laid in too small radiuses can risk being dragged along on the ground due to the high tension in the cable at the seabed. To avoid having the cable pull towards the obstacle as the curve is laid, it is recommended that the curve is not initiated until after a distance L_S after passing the obstacle. The radius R_S and length L_S can be calculated with the following equation

$$R_S = L_S = \frac{FH}{w\mu}$$

where F is the safety factor, H is the horizontal bottom tension in cable, w is the cable weight in water per unit length, and μ is the friction factor between cable and seabed soil (Worzyk, 2009).

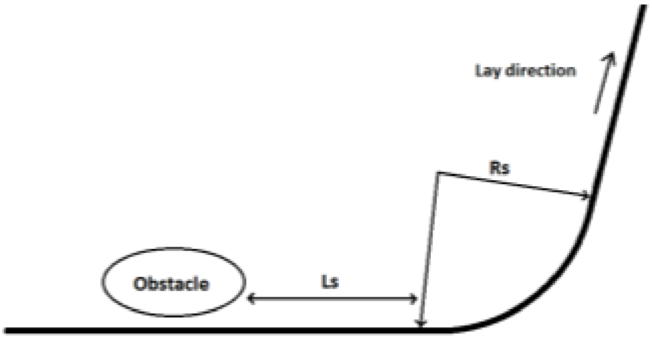


Figure 23: Laying cable in a curve after passing an obstacle.

4.3.2 Cable Suspension

The conditions on the seabed have a large effect on the tension in the cable. A smooth flat surface would be desirable, but that is commonly not the case. Other than regular up- and down-slops as one move into deeper or shallower water, an area can be characterized by an uneven terrain. When holding a constant vessel speed and cable payout moving in over an irregular seabed, the cable tends to get a too high tension causing cable suspension in between two higher points as seen in Figure 24. The cable is then subjected to a point load at the touching point between the cable and the high point. Over time it will tear and damage the cable due to unwanted friction and chafing and reduce the life expectancy. A thorough and good seabed survey in combination with the use of ROV during installation is important to achieve the best result. The survey provides a basis for planning and selection of the most appropriate route. The ROV can by using a camera assure that the cable ends up in the planned route. The camera can also capture elements that were not revealed in the survey or new elements that have emerged later.

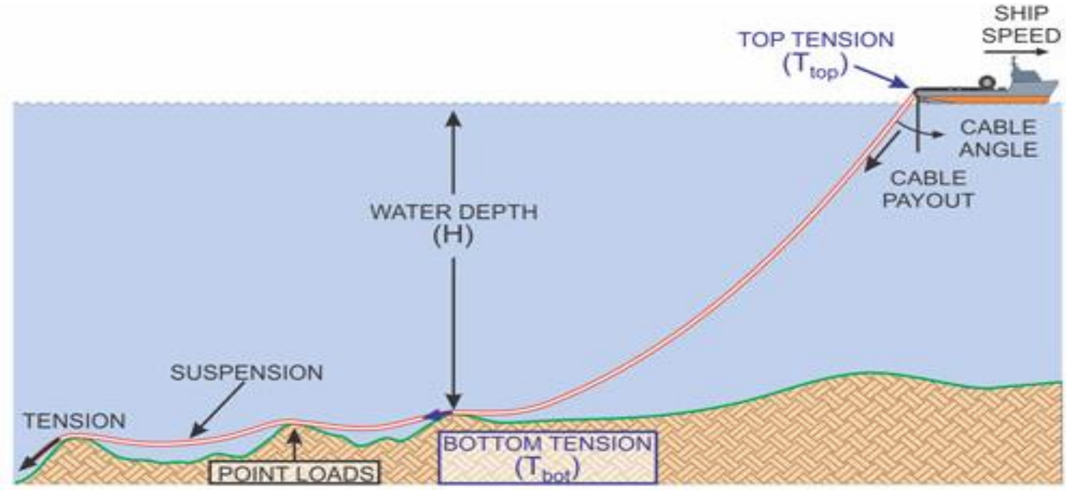


Figure 24: Too high top tension. (Makai Ocean Engineering)

With current in the area, the cable suspension may be subjected to vortex induced vibrations (VIV). If it results in a lock-in of the cables natural frequency and the vortex shedding frequency, one will experience a rapid decrease in the cables life expectancy. However, this is also influenced by the length of the free span. In DNV-RP-F105 it is stated that free span lengths that are less than 30 times the diameter ($L_s/D < 30$) will have very little dynamic amplification. "Normally not required to perform comprehensive fatigue design check. Insignificant dynamic response from environmental loads expected and unlikely to experience VIV" (DNV GL AS, 2006). Still, small suspensions are not desirable, as the damage of a dropped object impact load can be larger on a suspended cable section than on a cable laid flat on the seabed.

If it is not possible to avoid or lay around the obstacles, one should attempt to shorten the suspensions. By reducing the bottom tension the cable will follow the curves and be laid down into the gaps. The suspension and the corresponding point loads and friction reduces to a minimum as seen in Figure 25. One still needs to be careful and stay within the range of acceptable bottom tension to ensure sufficient bend radius, both near the TD and at other sharp angles. In cases where reduced tension is not enough to fix the problem other considerations need to be made. Over smaller areas, one can fill in the gaps with gravel. For a larger area where the cost of filling is large, one may have to consider another route or extended cable protection. By using a proper software combined with the right equipment one can always know the location of TD and the bottom tension to have control when the conditions change.

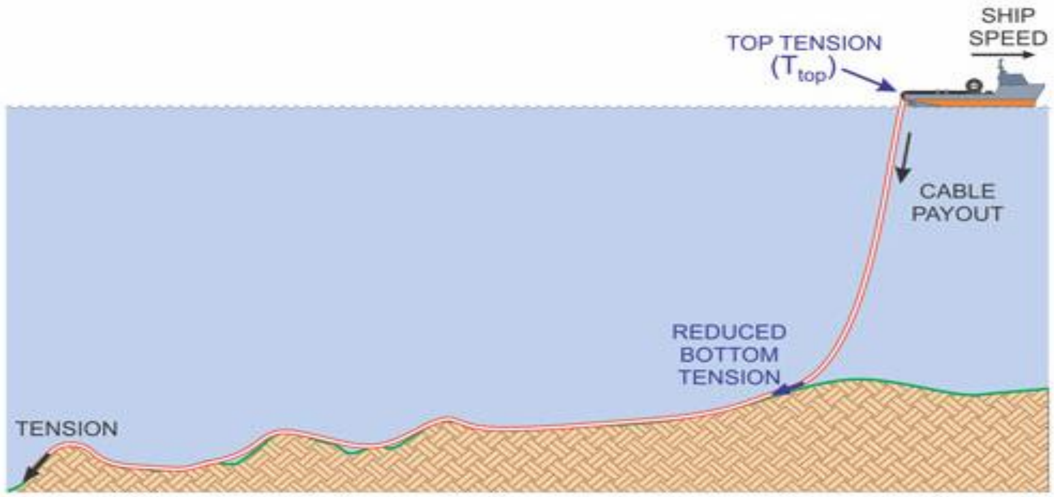


Figure 25: Reduced top tension. (Makai Ocean Engineering)

4.4 Cable Jointing

With many new projects the distance for cable installations increases, and with it increases the number of cable joints necessary to complete a project. Cable jointing occur during, at the end or after an installation, on board the CLV inside a special built jointing house. The operation is a very weather sensitive task due to its duration. Depending on the type and complexity of the cable, a jointing operation can take as much as 8 till 12 days (Solberg, 2017).

During cable installation, cables are jointed together at the end of a cable length. Before going back to shore to retrieve a new cable length, the end of cable A is carefully sealed and laid down at the seabed. When returning with the new cable, cable B, Cable A is picked up from the seabed and comes back up over the laying wheel, into the tensioner and onto the turntable and then further over to the jointing table as illustrated in Figure 26. Cable B goes directly from the turntable and over to the jointing table from the opposite direction, meeting cable A. The cable goes around the over-boarding bow at the end of the table. When the jointing is finished and the laying can continue, the bow moves down towards the turntable where the jointed cable is lifted off and laid down on the turntable.

Jointing can also be due to unplanned cutting of the cable in severe weather or other emergencies where the need to leave the site quickly is present. An iceberg approaching in the middle of a jointing, can result in cutting and re-jointing of the cable. The cable is then cut, sealed and carefully laid down at the seabed. The cables can then be jointed when returning to the location.

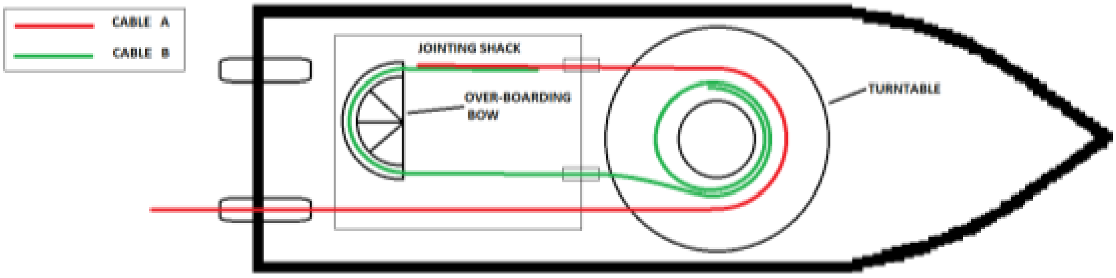


Figure 26: In-Line joint of two cables.

At the end of an installation, two cables coming from opposite directions can be laid down and jointed later. The cables will derail from the planned route and laid in a spur in an angle that is preferably to the wave direction. The length of the spur route is affected by the water depth and the magnitude of the bottom tension in order to keep the cable stable at the seabed. The length needs to account for the maximum tension in the cable at TD due to the waves.

When ready for jointing, both cables are pulled up over two different laying wheels or chutes and onto the vessel. Cable A is laid around an over-boarding bow, and is then meeting cable B at the jointing table, as seen in Figure 27. When the jointing is finished and the cable can be laid down, the bow starts to move down towards the stern of the CLV. The bow is held by winches and is then lowered into the sea with the cable still on. The bow is to ensure sufficient bending radius in the cable. At the seabed, the cable is disconnected from the bow, and the bow is lifted back up.

Figure 27: Hair-pin joint of two cables.

This jointing operation, also known as a hairpin-joint, is necessary when repairing a damaged cable. Cables that are damaged, e.g. by trawlers or anchors being hooked to the cable and dragging it along the seabed, need to be cut. When the cable is cut, the ends of the cable are pulled up, the damaged part is cut of and the first end can be jointed together with a new length of cable stored at the CLV with an in-line joint. With the first joint done, the new cable is laid down until it reaches the second end of the cut cable. The second joint result in a hairpin-joint, as the rest of the cable is already finished.

4.5 Cable Protection

As the cable is meant to last for many years to come, it need to be protected from both man-made and natural threats. Protective measures can be carried out at all stages of an installation; before, during and after, and include cable design, route selection and external protection of the cable (Worzyk, 2009).

The cable is designed to withstand external forces and the dimensions and armoring chosen is the first step in protecting the cable. The metallic armor gives strength to withstand both longitudinal tension forces and impact forces from the side. The water protection prohibit water from entering the cable and hence prevent the metal from corroding and weakening. To get some additional protection over a rough area or over cable and pipeline crossings, plastic shells, uraduct, can be attached to the cable before leaving the vessel. The covers can be used for the needed length when other methods are not feasible.

A well-planned cable route can be the whole difference between failure and success. Bottom tension in steep slopes or cliffs are hard to control and it is in many cases better to take a longer route than the shortcut. The same can be done to reduce the risk of cable suspensions. Laying around peaks and letting it follow the seabed's natural valley reduces the number of slopes and the peaks can function as protection for the cable.

The seabed soil can be too hard to make a trench or so soft that the cable risks sinking deeper than initially intended, or both, soft at the top and hard rock underneath, making it hard to get the desired burial depth. The motions of the sea, like waves, tidal flow and currents, can cause big changes to the environment after the installation is completed and render it unprotected. Erosion of the beach and sediment movement at the seabed can uncover and remove the protective layer over the cable and cause free spans to occur. These factors, as seen in Figure 28, are important when deciding the route and further protection.

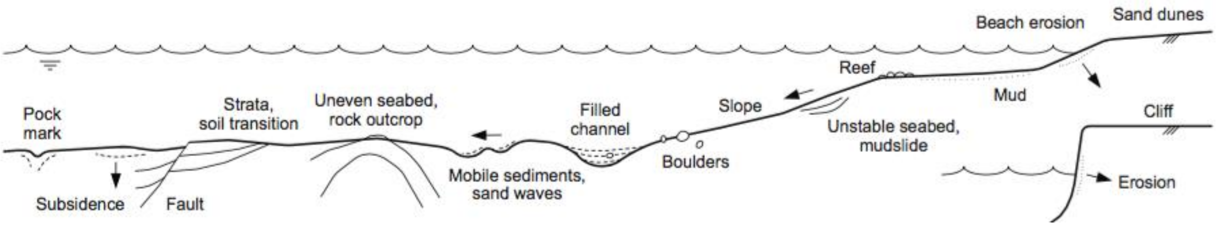


Figure 28: Potential geological features along a cable route. (DNV GL AS, 2014)

The route needs to avoid offshore oil projects, unless if that is the destination, as well as uneven seabed, steep slopes and canyons. Future oil projects should be avoided too if the location is already known, and one should stay well outside of the safety zone. Both the new cable and existing cables and pipelines need to be protected at a crossing. Reducing the number of crossings are desirable for both parties. Fishing areas and shipping lanes increase the risk of getting hooked by an anchor or damaged by trawlers, and the route through these areas should be limited. The location of a cable is not always known, and the activity in the water nearby will go on as if nothing is there. The activity is larger at shallow water and the need for protection is thus greater.

A widely-used protection method is to bury the cable, also known as trenching. Water depth and seabed conditions and sediments along the cable route are limiting factors for whether it is a suitable option, or which method to use. As seen in Figure 29, the different methods are suitable for different ground conditions.

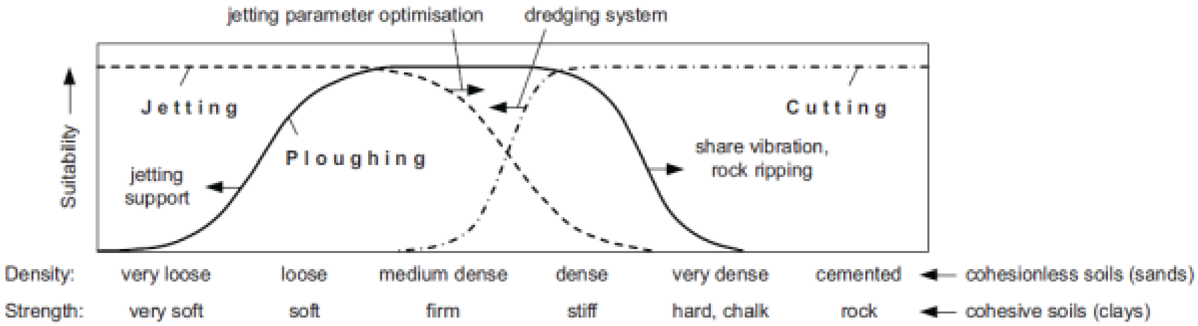


Figure 29: Burial method suitability in different ground conditions. (DNV GL AS, 2014)

A sea-plow buries the cable simultaneously with the installation and one gets immediate protection of the cable. The cable is threaded through the plow and just before the cable touch the seabed the plow makes a trench for the cable to insert in to. The plow is towed by the laying vessel, and when approaching an obstacle, like a crossing cable or pipe, which it cannot plow through, the plow is simply lifted up and set back down when the obstacle has passed, still with the cable going through the plow. It combines the work steps and require one large vessel that can handle laying and burial at the same time. The plow is large and heavy and therefore requires a large bollard pull. It has a limited use in deeper water as the towing chain becomes very heavy and the control over position is strongly reduced (Hettinger and Machin, 2006). The procedure has a high backfill quality over the cable, but is not very suitable close to existing infrastructure as it has a low maneuverability (DNV GL AS, 2014). It is not very suitable for post-lay burial (PLB) and not applicable for burying loops and repaired joints, like hairpin-joints. Some trenching systems have a plow combined with jetting to get the best result.

Water jetting by a ROV can be used in cases where the PLB is necessary, such as cable loops or after cable repair. Cable inspection and re-burial by ROV might be necessary as the cable can be exposed due to movements of the sediments over time. One should therefore not assume that burial equals full protection. Where the plow has more limitations due to uneven bathymetry, a ROV can be fully functional. The jetting is more dependent on softer soil to work and has a shallower burial depth, 1-2 m (Hettinger and Machin, 2006). The ROV is a lighter tool and thus more sensitive to the currents on the seabed.

In hard soil, like rock or hard chalk, mechanical cutting might be necessary. It is mostly used for trenching before the cable installation, but can also be used after. The hard soil results in slow progress forward and low backfill quality, and are therefore often used for shorter distances.

How deep a cable needs to be buried depends on the level of protection it needs and the movement of the sediments in the area. A shallow burial causes less disturbance to the environment and is an easier process, but it also leaves the cable more vulnerable to exposure by movements of sediments. Deeper burial is only efficient to a certain depth. After that, the cost of burial and retrieving the cable for repair is higher than the reward.

Other methods should be introduced in areas where seabed conditions or existing equipment, like pipes or cables, do not allow for cable burial. This can be rock placement, articulated ducting or concrete mattresses, seen in Figure 30, which all can be installed after the cable is installed. The ducting are half-pipes often made of cast iron or PE that can be installed by divers (Worzyk, 2009). It is often used in combination with mattresses or rocks. The concrete mattresses can be laid down from a vessel or by a ROV closer to the seabed. With the associated cost and its corrosion resistant properties, concrete matting has proven to be an effective method (SPS Concrete Specialists). Rock dumping should be performed by a flexible fall-pipe to increase the accuracy of the rock placement and reduce the waste of rocks falling elsewhere. To assure the on-bottom stability of the cable and prevent hydrodynamic forces to move the cable out of its position, one should follow the DNV recommended practice for subsea power cables (DNV GL AS, 2014).

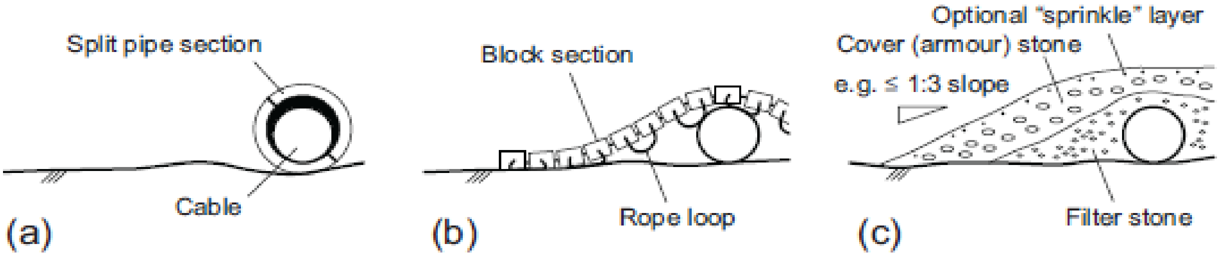


Figure 30: Cable protection; a) Tubular product, b) Mattress, c) Rock placement. (DNV GL AS, 2014)

4.6 Cable Installation Criteria

When installing a cable at the seabed there are certain criteria that need to be fulfilled to ensure a successful installation with a fully functional cable. These criteria are important at different stages of the installation, some of which are critical during laying, some during jointing of two cables, and some after installation to protect the cable. A summary of these criteria is represented in Table 3.

Table 3: Criteria for installation of a submarine cable.

Stage	Criteria	Response description
Cable laying	$T < T_{allowable}$	Reduce the top tension, while keeping $T > T_{critical}$. Top tension must never exceed cable or CLV's tension capacity.
	$T_{residual\ bottom\ tension} > 0$	Increase $T > T_{critical}$ to assure no compression in cable and no looping of cable
	$R_{min} > MBR$	Increase tension. No bending in cable smaller than the cables MBR-limit. Tension in cable must always be $T > T_{critical}$
Cable jointing	Cyclic bending < Fatigue limit	Cyclic bending of cable must never exceed fatigue limit
Cable protection	Flat seabed surface (desirable)	Route survey, seabed clearing
	No point load on cable	Reduced bottom tension over irregular seabed to avoid cable suspension, while keeping $R_{min} > MBR$ and $T > T_{critical}$.
	No VIV in cable	$L_s/D < 30$[1], minimize length of suspensions
	Cable stability	Avoid suspensions if possible. Cable protection: Burial, rock placement, external protection
	No snag- or impact load in cable	Cable protection: Burial, rock placement, external protection
	No exposure of cable [2]	Inspection, re-burial, external protection

[1] Where L_s is the suspension length and D is the outer diameter of the cable.

[2] Where protection is needed, to ensure stability and safety of the cable.

Although the stability and protection of the cable is critical after it is installed, these issues must be handled by different measures both before, during and after installation. When installing a cable close to existing infrastructure and areas with large human activity, special considerations should be made concerning protection of the cable.

5 Submarine Cable Installation HAZID

To contribute to the safety of a new project, operation or task, a risk analysis is carried out. As part of the analysis one can do a hazard identification (HAZID) (Trbojevic et al., 2008) to identify all the possible hazards that may occur and the threat they cause. It is much used in association with marine operations, but also in other industries.

The HAZID can be carried out as a brainstorm session or a more organized workshop where relevant members are present (El-Wardani, 2012). A team leader who has good understanding and experience with HAZID procedures should lead the group. The rest of the group should carefully be assembled by people from various disciplines that are relevant for the project, and with different experience, to increase the quality of the result. The goal is not to have a large team, but the right people in it (Trondheim Consulting AS).

Before a standard and more known task is carried out, a HAZID, also known as a job safety analysis (Aven, 2015), is often carried out as a checklist operation by the members of the workforce who do the job. This will increase the awareness among the workers and ensure a higher understanding of the threats that may arise. The task can be divided into sub-task where all sub-tasks are discussed in detail, identifying all the ways a task can go wrong or injuries occur.

For larger projects, the HAZID should be carried out at different stages, as the project is developing. The result of such sessions is then used for further decision making. To get the most out of the HAZID it is vital that all the members get all relevant documentation and info about the project that is gathered so far. At an early stage this might be of the more general sort, about the proposed location and choice of installation method. Previous experience with both similar projects and locations can be included. As one get further into the planning, the information becomes more specified. All assumptions and results are recorded and saved to know what still stands when new information arises and changes are made.

At an early stage with less specific information, the HAZID discussion can start out by the use of generic keywords (El-Wardani, 2012), and then by identifying the hazards. Potential causes to the hazard and consequences are identified for each one. The consequences are often divided into categories of asset, personnel, environment and reputations, as the hazard might not have the same harming effect on all groups. The rate of which this hazard might occur together with the level of impact it can have are evaluated and placed in a risk matrix. The matrix is often divided into different areas as acceptable, tolerable and intolerable, or as low, medium and high. The areas are then color coded to show the location, and hence the implications, the hazard might have. The use of such matrix and color coding should however be used with care, as it can be misleading if not used correctly (Cox, 2008). The ratings are subjective, and different people may present different results with the same project information. This can be due to different background and experience which lead to different knowledge and insight to the hazard at hand. Table 4 represents the risk assessment matrix used for the HAZID in this report, and Table 5 represent the risk levels.

The main objective of a workshop is to identify hazards, and not discuss the solution. If however one immediately has a possible solution it is recorded and taken into consideration at a later stage (Trondheim Consulting AS). The result of the meeting is presented in a table, with all the identified hazards listed. A short description of the barriers and how to handle the risks can then be presented in the same table next to each hazard.

Table 4: Risk Assessment Matrix.

Consequences		**Severity of Consequences**				
Assets		Minor damage	Significant damage	Severe damage	Major damage	Massive damage
Life/ health		Minor injury or health effect	Significant injury or health effect	Severe injury or health effect	Single or few fatalities	Many fatalities (>3)
Environment		Minor effect	Significant effect	Severe effect	Major effect	Massive effect
Reputation		Minor impact	Significant impact	Severe impact	Major impact	Massive impact
Likelihood of Event		1	2	3	4	5
Frequent	E	🟨	🟥	🟥	🟥	🟥
Probable	D	🟨	🟨	🟥	🟥	🟥
Unlikely	C	🟩	🟨	🟨	🟥	🟥
Very unlikely	B	🟩	🟩	🟨	🟨	🟥
Extremely unlikely	A	🟩	🟩	🟩	🟨	🟨

Table 5: Risk Level

Risk level	
Low	Acceptable; Monitor and further reduce where it is practicable
Medium	Tolerable; Close monitoring. Implement ALARP principle.
High	Intolerable; Mitigate identified failure causes. Implement ALARP principle.

For a visual effect and better understanding, a hazard can be represented in a bow tie diagram. The bow tie represents the hazard in the middle as the "initiating event". To the far left of the event is all the causes and small events that lead to the bigger one. In between the causes and the initiating event are the barriers that are in place to hinder the initiating event from happening. On the far-right side of the event is the consequences this event can cause, with barriers to reduce the impact of this main event in between. This representation of hazards, the associating barriers, causes and consequences makes it easier for the workforce to see the connections between them, and the possible outcome if something goes wrong. Weakened barriers and the cause for their weakness or failure can be mapped into the bow tie (Trbojevic et al., 2008), making it easier for the workforce who are responsible for the barriers to maintain them.

A HAZID for cable installation is carried out. As seen in the results in Appendix A, there are numerous accidents and hazardous events that can occur during the installation. Highlighting the many risks increase the awareness before the installation starts. When knowing what to look for, one has the chance to implement risk reducing measures.

After a HAZID, inspections of facilities and working environment can shed light on previously undetected hazards, e.g. lack of safety harness when working in heights or outdated life jackets which might not hold the required weight. Spending time testing equipment before the operation can also save the company both time and money, especially if overloading the equipment can render it completely useless. Overloading a turntable will, for example, damage the slewing rings, and its rotating ability will stop.

There is also a heightened focus on situations in which the cables integrity can be compromised. This include both damaged equipment or poor design of equipment and weather. Strong current and challenging sea states can both cause damage to the cable, which in return cause delays and cost overruns to the project.

When applying barriers for each hazard, the severity of the consequences and the likelihood of the event will reduce, keeping the total risk within an acceptable or tolerable region. The ALARP principle (Aven, 2015), "as low as reasonable practicable", should however still be implemented, especially in the tolerable level. This means that one should implement risk reducing measures, unless the cost of implementation is grossly disproportionate to the benefits one may gain.

6 Cable Installation Analysis

6.1 OrcaFlex Modelling and Simulation

OrcaFlex (Orcina) is used for simulation of a submarine cable installation. The program is widely known and used for dynamic analysis for a variety of different offshore marine systems, but also very useful for static calculations.

The case to be modelled comprises of a vessel with a stern wheel and the cable. For this case, the default vessel model in the program is used (Figure B-1 in Appendix B), and its RAO (Figure B-2 to Figure B-5 in Appendix B) is used as a reference point for the simulations. The vessel is equipped with a laying wheel and supports to guide the cable out into the sea in a controlled manner. The diameter of the wheel is 10 m, and it is located at the stern of the vessel, 5 m offset from the center.

The cable is modelled to have the same characteristics as the North Sea Link (NSL) cable that will be laid between Kvilldal in Norway and Blyth in England and is planned to be in operation in 2021 (Statnett SF). The data for the HVDC cable are found in Appendix C. The cable is connected at the vessel deck and anchored at the seabed 200 m after the expected TD point as seen in Figure 31.

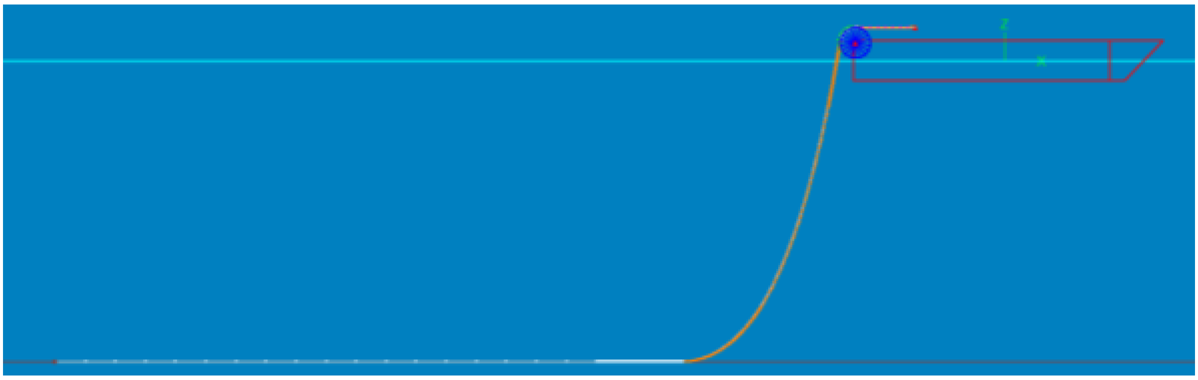


Figure 31: Cable installation simulation setup.

To make sure the anchor length would not affect the simulation result, a test of different lengths was carried out. The lengths 100m, 200m and 400m were tested and the results are shown in Table 6. As the results show, the anchoring length does not affect the tension result in any way. This is assumed to be valid for all water depths and sea states if the anchor lies flat on the seabed after TD. This setup is used for both static and dynamic simulation at different water depths and sea states.

Table 6: Test of various anchoring lengths.

Input:		Output:				
Anchor length [m]	Water depth [m] d	Layback length [m] L	Cable length [m] s	Top tension [kN] T	Horizontal force at TD [kN] H	Min. radius [m] R_{min}
100	100	40,92	114,06	42,791	5,359	17,24
200	100	40,32	114,06	42,791	5,354	17,24
400	100	40,3	114,04	42,791	5,352	17,24

6.2 Static Analysis

6.2.1 Static theory

A catenary mooring line system is characterized by its shape. It is a free hanging line connected at the top, by the fairlead, and anchored at the bottom. The tension at the top is due to gravity, the weight of the mooring line, and the horizontal force at the bottom, from the anchoring. Due to its similarity, the static theory for a catenary mooring line for a vessel (Gudmestad, 2015, p.p. 313-315) should also be applicable for a cable-laying situation. The cable is connected to the vessel at the top with the applied tension, where the absolute minimum tension is the weight of the cable hanging straight down, as there are no buoyancy elements in this case. To increase the bend radius at the seabed and avoid compression in the cable, the cable should have more tension than just the weight of the cable. Figure 32 represents the situation.

The top tension in the cable can be found by

$$T = \sqrt{H^2 + (ws)^2}$$

where *H* is the horizontal force at TD point, *w* is the submerged weight of the cable and *s* is the actual cable length following the curve from TD point to the laying wheel where the cable leaves the vessel. The vertical force in the cable becomes

$$V = ws = \sqrt{T^2 - H^2}$$

The cable catenary length *s* is calculated by

$$s = \frac{H}{w}\left(\sinh \frac{w}{H} L\right)$$

where *L* is the layback length, the horizontal distance between TD point and laying wheel. The layback length is found by

$$L = \frac{H}{w}\cosh^{-1}\left[\frac{w}{H} d + 1\right]$$

where *d* is the water depth.

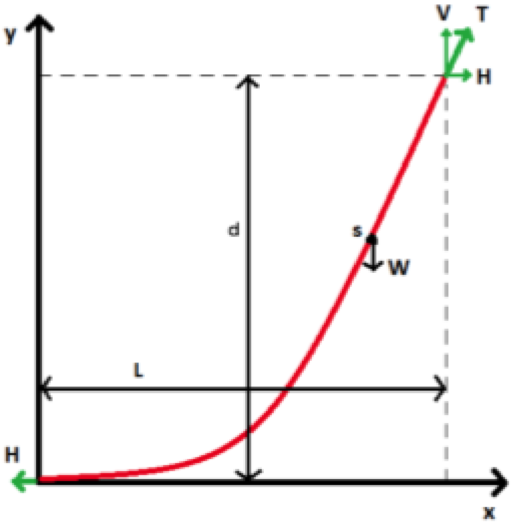


Figure 32: Catenary mooring line with forces. (Gudmestad, 2015)

6.2.2 Static Tension Control

There are three main ways of calculating the residual bottom tension during laying and assuring high enough top tension (Solberg, 2016). By measuring the top tension and water depth the horizontal bottom tension can be found by

$$H = T - wd$$

where T is the top tension, w unit weight of the cable in water and d is the water depth. This method is very unpredictable as the top tension is hard to measure accurately.

The 2nd way is to measure the departure angle of the cable when it leaves the laying wheel. Together with the water depth the top tension can be calculated by

$$T = \frac{wd}{1 - \sin\alpha}$$

where α is the departure angle. The bottom tension at TD can then be found by

$$H = T * \sin\alpha$$

At deeper water depths, it is harder to get an accurate result as the angle of departure decrease to a minimum. As seen in Figure 33, just a tiny error in the angle measurements can result in large difference in the calculated tension. This can lead to a false feeling of safety during laying.

Figure 33: Departure angle versus residual tension for various water depths.

The 3rd, and most trusted, method is by gathering exact data of water depth and TD point location by using ROV or a Captrack. The bottom tension can then be found by iteration

$$L = \frac{H}{w} * \cosh^{-1}\left[\frac{wd}{H} + 1\right]$$

where L is the layback length from CLV's laying wheel to TD point (Gudmestad, 2015).

Figure 34 represents a static simulation done in OrcaFlex at water depths from 50 m till 2000 m where the target residual tension is 800 kg (grey solid line). Simulations of methods 2 and 3 (orange and blue solid lines) are carried out with data obtained from the OrcaFlex simulation.

By the look of it, both methods should be equally suitable, but as previously discussed, the departure angle decrease with increasing depth. A measurement error of +/- 0.1 degrees in departure angle (light/dark orange dotted lines) has little effect in 50 m water depth, but a large effect in 2000 m. An error of 1.0 degree will cause the results to be useless in deep water.

The layback length of the cable increases with water depth. At 50 m water depth, a measure error of 1 m (light/dark blue dotted lines) is noticeable, but as the depth increase, the effect of 1 m error become less.

Because of this, using the departure angle for tension control is only useful for shallow to intermediate water depth, while measuring the layback length can be used for all water depths.

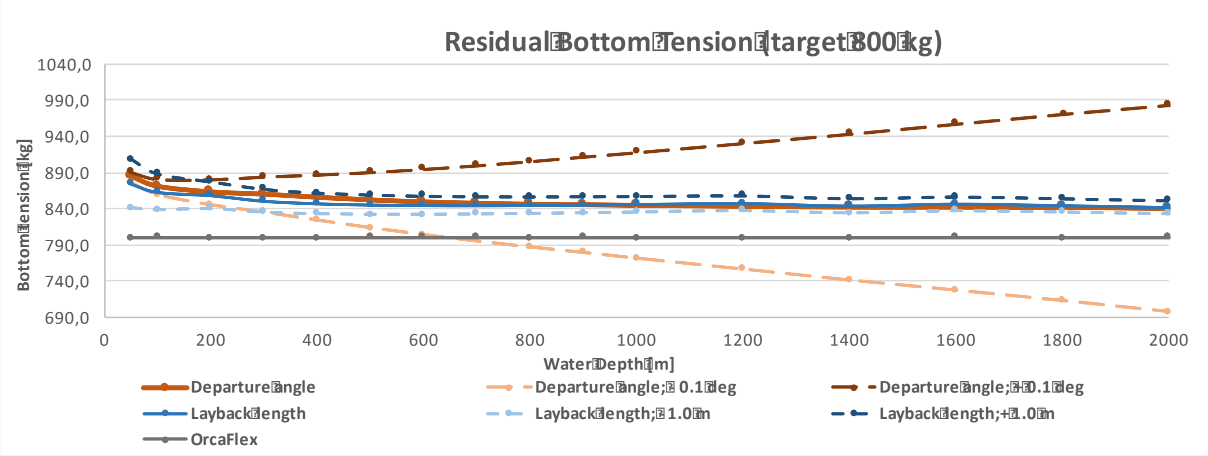


Figure 34: Residual bottom tension by OrcaFlex simulation and by departure angle and layback length from OrcaFlex simulation for water depth 50 – 2000 m.

6.2.3 Current

The effect of current forces on the cable can be seen in a static analysis when current is added as a static force. If no specific location is chosen, the analysis can be treated as a “no current data available” case. According to the NORSOK standard, when no coastal eddies is present the current profile can be set linear over the whole water depth (Standard Norge, 2016), as seen in Figure 35. With coastal eddies the current is set higher at still water level (SWL).

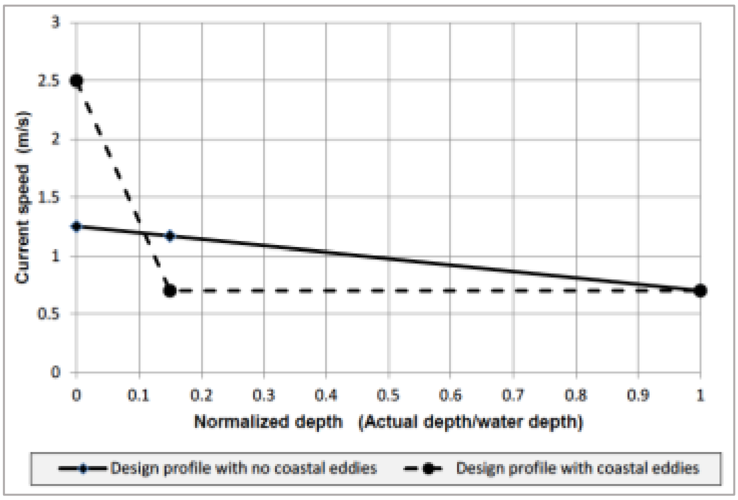


Figure 35: Current profile for cases with no current data available (Standard Norge, 2016).

A small study of how current forces affect the cable during installation is carried out in an OrcaFlex analysis. Current, both with and without coastal eddies, is considered from directions 0 to 180 degrees relative to the vessel for various water depths.

Although the current profile is equal for all water depths, one can see from the graph in Figure 36 that the effect of the current force become more noticeable in deeper water. The original bottom tension in the cable is 800 kg, but with current the tension change significantly. An increase in tension is seen at 0 degrees, while a decrease is seen at 180 degrees. Between 90 and 112.5 degrees the tension is close to normal.

With strong current, it becomes difficult to use departure angle of cable as a measurement for simple tension calculations, as it behaves opposite to a situation with no current. The current at 0 degrees push the cable down, minimizing the angle and increasing the tension, while at 180 degrees it lifts the cable, decreasing the tension and expanding the angle. Using the layback length for tension calculations is possible if accounting for the current forces, as it behaves in a similar manner as without current.

The coastal eddies cause a higher current at SWL, but once under the wave trough it is assumed to be less than the regular current until the seabed. As seen in Figure 36, the regular current has stronger effect on the cable and is thus used for later cases.

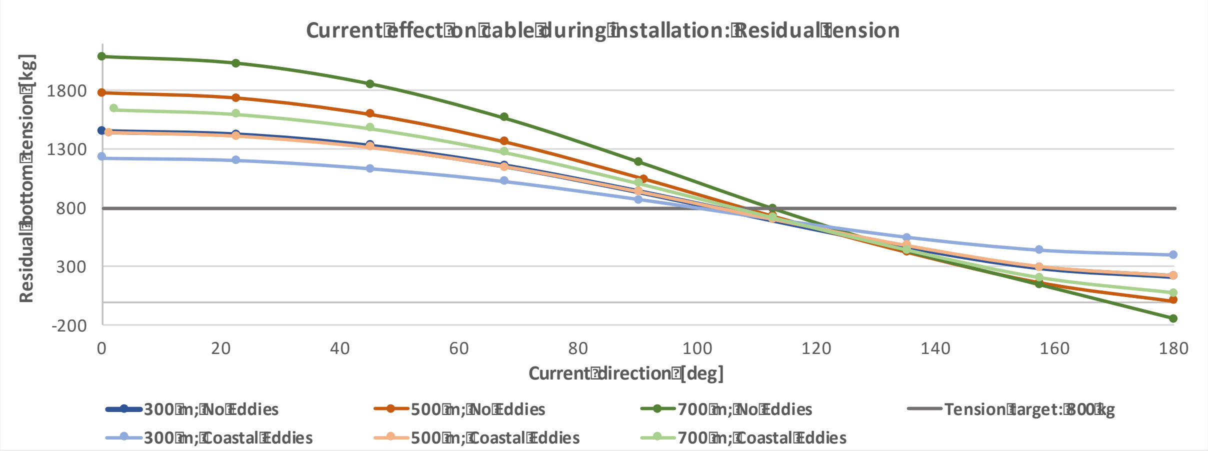


Figure 36: Current effect on residual bottom tension in cable at water depth 300 -700 m with residual tension of 800 kg when no current is present.

With current parallel to cable, the cable will never leave its route. As the current change direction, the TD point may change and become offset from the planned route. As seen in Figure 37, the TD point offset, normal to a planned straight route, increase when the current becomes closer to approach normal to the cable and vessel. The offset is largest with no eddies and when current direction is between 90 and 112.5 degrees. At these angles, the current get "under" the cable and lift it out of its path, resulting in a large offset. At deeper water this offset increase substantially.

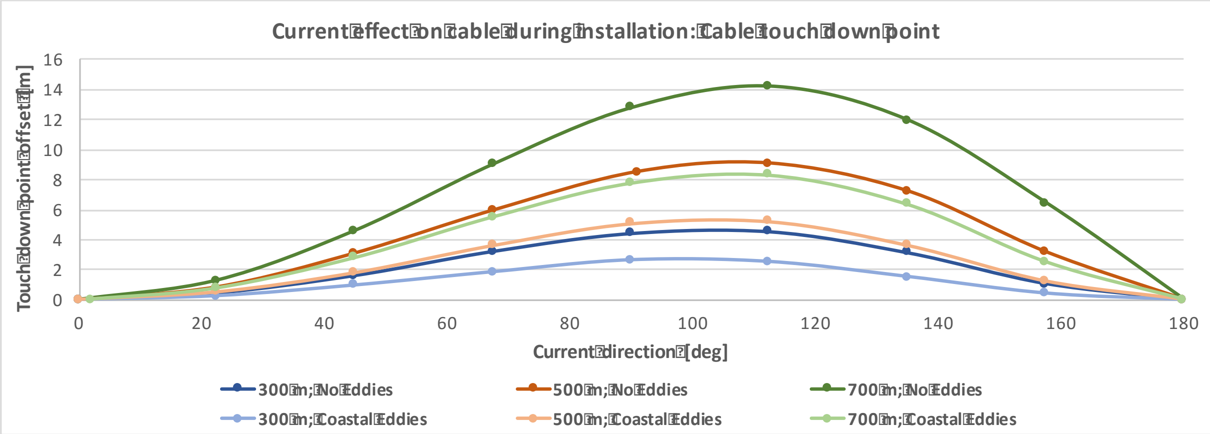


Figure 37: Current effect on touch down point of cable in direction normal to cable route for water depth 300 -700 m with and without coastal eddies.

To minimize the TD offset and get the cable TD within its planned route, the vessel can be placed offset. To increase the tension in the cable has a small effect, as seen in Figure 38. This solution could be effective in a weaker current, but is not sufficient to correct the TD point in strong current. Increasing the tension is however not a suitable option if the cable is planned to be trenched post installation. High tension will prevent the cable from falling into the trench and may also cause more cable suspensions.

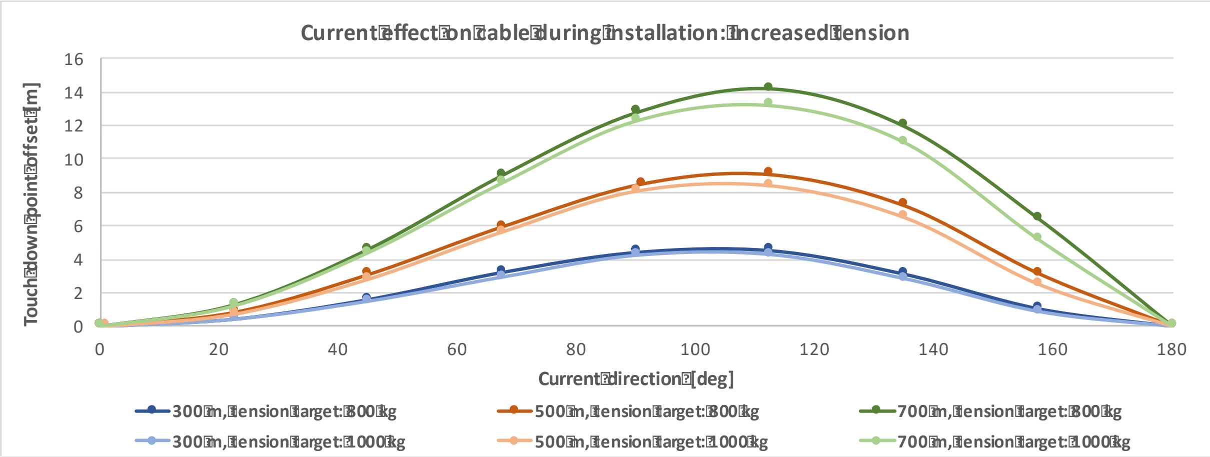


Figure 38: Current effect on touch down point of cable in direction normal to cable route for water depth 300 -700 m with bottom tension target of 800 kg and increased bottom tension of 1000 kg.

6.2.4 Static Limitations

Static simulation and calculations of a case is for a state of absolute no vessel movement. This result in absence of wave forces. The simulation result does not reflect the effect the waves have on ship motions, and how this would directly influence both the tensions and bending in the cable.

Current forces can be included as a static force, but the static calculations do not account for how it can behave as a dynamic force and result in VIV in cable suspensions. For an analysis of how a full weather state influences the laying situation, a dynamic analysis must be carried out. This way one can evaluate different extreme cases and set limitations to the operation.

6.3 Dynamic Analysis

A dynamic analysis will determine the impact of different loads over time. The analysis use a model where all sections that are to be analyzed are divided into elements, as seen in Figure 39. Smaller elements give a more accurate result of the exact point of interest.

In an analysis of a cable installation the point of interest is mainly at the top and bottom of the cable, the top tension and departure angle, and at the horizontal bottom tension and the bending radius near the TD point.

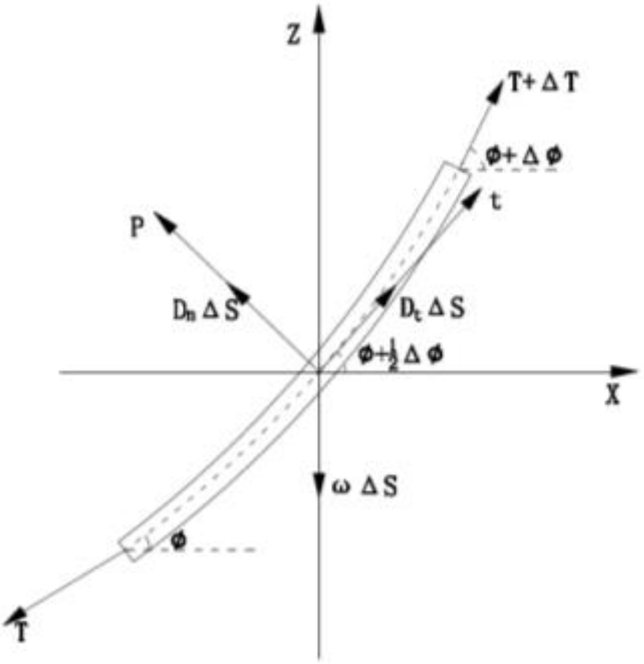


Figure 39: 2D- sketch of cable element including forces acting on element (Yang et al., 2013).

The analysis method lets the load change over time, and shows how the impact affects the cable installation. The analysis includes the forces caused by the vessel motions. These forces are a result of the effect the waves has on the vessel. The vessel's behavior is represented through a set of transfer functions, also known as the response amplitude operator (RAO). Each vessel has a unique RAO, which is usually confidential, and is used to determine the effect the sea state will have on the vessel motion.

Dynamic cable analysis can be carried out by use of OrcaFlex. Through such analysis one can determine what is a suitable sea state by applying waves and currents.

6.3.1 Dynamics during Jointing of Cable-ends

Jointing of cables mid sea, as described in 4.4, become more common and is a part of most every long-distance installation. The duration of the operation varies for different types and size of cable, but often lasts 8-12 days (Solberg, 2017). During the jointing, the cable is held still at the vessel, as any movement of the cable on board the vessel will disturb the jointing process. Contrary to the laying where the cable constantly moves over the laying wheel, the cable is staying still over the wheel, and excessive cyclic bending of the cable become critical. Wave induced vessel motion, like pitch, roll and heave, result in change in departure angle and residual bottom tension over time. To get a successful operation one need to assure adequate tension at all times and keep departure angle change to a minimum. By establishing weather criteria one can determine whether to start, delay or abort a jointing operation.

How many cycles of bending a cable can endure without getting fatigue damage need to be tested at a laboratory, and will depend on the degree of bending and type of cable.

A study is carried out to find limiting sea state for a fictitious case. As the location of jointing is unknown, the main variables are wave direction, wave height and wave period, current direction and strength, water depth and initial residual tension in cable.

Assumptions:

- Vessel is same as default vessel in OrcaFlex (Appendix B)
- Cable is of the type described in Appendix C
- Cable is tested in lab to see how many cycles of bending it can handle;
    - very high number of cycles less than 1 degree,
    - about 12500 cycles of 1-2 degrees
    - or about 500 cycles of 2-4 degrees
    - or about 80 cycles of 4-6 degrees.
    - If exceeding these numbers, there is high risk of fatigue damage.
- 10 min simulations are a valid representation of how the vessel and cable behave in the different sea states.

10 min dynamic simulations are done using OrcaFlex where data of tension and cable bending is gathered. Criteria for residual bottom tension is set according to Table 7. For every simulation, the bottom tension is evaluated and an acceptance level is set according to the lowest bottom tension.

Table 7:Sea state acceptance-level criteria for residual bottom tension in cable.

Residual bottom tension		
Acceptance level	Lowest measured value	Comment
🟩	> 500 kg	No compression, low risk of loops
🟩	> 300 kg	No compression, loops may happen
🟩	> 0 kg	No compression, risk of loops
🟧	1 time "< 0 kg"	Risk of compression, risk of loops
🟧	≤ 3 time "< 0 kg"	High risk of compression and loops
🟧	≥ 4 times "< 0 kg"	Very high risk of compression and loops
🟥	Not applicable; No/rarely waves in this range	

Criteria for the bending in cable over the laying wheel is dependent on the degrees of angle change. For every simulation, angle data of the cable when leaving the wheel is gathered, and the bending cycles are split into groups, dependent on the angle of bending. As stated in the assumptions, bending's less than 1 degree is assumed to have very little effect on fatigue, and is therefore not considered further. Bending's between 1-2 degrees and higher are of concern, and the criteria are as seen in Table 8. The acceptance level is set according to how long time the cable can handle the wave load without being concerned about fatigue. In the "green" level, the cable should, depending on the duration of the jointing operation, be able to endure the wave loads throughout the entire jointing operation, as it results in very little cyclic bending in the cable per time unit. After that, the jointing may have to be terminated, unless the sea state of concern appears later or towards the end of the jointing process.

Table 8: Sea state acceptance-level criteria for cable bending over laying wheel.

Cyclic bending in cable at departure of laying wheel		
Acceptance level	Number of 1-2 degree bending / 10 min	Comment
🟩	x ≤ 4	Can withstand this loading over entire jointing operation
🟩	x ≤ 7	Risk of fatigue damage after 12 days
🟩	x ≤ 10	Risk of fatigue damage after 8 days
🟨	x ≤ 15	Risk of fatigue damage after 5 days
🟨	x ≤ 28	Risk of fatigue damage after 3 days
🟧	x ≤ 40	Risk of fatigue damage after 2 days
🟧	41 ≤ x < 60	Risk of fatigue damage in less than 2 days
🟫	x ≥ 41 + higher angles	Risk of fatigue damage in less than 1 day
🟥	Not applicable; No/rarely waves in this range	

Determination of Wave Direction

During vessel operations one would normally choose to position the vessel parallel to the wave direction (0 or 180 degrees) to avoid excessive rolling motion in the vessel. Having the vessel in this position will, however, result in pitch motion of the vessel. Analysis is carried out to see the effect of waves approaching the vessel at 0 degrees and 90 degrees in 300 m and 1200 m water depth. As seen in Table D-3 to Table D-6 in Appendix D, waves at 0 degrees have less effect on the tension in the cable than waves at 90 degrees. This applies for both cases, at 300 m and at 1200 m water depth, and is very noticeable for wave heights of 1.5 m and higher.

Bending in the cable at departure of the laying wheel is however very sensitive to the pitch motion that occurs with waves at 0 degrees (i.e. waves from behind), and is seen well for wave heights of 1.0 m and higher. As the wave peak period increases, the bending in the cable gets worse. This is seen for both water depths, 300 m and 1200 m, and one can assume the same trend would be seen for water depths in between.

With waves approaching at 90 degrees, the bending in the cable starts at wave peak periods of 5 and 6 seconds, but then decreases at higher wave periods. Due to the huge difference in cyclic cable bending, the wave direction of 90 degrees is chosen for this analysis.

Determination of Residual Tension Target

During the jointing operation, the CLV is operating on DP and will remain at the same position during the whole procedure. As the cable is also held still over the laying wheel, one cannot intentionally change the residual tension in the cable, and an initial tension in the cable must be set before starting the operation. An initial tension of 1000 kg is chosen after a test of various residual tensions is carried out for water depths 300m, 700m and 1200m, as seen in Appendix D Table D-7, Table D-8 and Table D-9.

Waves

To determine suitable sea states for jointing operation, wave loads with significant wave height varying from 0.5m to 2.5m and wave peak periods from 2sec to 14sec are applied to the simulation. This is carried out for water depths of 100m to 1200m, as seen in Table D-10 to Table D-17 in Appendix D.

Waves and Current

As discussed in chapter 6.2.3, current forces affect the cable tension and behavior in different ways, depending on its direction relative to the cable and vessel. Current forces alone at 0 degrees increase the tension while current at 180 degrees reduce the tension, and current at 112.5 degrees moves the cable sideways out of its path.

To see how the cable behaves with both current and wave forces, a reduced current force, following the same profile as in Figure 35, in directions 0, 112.5 and 180 degrees are added to the simulation, as seen in Table D-18 to Table D-21 in Appendix D. Here the CLV has moved backwards, sideways and forward to achieve an initial residual bottom tension of approximately 1000 kg.

Centralized Laying Wheel

Many CLV's have two laying wheels or laying chutes at the stern of the vessel some meters apart (Nexans Norway AS) to use during hairpin-jointing. During an in-line joint, only one laying wheel is in use. A simulation is done centralizing this laying wheel at the stern, as seen in Appendix D, Table D-22 and Table D-23, to see if the location of the wheel has any significant effect on the cable tension and cable bending during an in-line jointing operation.

6.3.2 Reliability of DP operations

To maintain the cables structural integrity and prevent damage, it is of crucial importance to keep the correct position and heading of the vessel throughout the entire cable installation period, both during laying and during jointing. Because of this, most CLV's have a DP-2 system, which means the vessel is *"capable of automatically maintaining the position and heading of the vessel within a specified operating envelope under specified maximum environmental conditions during and following any single fault, excluding a loss of compartment or compartments"* (ABS, 2016).

In areas with less GPS and satellite coverage (for example in northern regions), an accurate position is harder to maintain, and drifting backwards or drifting off position may become critical. How much offset backwards the cable can handle depends on the water depth. Figure 40 shows how the static tension reduces when the horizontal distance between the laying wheel and TD point of cable reduces. A vessel offset of 10 m in 100 m water depth has larger effect on tension than in 1200 m water depth.

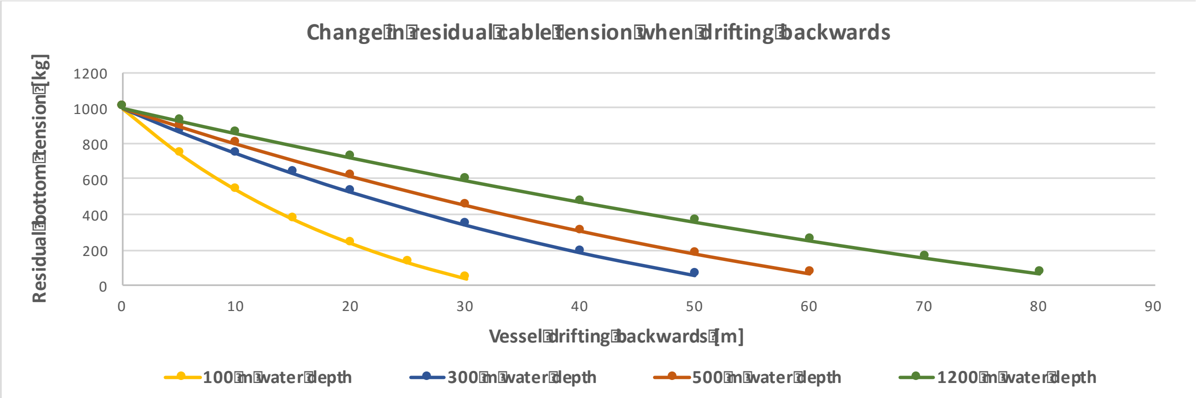
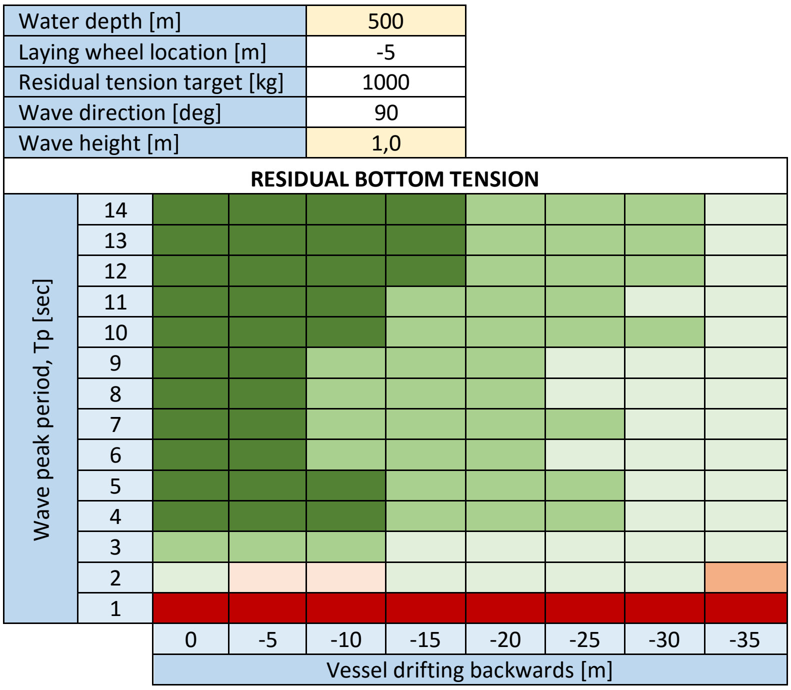


Figure 40: Change in residual bottom tension when vessel is drifting backwards.

With waves present (dynamic analysis), the tension becomes critical sooner than in a static situation. Table 9 shows the residual bottom tension in a cable at 500 m water depth and with wave height of 1.0 m. Once the vessel starts drifting backwards, the tension in the cable decrease. After passing 20 m offset, the risk of coming below 300 kg tension increases greatly, while in the static analysis one can endure 40 m offset before getting below 300 kg at 500 m water depth. With higher waves, the tolerable offset distance becomes shorter, and the risk of loops increases faster than with no waves present. The rapid vessel movements due to high waves may cause a loop to occur in a wave trough, and then the loop may tighten in a wave crest, resulting in a kink or knot that breaks the cable. When a sea state is confirmed as acceptable, the whole operation depends on the DP system to work.

Table 9: Residual tension in cable when vessel is drifting backwards, for legend, see Table 7.

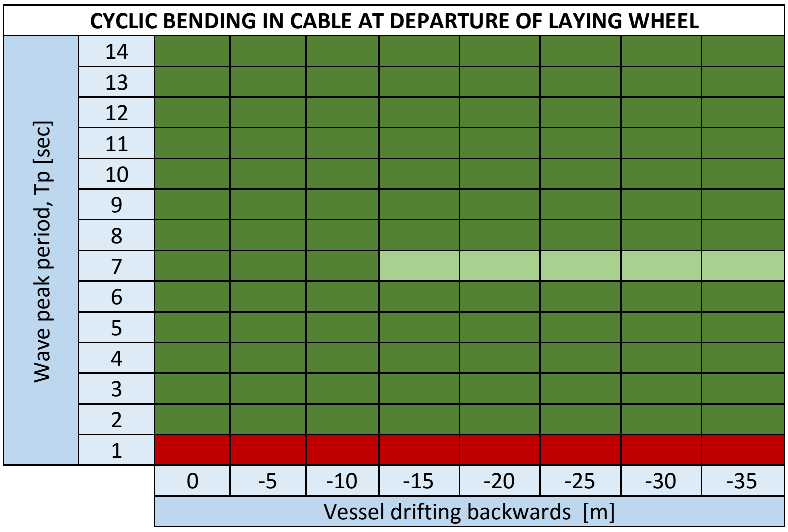


Water depth [m]	500
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90
Wave height [m]	1,0

		RESIDUAL BOTTOM TENSION							
Wave peak period, Tp [sec]	14	🟩	🟩	🟩	🟩	▨	▨	▨	░
	13	🟩	🟩	🟩	🟩	▨	▨	▨	░
	12	🟩	🟩	🟩	🟩	▨	▨	▨	░
	11	🟩	🟩	🟩	▨	▨	▨	░	░
	10	🟩	🟩	🟩	▨	▨	▨	▨	░
	9	🟩	🟩	▨	▨	▨	░	░	░
	8	🟩	🟩	▨	▨	▨	░	░	░
	7	🟩	🟩	▨	▨	▨	▨	░	░
	6	🟩	🟩	▨	▨	▨	░	░	░
	5	🟩	🟩	🟩	▨	▨	▨	░	░
	4	🟩	🟩	🟩	▨	▨	▨	░	░
	3	▨	▨	▨	░	░	░	░	░
	2	░	▫	▫	░	░	░	░	🟧
	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		0	-5	-10	-15	-20	-25	-30	-35
		Vessel drifting backwards [m]							

Lower tension reduces the departure angle of the cable, and hence an offset backwards will have little to no negative effect on cable bending over the laying wheel, as seen in Table 10 below.

Table 10: Cable bending at laying wheel when vessel is drifting backwards, for legend, see Table 8.



		CYCLIC BENDING IN CABLE AT DEPARTURE OF LAYING WHEEL							
Wave peak period, Tp [sec]	14	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	13	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	12	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	11	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	10	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	9	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	8	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	7	🟩	🟩	🟩	▨	▨	▨	▨	▨
	6	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	5	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	4	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	3	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	1	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥
		0	-5	-10	-15	-20	-25	-30	-35
		Vessel drifting backwards [m]							

6.4 Weather restrictions

When planning an operation, it is very important to the success of the task that it is established beforehand which sea states are acceptable. If the operation is sensitive to the vessel motion, vessel data and RAO for the exact vessel to be used must be present in the analysis.

Restrictions due to other weather characteristics for the location of the operation, like current and wind, should also be established, as different strength and directions can have different effects on the operation’s critical parameters.

7 Discussion of Results

Installation of subsea power cables has been state-of-the-art for many years. Through this work, the author intended to examine the installation procedure of cables and how different sea states influence the operation at deep water. The objective was to establish weather criteria for the operation. In the beginning, the scope of the analysis was large, and the analysis was limited subsequently by focusing on how different sea states affects the jointing operation of two cables, which could take from 8 to 12 days. As the vessel, cable and location was not specified or related to a current project, this resulted in the task becoming methodical. The OrcaFlex software was used for the analysis.

A HAZID analysis needs to be performed in order to identify all potential hazards related to the operation. It is important to conduct this analysis before and during the planning of a specific installation. The HAZID showed a wide range of accidents of which the cables integrity would be compromised, including challenging weather and equipment failure. By highlighting the many hazardous events that may occur, one can implement risk reducing measures.

Most cable-lay vessels have the chute or laying wheel at the stern of the vessel. With the cable entering the water at this location, one can see from the results in this analysis that the cable is very sensitive to the wave induced vessel motions. Cable movement at sea water level is highly affected by pitch motion in the vessel. By heading the vessel perpendicular to the wave direction, the cable movements were reduced significantly.

During a jointing operation, the most critical parameters in a cable are the horizontal bottom tension and the cyclic cable bending at departure of the laying wheel. This is because the cable needs to stand still over the laying wheel throughout the entire jointing procedure and all bending will occur at the same point. This bending in the cable can be a limiting factor for sea states during time consuming jointing operations.

From the results, one can see that the cable behaves different during laying in deep water and shallow water. Although the initial residual bottom tension is the same for all water depths analyzed, the tension seems to be more sensitive to the wave induced vessel motions in deep water than in shallow water, especially in waves with short wave period. Rapid movements could cause the cable to loop and bend beyond its limitations, and the simulation would automatically be aborted.

To obtain an adequate tension in the cable, the cable departure angle is larger in shallow water than in deep water. The change in departure angle due to vessel motions, and hence the bending of the cable, seems to be more sensitive to the wave induced vessel motion in shallow water when this angle is larger, than in deep water. In water depth of 500 m and above, the initial departure angle becomes very small, and any further changes in depth have no effect on the cyclic bending due to vessel motion.

To reduce the cable bending in shallow water (100 m), smaller initial values of the tension were tested. A small improvement in bending is seen, but the main outcome was less control on the bottom tension with higher risk of looping and compression in the cable.

When jointing in areas with strong current, one needs to take the effect of the current's direction into account when determining if the sea state is acceptable or not. A current at 0 degrees (from behind) has an improving effect on the operation. The current reduces the departure angle and hence the cyclic bending of cable. The control of the bottom tension is also increased, resulting in less risk of looping and compression. A current at 180 degrees has the opposite effect, and cable jointing in this position should be avoided. The risk of looping and compression in the cable increases significantly as the current is reducing the tension and increasing the departure angle.

At 112.5 degrees, the current had minor effect on tension and bending, but could have an effect on the touch down location of the cable. Strong current can move the cable out of its path. As the vessel is not changing position or heading during the jointing, this should not be very critical. During laying, however, the cable would be laid outside of its planned route, which can lead to other issues, like the cable getting too close to on-bottom structures or seabed features, e.g. large rocks and boulders, that are not desirable.

In-line jointing of cables only require one laying wheel for the operation. The wheel was moved to the center of the stern in order to analyze the location's effect during jointing. Centralizing the wheel had little to no effect on the bending of the cable, but a noticeable improvement on bottom tension in the cable. At the center location, the cable is less exposed to the roll motions of the vessel and can tolerate the effect of higher waves.

Throughout the analysis, one can see that the success of a jointing operation is highly dependent on the conditions of the sea state. The benefit of reducing the time it takes to prepare a connection offshore is obvious as one then could do the connection within a weather window forecasted by meteorologists.

8 Conclusions

The analysis method presented in this report can be a tool to assist when planning future cable installations. This procedure alone should however not be used to conclude whether the sea state is acceptable or if the cable will experience compression, looping or fatigue damage. It is very important to include the test results of the exact cable type that is to be installed, as different types of cables may have different limitations. Experience from preceding projects should also be included to establish whether the software is more conservative than it needs to be, and hence its reliability in real-life situations.

Including more data about the weather, sea state and seabed features at the location of the installation in the analysis will increase the reliability of the results.

The HAZID analysis showed numerous of hazardous events that may occur. By highlighting the many risks, before the installation starts, it will increase the awareness throughout the entire process.

The vessel used in this analysis (OrcaFlex default vessel) would not be appropriate to use in an analysis of a real-life situation. The features of the vessel's RAO will have a huge impact on the results and may increase the number of suitable sea states. For a vessel with less pitch motions, one could argue that it would be better to be heading into the waves, instead of 90 degrees as in this analysis. This would be better for the cable, but it would also increase the crew's comfort tremendously.

Although the results from this analysis showed only a small amount of sea states to be suitable for this jointing operation, the technology in this field is continuously developing. New equipment and procedures are being developed, making the jointing operation quicker and more suitable for rougher sea states. By developing solutions for faster jointing one could increase number of feasible situations because one could perform the operation in a more challenging sea state or within a shorter weather window. The submarine power cable industry can adopt practices and technology from other industries. From the oil and gas industry it might be possible to make use of subsea technology connectors.

The top tension in the cable need to be kept below the cable's and the vessel's tension capacity during the entire installation. Further development of installation methods for deep water may be necessary, as the tension can quickly become very high, especially in rougher sea states.

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Appendix A

Risk HAZID of submarine cable installation. References for HAZID: (El-Wardani, 2012), (Russian-Norwegian Cooperation Project, 2012) and (Solberg, 2017).

Hazard Identification: Submarine Cable Installation									
Hazard number	**Category**	**Hazard/ Event**	**Potential threats**	**Controls/ Barriers**	**Asset**	**Life/ Health**	**Environ-ment**	**Repu-tation**	**Additional controls/ Recommendation**
1.1	Natural and Environmental	Strong/high waves	Over tensioning, compression. Unstable, hard to control tension in cable, low tension/compression cause loops and snaking	Weather forecast studies, limit installation to suitable sea state	D2			B1	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 vaning	Weather forecast studies, limit installation to suitable sea state. Limit ship movement and duration exceeding allowable parameters.	C2			B1	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. Should be certain of damage before cutting, to avoid extra costs.
			Bad sea state: increased risk of 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	B1	B4		B1	
1.2		Strong current	Unknown impact on tension in cable, can cause over tensioning or compression in cable	Gather current data for location, adjust payout speed and CLV location to local current conditions	C2			B1	
			Current impact moves cable TD out of path, TD not on planned route	Gather current data for location, use of ROV, adjust vessel location	C1		B1	B1	

			Cable breakage; Current impact moves cable floating on buoyancy elements off track	Limit cable movements; tug boats holding cable back and assure MBR	C1			B1	
1.3		Storm, rain, adverse weather	Low visibility, possibility of vessel collision	Weather forecast studies, limit installation to suitable weather	B3	B4		B2	
			Bad sea state: increased risk of 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	B1	B4		B1	
1.4		Lightning	Lightning in CLV, injury/fatality of personnel	Lightning arrestors	B2	B4			
1.5		Erosion, unstable seabed, mudslide	Cable suspensions due to eroding seabed, VIV in cable suspension	Route survey, cable protection, trenching	B2				Avoid unstable areas if possible
1.6		Rocks, boulders	VIV in cable suspensions and wear and tear at point loads if cable is laid on them	Limit cable-rock interaction by a thorough route survey, route clearing, cable protection; uraduct, etc.	B2				Avoid rough seabed if possible, evaluate possible damage of each case
1.7		Sediments, muddy seabed	Loss of sight for ROV; loss of control	Wait for seabed to settle	D1				
2.1	External/ man-made	Fishing gear	Snagging of cable; cable damage	Route survey, cable protection; trenching, uraduct	C2				Avoid fishing areas if possible, inform about cables location
2.2		Anchors	Snagging of cable; cable damage	Route survey, cable protection; uraduct, trenching	C2				Cross shipping-lanes at shortest distance, avoid crossing if possible, inform about cable location
2.3		Existing pipes/cables	Cable crossing; VIV in cable suspensions and wear and tear at point loads	Cable protection; e.g. uraduct,	D1			A1	Plan cable route to cross as few cables as possible

2.4		Structures placed/ dumped at seabed	VIV in cable suspensions and wear and tear at point loads if cable is laid over them. Snagging in cable if cable is laid next to it in a curve	Thorough route survey, well planning of laying cable curves, cable protection; e.g. uraduct	C1			B1	Create distance between cable and known structures, stay clear safety zones of gas and oil installations
2.5		Local population	Conflict with local population; disturbance of daily life/ local events	Planning and cooperating with local community	B1			A1	Cooperate to avoid disturbance of yearly events/festivals
3.1	CLV equipment	Turntable	Malfunction; not rotating,	Power supply x2, can function with one	B2			A1	Have mechanics on board
			Overloaded; deformation, damaged slewing ring	Design with SF, test with load beforehand (dry run)	B2			A2	
3.2		Tensioners	Danger of personnel injury/ fatality	Sufficient training of personnel, safety procedures/ routines, adequate protective equipment		B2		A1	Medical assistance on board
			Malfunction; not capable of holding cable, uncontrolled cable payout	Power supply x2, can function with one	B3			A1	Have mechanics on board
			Overload; not capable of holding cable, uncontrolled cable payout	Design with sufficient SF	A3			A2	Design need to account for increased load in severe weather and wet cable
			Pull the "skin" off the cable	High friction between layers in cable, high pressure in tensioners	A2			A1	Less likely to happen with MI cables as it has higher internal friction between layers
			Too high pressure, damage/crush cable	More than one tensioner, even out pressure by applying load to longer sections of cable, design with SF	A2			A1	
			Local loss of grip on cable	Redundancy in tension design, liquid/oil desiccants available	B2			A1	

3.3		Stern wheel	Danger of personnel injury	Sufficient training, safety procedures/ routines		B2		A1	Medical assistance on board
3.4		Cranes	Failure during lifting, not able to hold load, load falling,	Testing, certification of equipment acceptable load, trained personnel, safety zone for personnel	B3	B4		A2	Certification by a competent person approximately every 2nd year
3.5		ROV	Malfunction; no/bad output data	Regularly testing and inspection of equipment	B2			A1	
3.6		Cable, ROV, plow, capjet, captrack, etc.	Disturbing vulnerable marine flora and fauna	Thorough survey of route and adjacent area, follow government requirements	B1		B3	A2	Limit disturbing actions if possible,
3.7		Falling objects	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	B1	B3		A1	
			Objects/tools falling overboard of vessel and damage existing structure at seabed	All tools/equipment must be secured when working in areas of risk	A3			A1	
			Injury/ fatality of personnel falling overboard of vessel	All personnel must be secured when working in area of risk, use of safety vest		B4		B2	
3.8		DP-system, thrusters	Malfunction; loss of control, drifting into shallow water, collision	DP2, tugboats and anchors, GPS, echo	B3	B4		B3	Two separate DP systems
3.8		DP-system, thrusters	Malfunction; drifting backwards, loss of tension in cable	Tugboats and anchors during jointing/ standby,	A2			A1	
3.9		Tugboats	Malfunction; loss of power	Redundancy; 2 or more tugs available	A1			A1	If used for tension/pulling of barge, a minimum of two tugs to be used
3.10		anchors	Loss of grip, snap	Redundancy; 4 or more in use when used for pulling of barge	A2			A1	

3.11		Jointing equipment/ procedure	Welding, hot-work, gas	Sufficient training/skills, safety procedures/ routines, adequate safety equipment		B2		A1	
			Faulty jointing, water leakage	NDT (x-ray) before installing cable at sea	A2			A1	
			Faulty temporary cable end caps; water leakage	Experienced workers, NDT before laying cable end down	A2			A1	
3.12		Chinese finger	slippage of cable, loose cable at seabed	Methods for retrieving cable w.o. Chinese finger installed	A1			A1	
.13		Buoyancy elements	Collapse of elements; cable sinking if many elements fail, tug/vessel (connected to cable) sinking	Redundancy in buoyancy elements, water depth restriction (about 20 m),	B2	B4		A1	Examine cause of element failure to determine if it is a natural cause or sabotage
4.1	Health Hazards	Physical working environment	Bad ergonomics, injury, fatality of personnel	Use of right equipment, lifting mechanisms, working height,		C3		A2	
			High noise under normal working conditions over long time	Hearing protection, earplug, noise cancelling equipment		B2		A2	
4.2		Shift patterns	Irregular working hours, long hours, nights, little rest	Fixed working schedules, follow regulations for working hours and shift-work		B2		A2	Unrested and unfocused personnel may cause hazards
5.1	Control-methods	Manning	Low/insufficient manning; cause delays, increase risk of accidents	Redundancy; extra manning, manning with multiple skills	C1	B2		A2	
			Wrong skills/insufficient experience/skills; cause delays, increase risk of accidents	Experienced workers in charge of their field, sufficient training and practice with exp. workers, practice multiple skills	C1	B2		A2	
5.2		Contract	Time delay, cost increase due to unforeseen events	Choice of contract; include a margin for error and delays in the initial price	C2			C2	

Appendix B

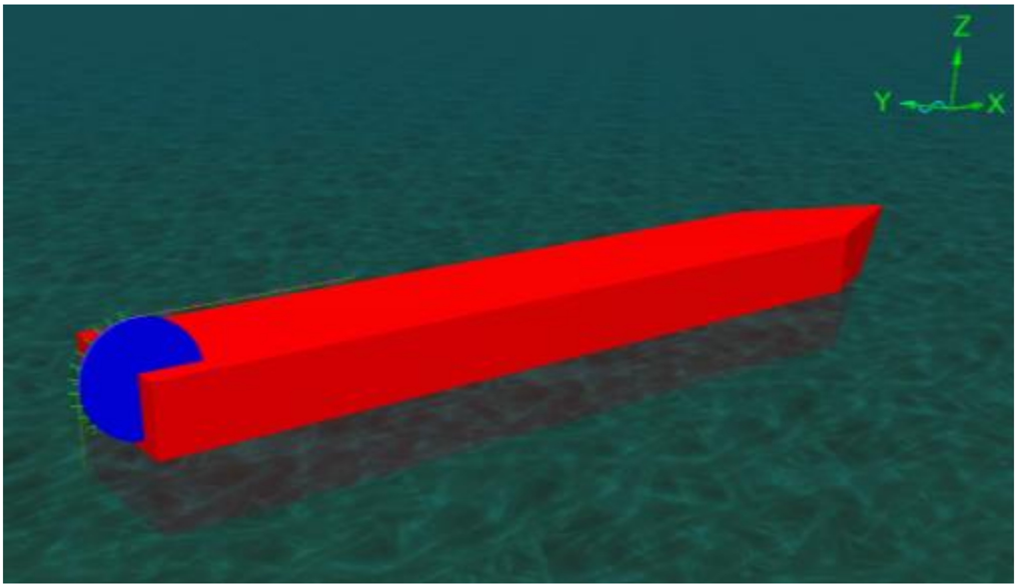
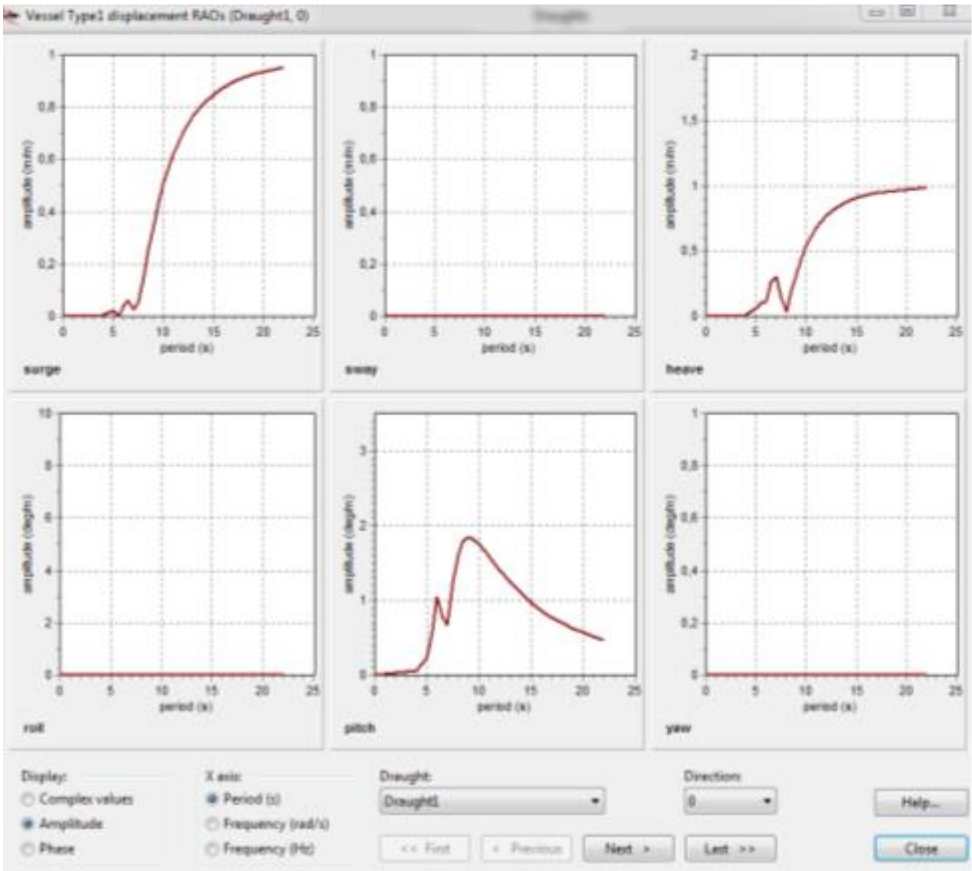


Figure B-1: OrcaFlex default vessel.


Vessel Type1 displacement RAOs (Draught1, 0)

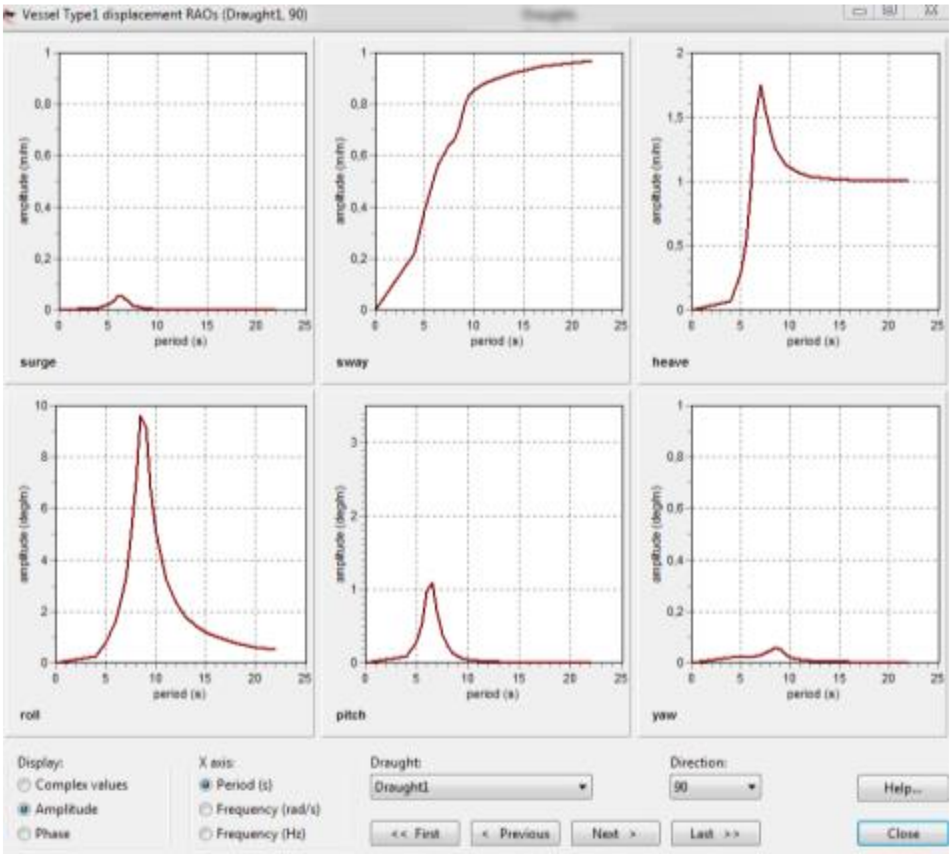
Display:
○ Complex values
● Amplitude
○ Phase

X axis:
● Period (s)
○ Frequency (rad/s)
○ Frequency (Hz)

Draught: Draught1

Direction: 0

Figure B-2: OrcaFlex default vessel displacement RAOs, direction 0 degrees.


Vessel Type1 displacement RAOs (Draught1, 90)

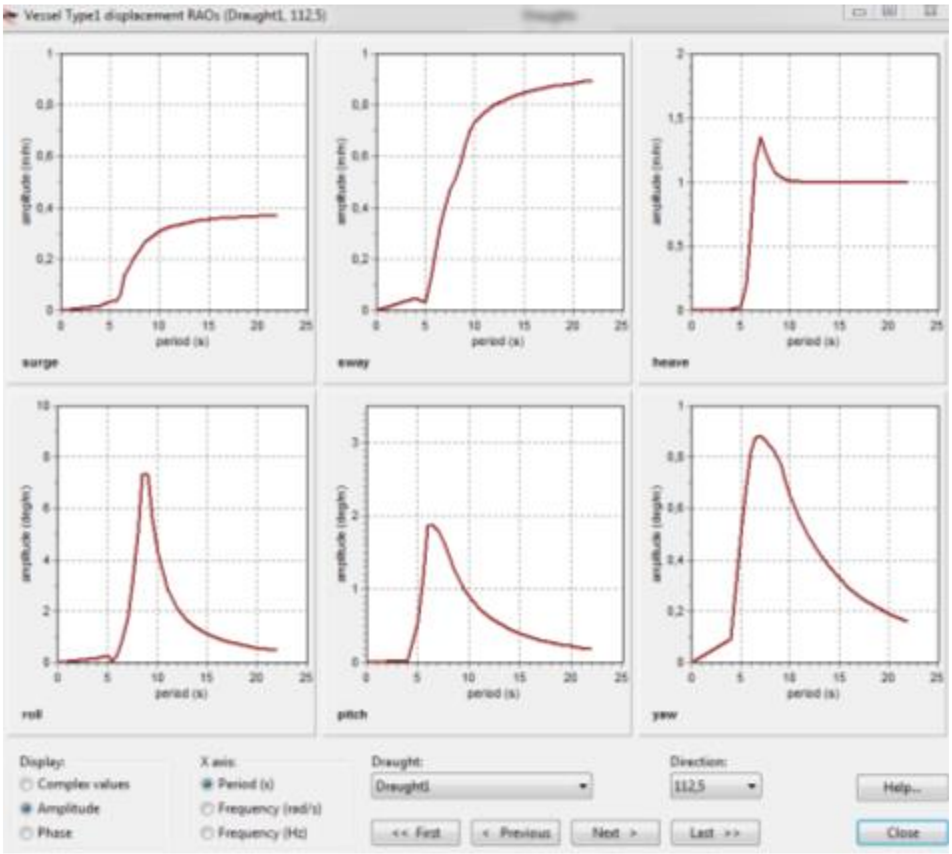
Display:
○ Complex values
● Amplitude
○ Phase

X axis:
● Period (s)
○ Frequency (rad/s)
○ Frequency (Hz)

Draught: Draught1

Direction: 90

Figure B-3: OrcaFlex default vessel displacement RAOs, direction 90 degrees.


Vessel Type1 displacement RAOs (Draught1, 112.5)

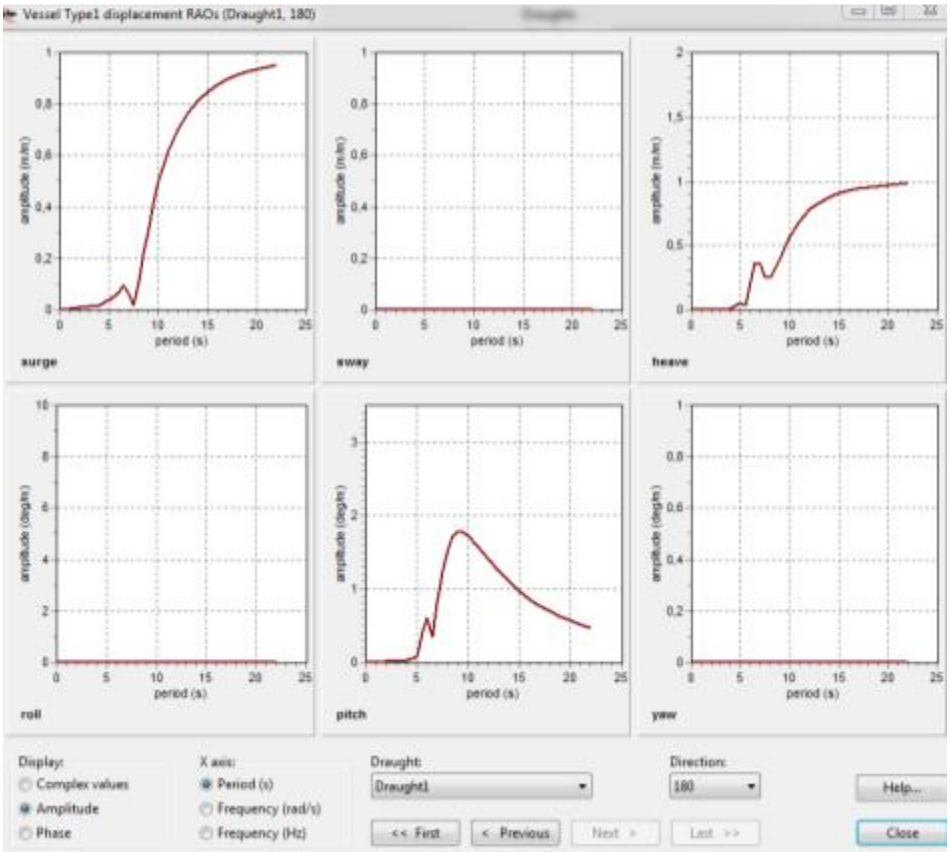
Display:
○ Complex values
● Amplitude
○ Phase

X axis:
● Period (s)
○ Frequency (rad/s)
○ Frequency (Hz)

Draught: Draught1

Direction: 112.5

Figure B-4: OrcaFlex default vessel displacement RAOs, direction 112.5 degrees.


Vessel Type1 displacement RAOs (Draught1, 180)

Display:
○ Complex values
● Amplitude
○ Phase

X axis:
● Period (s)
○ Frequency (rad/s)
○ Frequency (Hz)

Draught: Draught1

Direction: 180

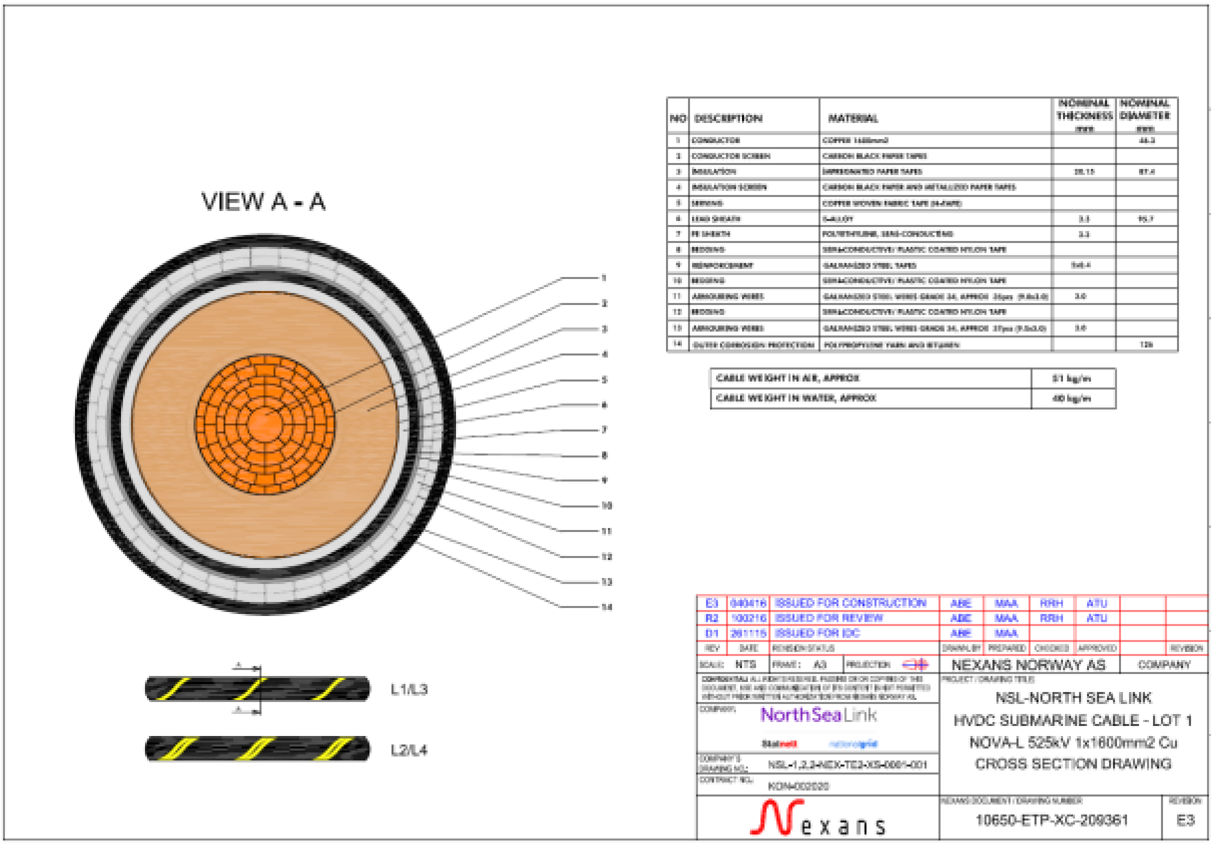
Figure B-5: OrcaFlex default vessel displacement RAOs, direction 180 degrees.

Appendix C

Cable data, used for tension calculations and OrcaFlex simulations, in Table C-1. Cross section sketch of cable in Figure C-1.

Table C-1: Cable data used for tension calculations and OrcaFlex simulations (Tunheim, 2016).

Cable data:	Sign:	Value:	Unit:
Cable diameter	OD	0,126	[m]
Weight in air	wd	51	[kg/m]
Weight in water	ww	40	[kg/m]
Bending stiffness		30	[kNm^2]
Axial stiffness		419	[MN]
Torsional stiffness		45	[kNm^2/rad]
Ultimate strength		70	[ton]
Minimum bending radius	MBR	3	[m]



NO	DESCRIPTION	MATERIAL	NOMINAL THICKNESS mm	NOMINAL DIAMETER mm
1	CONDUCTOR	COPPER 1600mm2		48.3
2	CONDUCTOR SCREEN	CARBON BLACK PAPER TAPES		
3	INSULATION	IMPREGNATED PAPER TAPES	20.15	87.4
4	INSULATION SCREEN	CARBON BLACK PAPER AND METALLIZED PAPER TAPES		
5	SERVING	COPPER WOVEN FABRIC TAPE (4-TAPE)		
6	LEAD SHEATH	E-ALLOY	3.3	95.7
7	PE SHEATH	POLYETHYLENE, SEMI-CONDUCTING	3.3	
8	BEDDING	SEMICONDUCTIVE/ PLASTIC COATED NYLON TAPE		
9	REINFORCEMENT	GALVANIZED STEEL TAPES	5x0.4	
10	BEDDING	SEMICONDUCTIVE/ PLASTIC COATED NYLON TAPE		
11	ARMOURING WIRES	GALVANIZED STEEL WIRES GRADE 34, APPROX 35pcs (9.0x3.0)	3.0	
12	BEDDING	SEMICONDUCTIVE/ PLASTIC COATED NYLON TAPE		
13	ARMOURING WIRES	GALVANIZED STEEL WIRES GRADE 34, APPROX 37pcs (9.5x3.0)	3.0	
14	OUTER CORROSION PROTECTION	POLYPROPYLENE YARN AND BITUMEN		126

CABLE WEIGHT IN AIR, APPROX	51 kg/m
CABLE WEIGHT IN WATER, APPROX	40 kg/m

REV	DATE	REVISION STATUS	DRAWN BY	PREPARED	CHECKED	APPROVED		REVISION
E3	040416	ISSUED FOR CONSTRUCTION	ABE	MAA	RRH	ATU		
R2	100216	ISSUED FOR REVIEW	ABE	MAA	RRH	ATU		
D1	281115	ISSUED FOR IDC	ABE	MAA				

SCALE: NTS FRAME: A3 PROJECTION

NEXANS NORWAY AS COMPANY

PROJECT / DRAWING TITLE:
NSL-NORTH SEA LINK
HVDC SUBMARINE CABLE - LOT 1
NOVA-L 525kV 1x1600mm2 Cu
CROSS SECTION DRAWING

COMPANY'S DRAWING NO.: NSL-1,2,3-NEX-TE3-XS-0001-001

CONTRACT NO.: KON-002020

NEXANS DOCUMENT / DRAWING NUMBER: 10650-ETP-XC-209361

REVISION: E3

Figure C-1: Cross section sketch of HVDC cable (Tunheim, 2016).

Appendix D

Simulation results from OrcaFlex simulations.

10 min dynamic simulations are done using OrcaFlex where data of tension and cable bending is gathered. Criteria for residual bottom tension is set according to Table D-1. For every simulation, the bottom tension is evaluated and an acceptance level is set according to the lowest bottom tension.

Table D-1: Sea state acceptance-level criteria for residual bottom tension in cable.

Residual bottom tension		
Acceptance level	Lowest measured value	Comment
🟩	> 500 kg	No compression, low risk of loops
🟩	> 300 kg	No compression, loops may happen
🟩	> 0 kg	No compression, risk of loops
🟧	1 time "< 0 kg"	Risk of compression, risk of loops
🟧	≤ 3 time "< 0 kg"	High risk of compression and loops
🟧	≥ 4 times "< 0 kg"	Very high risk of compression and loops
🟥	Not applicable; No/rarely waves in this range	

Criteria for the bending in cable over the laying wheel is dependent on the degrees of angle change. For every simulation, angle data of the cable when leaving the wheel is gathered, and the bending cycles are split into groups, dependent on the angle of bending. As stated in the assumptions in chapter 6.3.1, bending's less than 1 degree is assumed to have very little effect on fatigue, and is therefore not considered further. Bending's between 1-2 degrees and higher are of concern, and the criteria are as seen in Table D-2. The acceptance level is set according to how long time the cable can handle the wave load without being concerned about fatigue. In the "green" level, the cable should, depending on the duration of jointing, be able to endure the wave loads throughout the entire jointing operation, as it results in very little cyclic bending in the cable per time unit. After that, the jointing may have to be terminated, unless the sea state of concern appears later or towards the end of the jointing process.

Table D-2: Sea state acceptance-level criteria for cable bending over laying wheel.

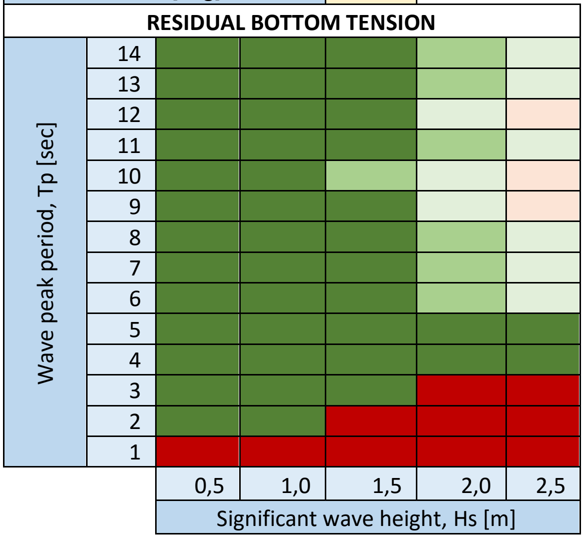
Cyclic bending in cable at departure of laying wheel		
Acceptance level	Number of 1-2 degree bending / 10 min	Comment
🟩	x ≤ 4	Can withstand this loading over entire jointing operation
🟩	x ≤ 7	Risk of fatigue damage after 12 days
🟩	x ≤ 10	Risk of fatigue damage after 8 days
🟨	x ≤ 15	Risk of fatigue damage after 5 days
🟨	x ≤ 28	Risk of fatigue damage after 3 days
🟨	x ≤ 40	Risk of fatigue damage after 2 days
🟧	41 ≤ x < 60	Risk of fatigue damage in less than 2 days
🟧	x ≥ 41 + higher angles	Risk of fatigue damage in less than 1 day
🟥	Not applicable; No/rarely waves in this range	

Wave direction

Dynamic simulation results from testing the effect of wave direction on cable tension and cable bending for a cable jointing operation. Legend in Table D-1 and Table D-2.

Table D-3: Residual tension and bending in cable at 300 m water depth for various wave heights and peak periods, with waves approaching at 0 degrees.

Water depth [m]	300
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	0



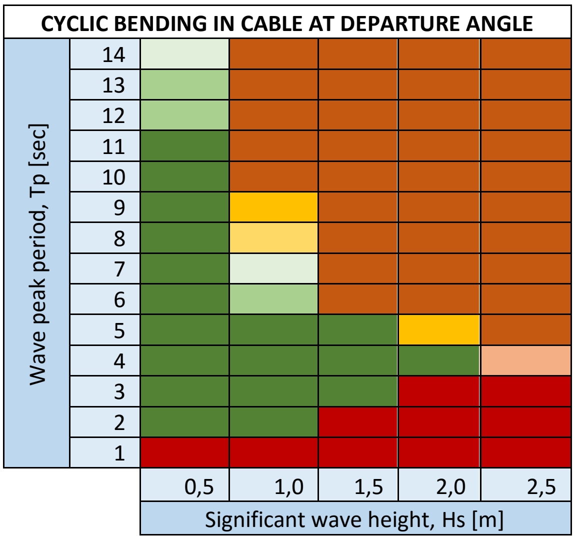
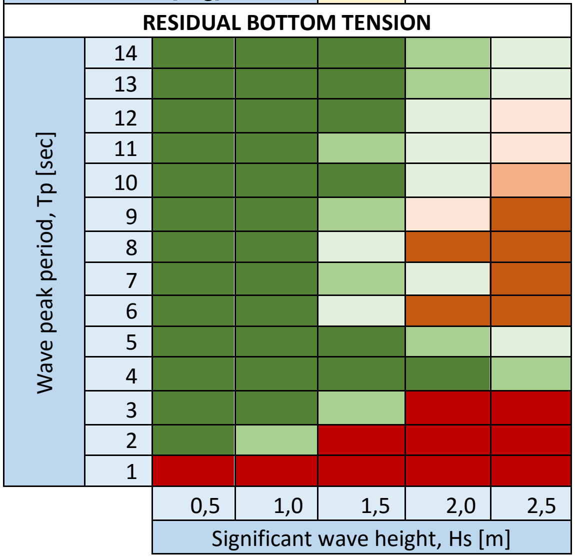


Table D-4: Residual tension and bending in cable at 300 m water depth for various wave heights and peak periods, with waves approaching at 90 degrees.

Water depth [m]	300
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



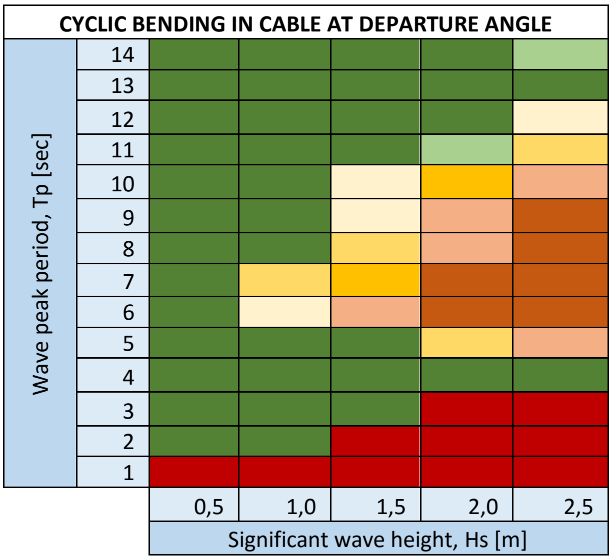
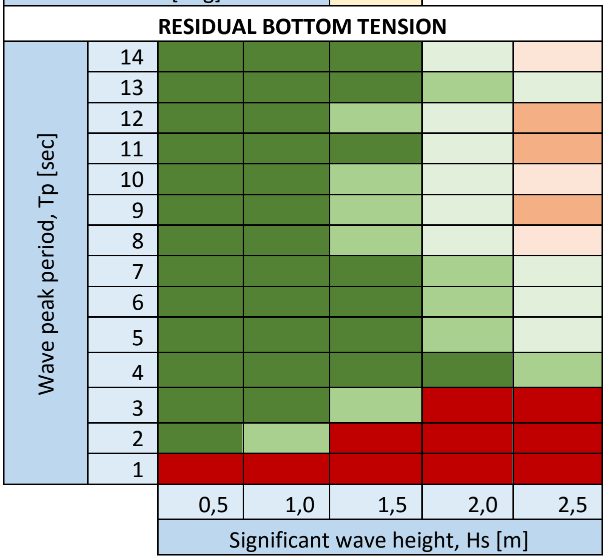


Table D-5: Residual tension and bending in cable at 1200 m water depth for various wave heights and peak periods, with waves approaching at 0 degrees.

Water depth [m]	1200
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	0



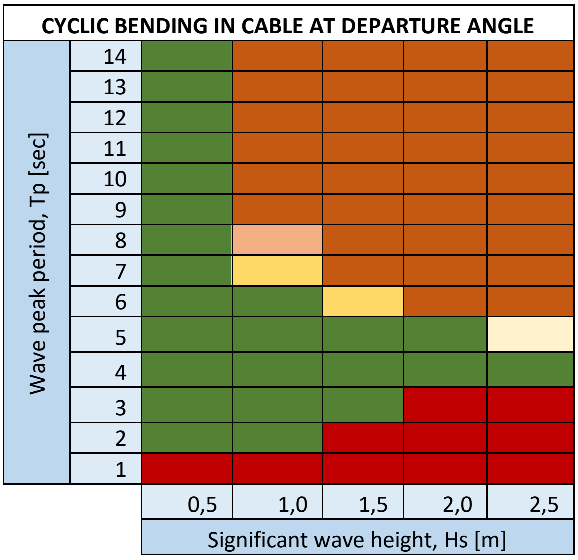
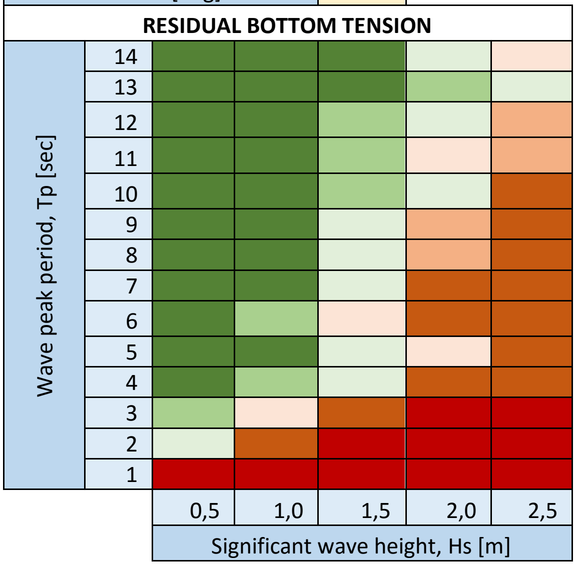
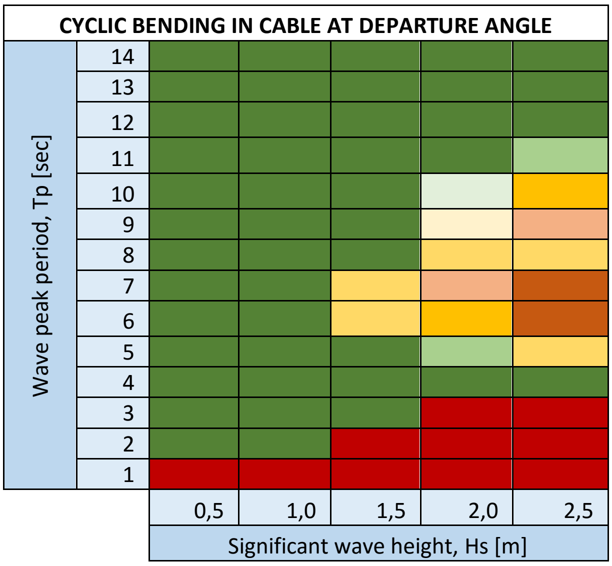


Table D-6: Residual tension and bending in cable at 1200 m water depth for various wave heights and peak periods, with waves approaching at 90 degrees.

Water depth [m]	1200
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



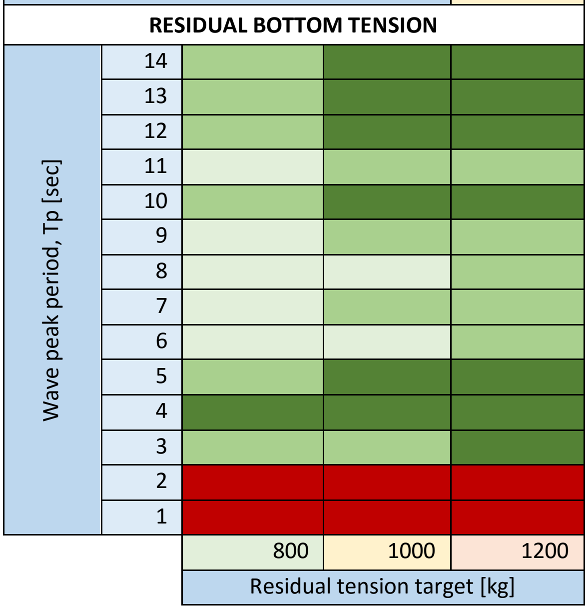


Residual bottom tension

Dynamic simulation results from testing various initial bottom tensions to find what is suitable for a jointing operation when waves are present. Legend in Table D-1 and Table D-2.

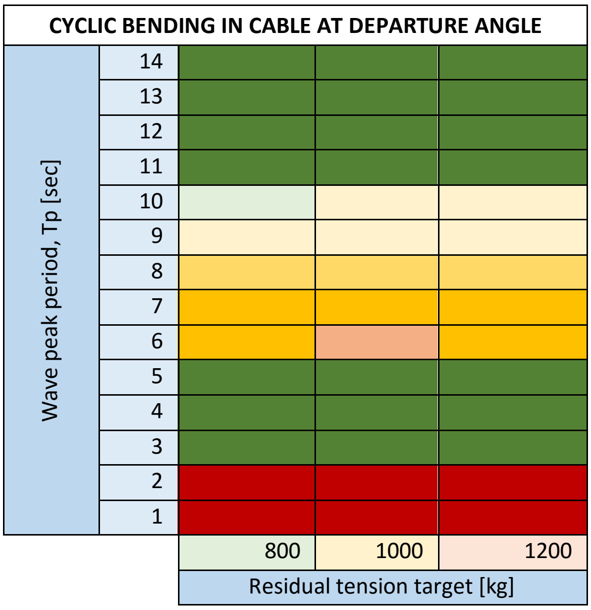
Table D-7: Residual tension and bending in cable at 300 m water depth for various residual bottom tension targets.

Water depth [m]	300
Laying wheel location [m]	-5
Wave direction [deg]	90
Significant wave height, Hs [m]	1,5



RESIDUAL BOTTOM TENSION

Wave peak period, Tp [sec]				
	14	▩	🟩	🟩
	13	▩	🟩	🟩
	12	▩	🟩	🟩
	11	▢	▩	▩
	10	▩	🟩	🟩
	9	▢	▩	▩
	8	▢	▢	▩
	7	▢	▩	▩
	6	▢	▢	▩
	5	▩	🟩	🟩
	4	🟩	🟩	🟩
	3	▩	▩	🟩
	2	🟥	🟥	🟥
	1	🟥	🟥	🟥
		800	1000	1200
		Residual tension target [kg]		

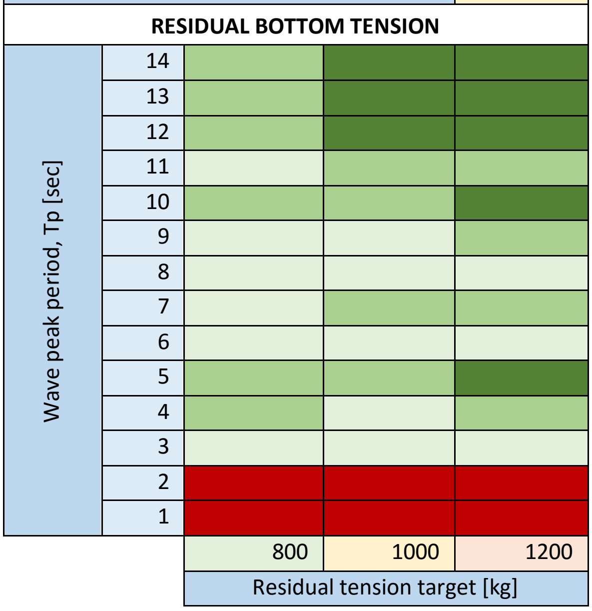


CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE

Wave peak period, Tp [sec]				
	14	🟩	🟩	🟩
	13	🟩	🟩	🟩
	12	🟩	🟩	🟩
	11	🟩	🟩	🟩
	10	▢	░	░
	9	░	░	░
	8	🟨	🟨	🟨
	7	🟧	🟧	🟧
	6	🟧	▨	🟧
	5	🟩	🟩	🟩
	4	🟩	🟩	🟩
	3	🟩	🟩	🟩
	2	🟥	🟥	🟥
	1	🟥	🟥	🟥
		800	1000	1200
		Residual tension target [kg]		

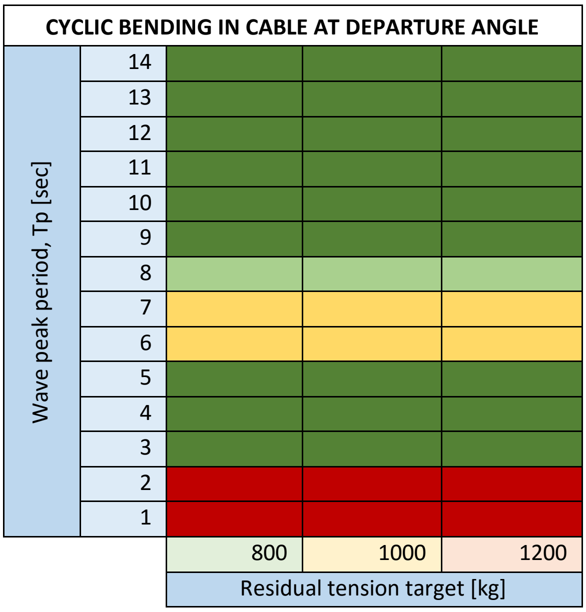
Table D-8: Residual tension and bending in cable at 700 m water depth for various residual bottom tension targets.

Water depth [m]	700
Laying wheel location [m]	-5
Wave direction [deg]	90
Significant wave height, Hs [m]	1,5



RESIDUAL BOTTOM TENSION

Wave peak period, Tp [sec]				
	14	▩	🟩	🟩
	13	▩	🟩	🟩
	12	▩	🟩	🟩
	11	▢	▩	▩
	10	▩	▩	🟩
	9	▢	▢	▩
	8	▢	▢	▢
	7	▢	▩	▩
	6	▢	▢	▢
	5	▩	▩	🟩
	4	▩	▢	▩
	3	▢	▢	▢
	2	🟥	🟥	🟥
	1	🟥	🟥	🟥
		800	1000	1200
		Residual tension target [kg]		

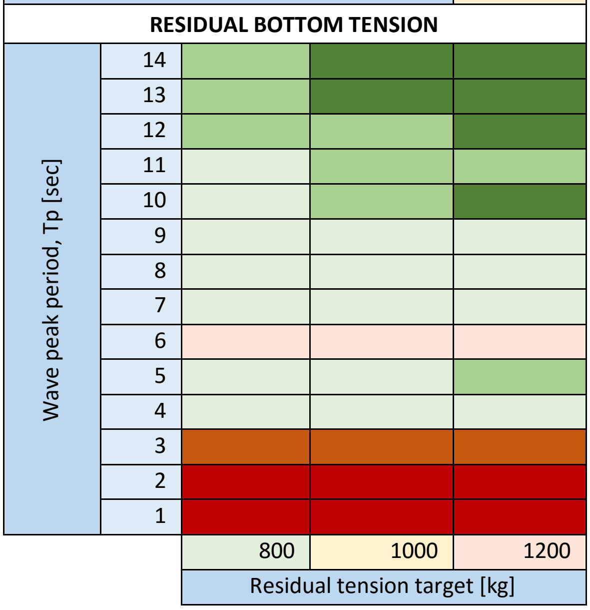


CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE

Wave peak period, Tp [sec]				
	14	🟩	🟩	🟩
	13	🟩	🟩	🟩
	12	🟩	🟩	🟩
	11	🟩	🟩	🟩
	10	🟩	🟩	🟩
	9	🟩	🟩	🟩
	8	▩	▩	▩
	7	🟨	🟨	🟨
	6	🟨	🟨	🟨
	5	🟩	🟩	🟩
	4	🟩	🟩	🟩
	3	🟩	🟩	🟩
	2	🟥	🟥	🟥
	1	🟥	🟥	🟥
		800	1000	1200
		Residual tension target [kg]		

Table D-9: Residual tension and bending in cable at 1200 m water depth for various residual bottom tension targets.

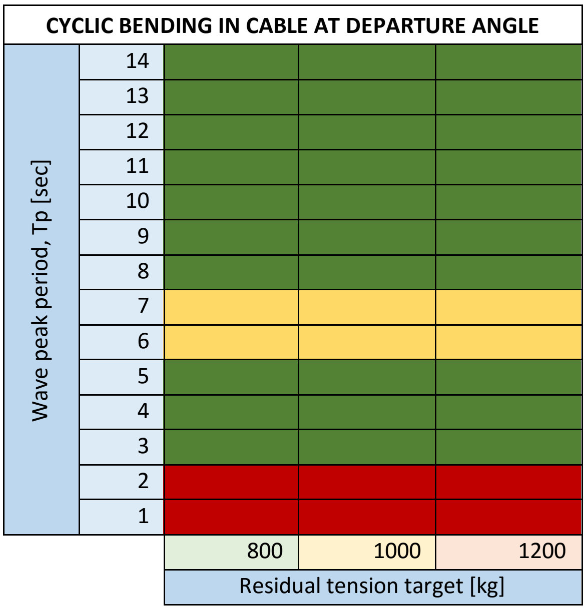
Water depth [m]	1200
Laying wheel location [m]	-5
Wave direction [deg]	90
Significant wave height, Hs [m]	1,5



RESIDUAL BOTTOM TENSION

Wave peak period, Tp [sec]	800	1000	1200
14	🟩	🟩	🟩
13	🟩	🟩	🟩
12	🟩	🟩	🟩
11	🟩	🟩	🟩
10	🟩	🟩	🟩
9	🟩	🟩	🟩
8	🟩	🟩	🟩
7	🟩	🟩	🟩
6	🟥	🟥	🟥
5	🟩	🟩	🟩
4	🟩	🟩	🟩
3	🟧	🟧	🟧
2	🟥	🟥	🟥
1	🟥	🟥	🟥

Residual tension target [kg]



CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE

Wave peak period, Tp [sec]	800	1000	1200
14	🟩	🟩	🟩
13	🟩	🟩	🟩
12	🟩	🟩	🟩
11	🟩	🟩	🟩
10	🟩	🟩	🟩
9	🟩	🟩	🟩
8	🟩	🟩	🟩
7	🟨	🟨	🟨
6	🟨	🟨	🟨
5	🟩	🟩	🟩
4	🟩	🟩	🟩
3	🟩	🟩	🟩
2	🟥	🟥	🟥
1	🟥	🟥	🟥

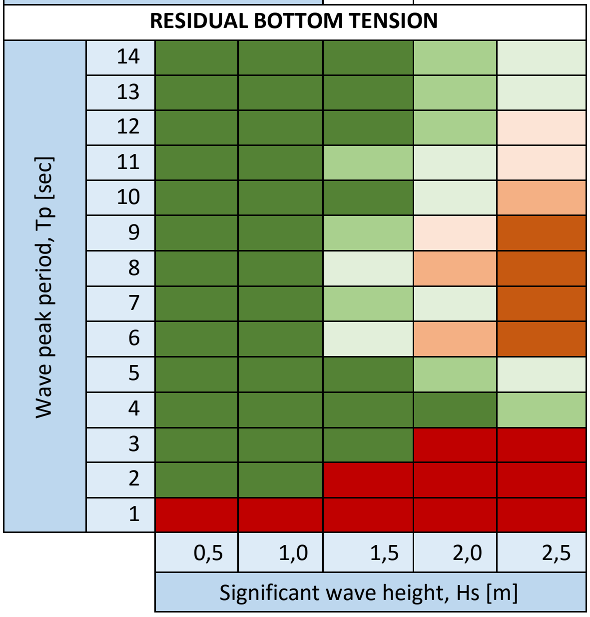
Residual tension target [kg]

Wave loads on cable

Dynamic simulation results for a jointing operation with waves present. Legend in Table D-1 and Table D-2.

Table D-10: Residual tension and bending in cable at 100 m water depth for various wave heights and peak periods.

Water depth [m]	100
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



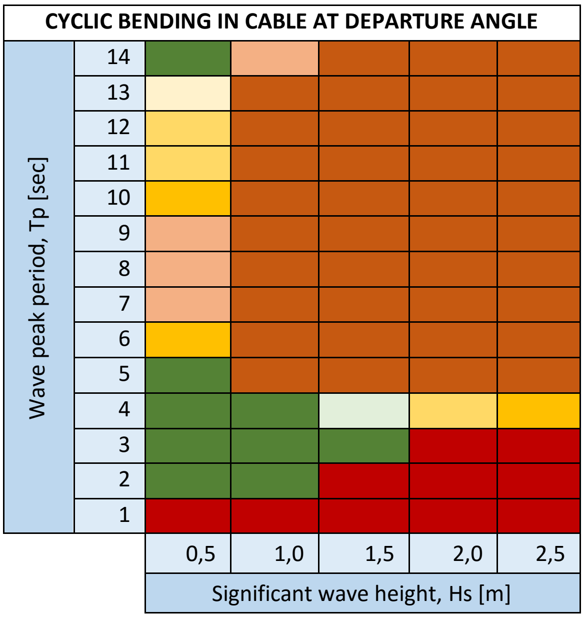
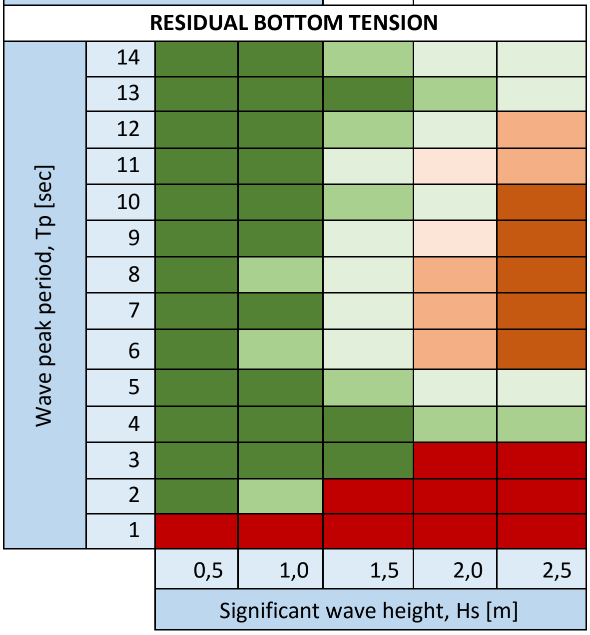


Table D-11: Residual tension and bending in cable at 100 m water depth for various wave heights and peak periods and a reduced initial tension of 800 kg.

Water depth [m]	100
Laying wheel location [m]	-5
Residual tension target [kg]	800
Wave direction [deg]	90



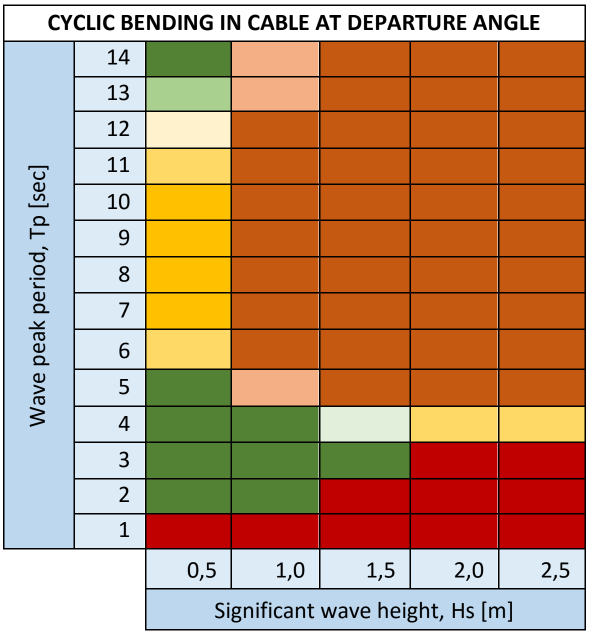
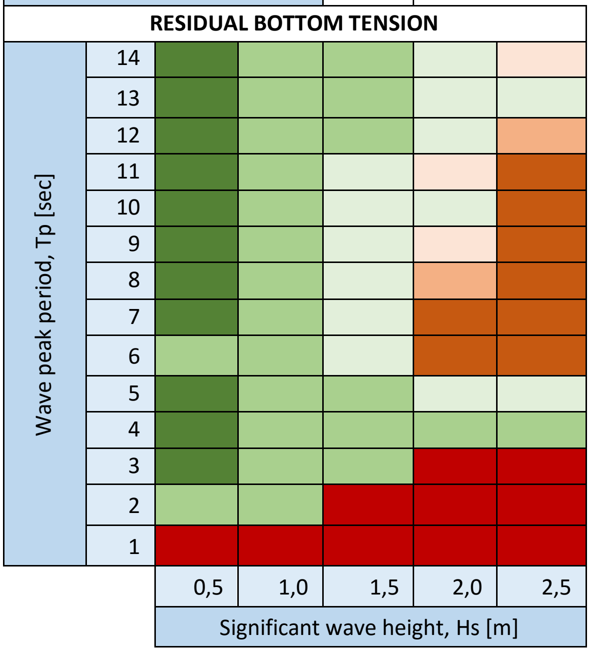


Table D-12: Residual tension and bending in cable at 100 m water depth for various wave heights and peak periods and a reduced initial tension of 600 kg.

Water depth [m]	100
Laying wheel location [m]	-5
Residual tension target [kg]	600
Wave direction [deg]	90



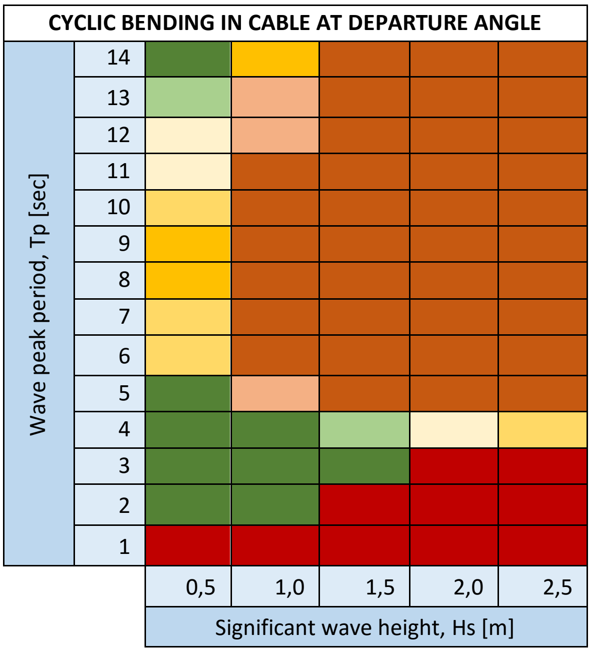
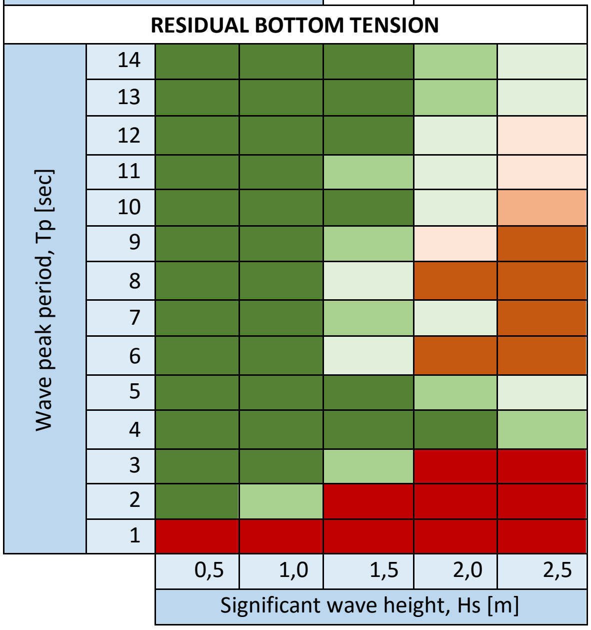


Table D-13: Residual tension and bending in cable at 300 m water depth for various wave heights and peak periods

Water depth [m]	300
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



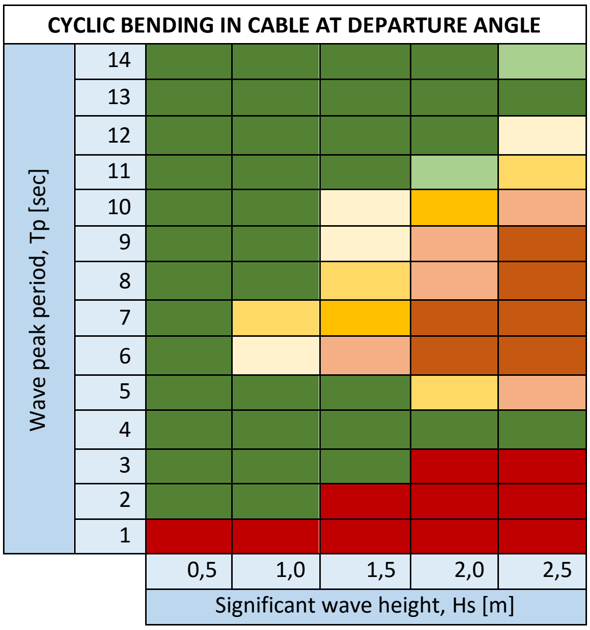
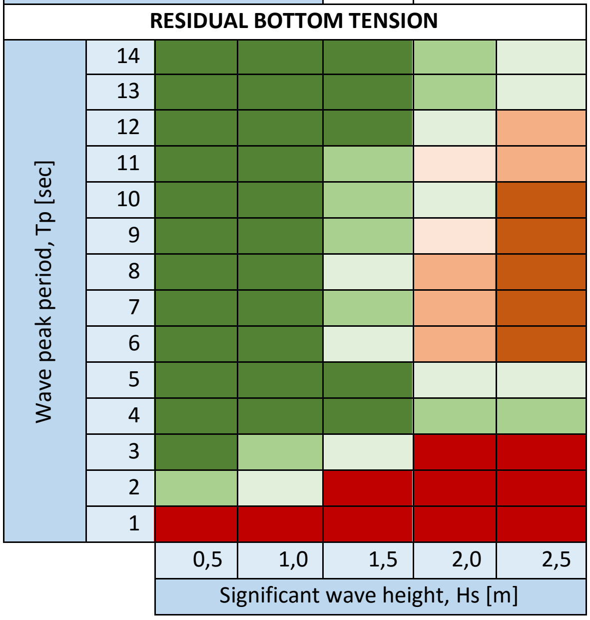


Table D-14: Residual tension and bending in cable at 500 m water depth for various wave heights and peak periods

Water depth [m]	500
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



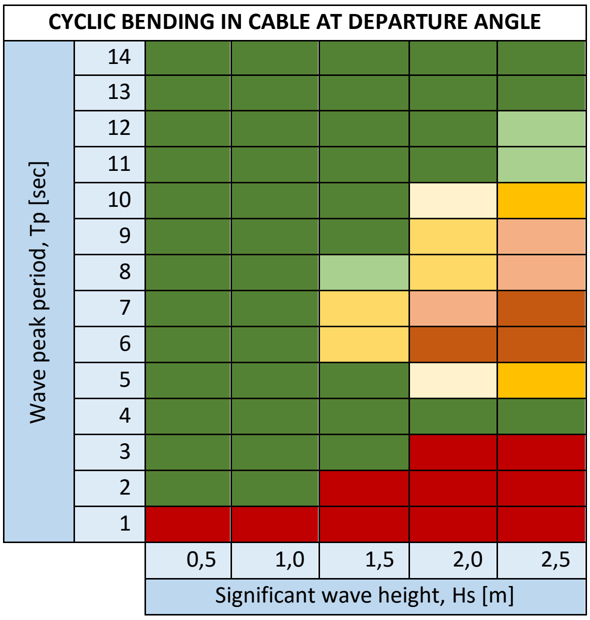
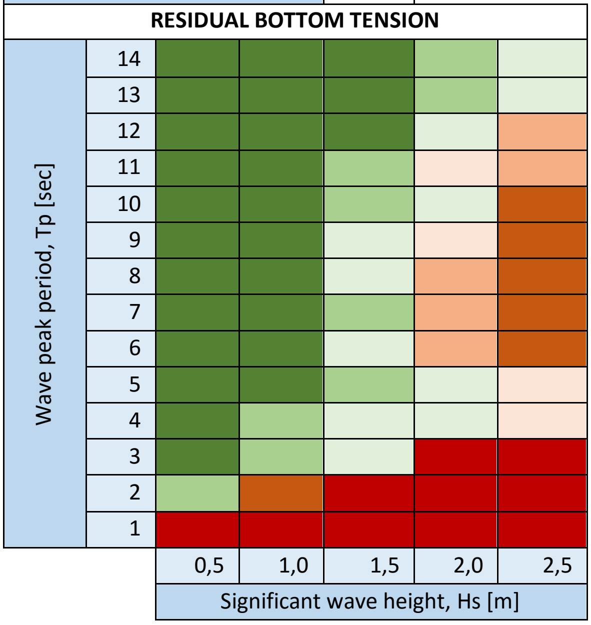


Table D-15: Residual tension and bending in cable at 700 m water depth for various wave heights and peak periods

Water depth [m]	700
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



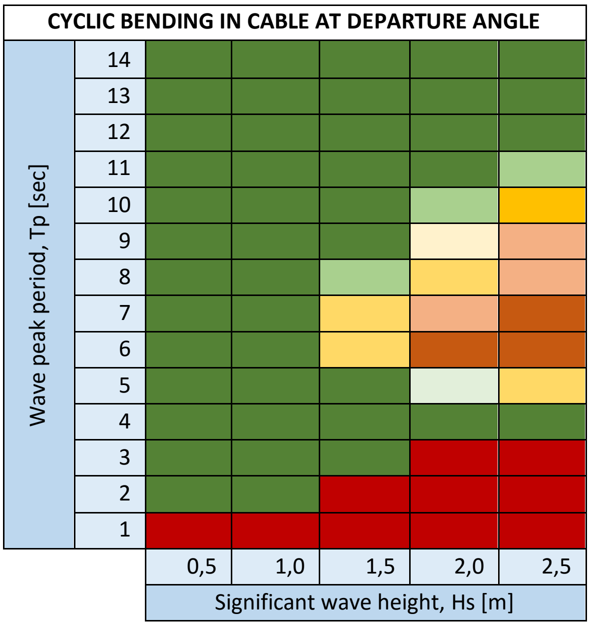
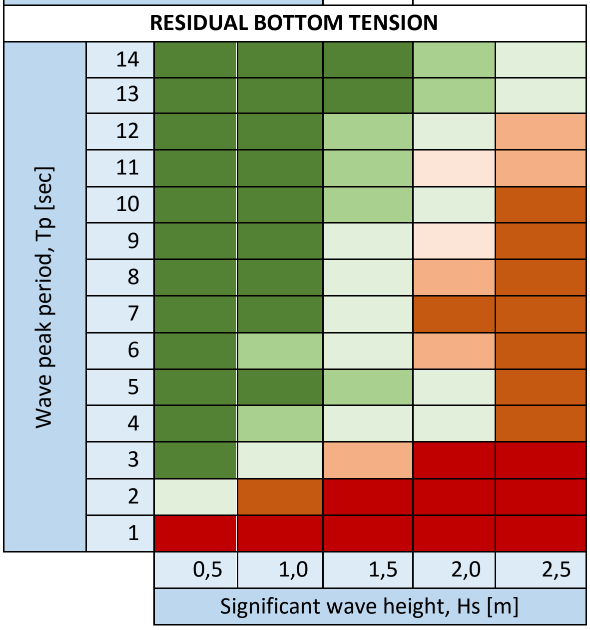


Table D-16: Residual tension and bending in cable at 900 m water depth for various wave heights and peak periods

Water depth [m]	900
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



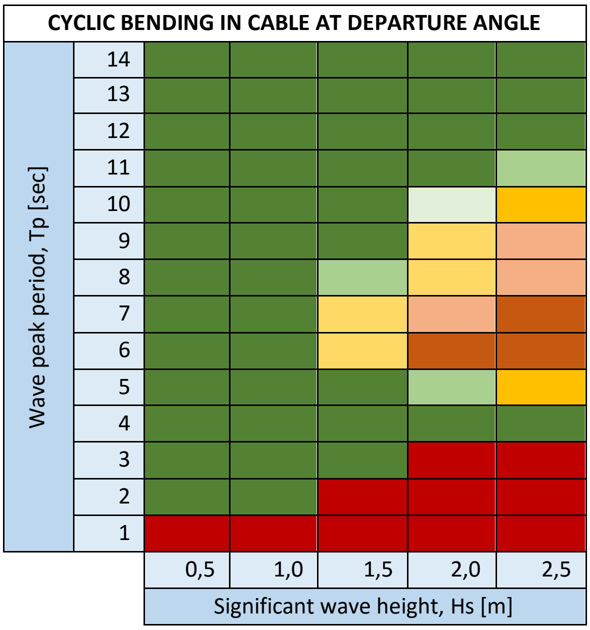
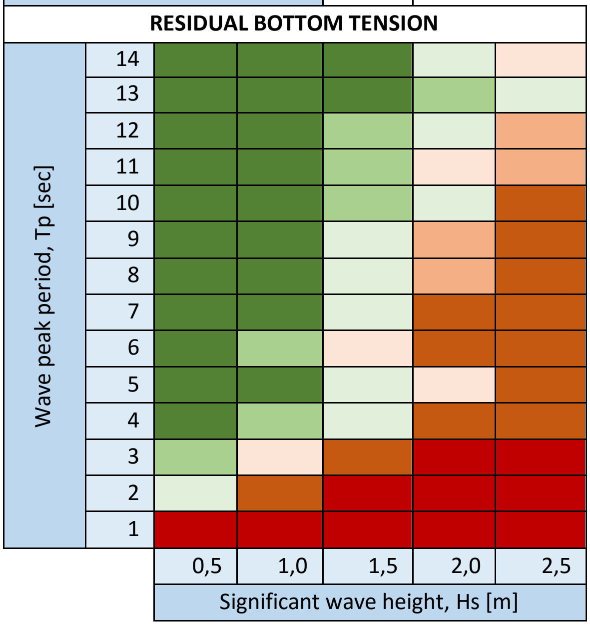
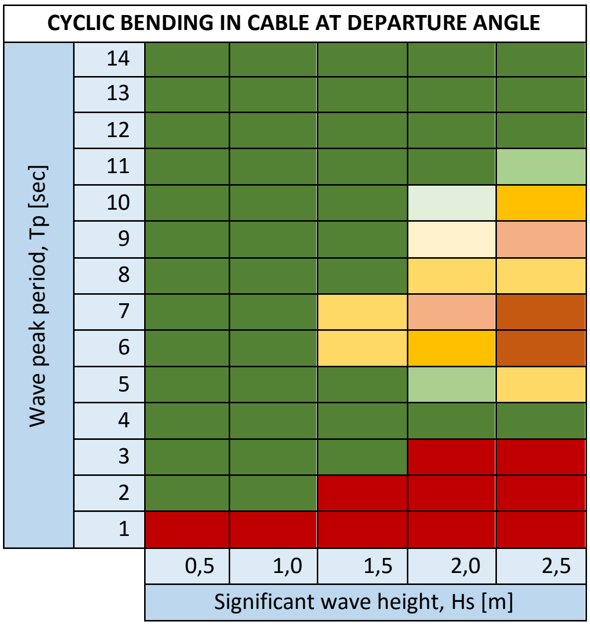


Table D-17: Residual tension and bending in cable at 1200 m water depth for various wave heights and peak periods

Water depth [m]	1200
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Wave direction [deg]	90



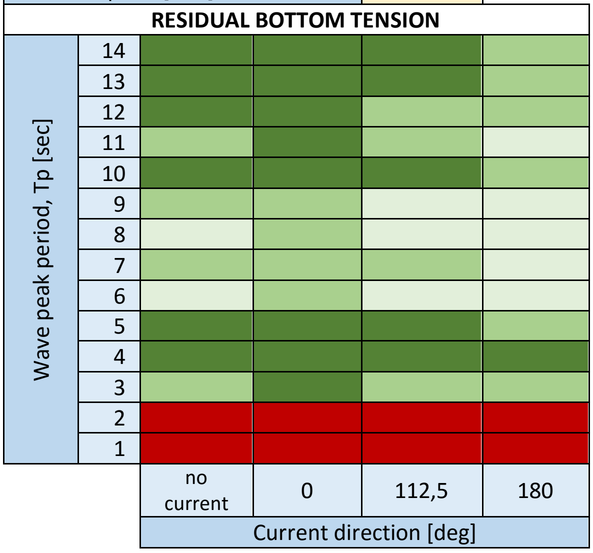


Wave and Current loads on cable

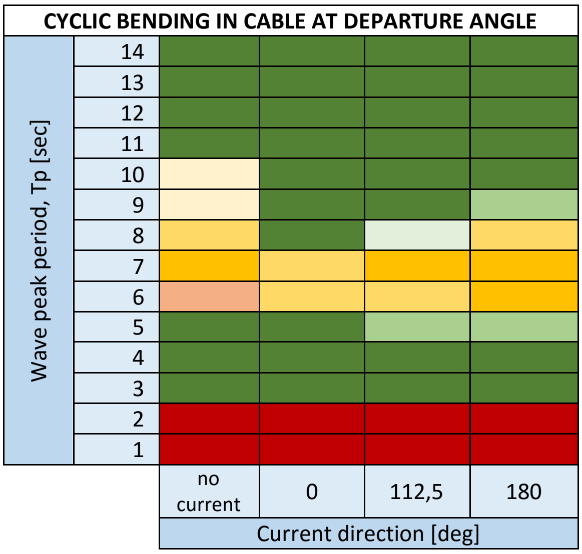
Dynamic simulation results for a jointing operation when waves and current are present. Legend in Table D-1 and Table D-2.

Table D-18: Residual tension and bending in cable at 300 m water depth when current forces at different directions are added.

Water depth [m]	300
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Significant wave height [m]	1,5
Wave direction [deg]	90
Current speed [m/s]	0,75



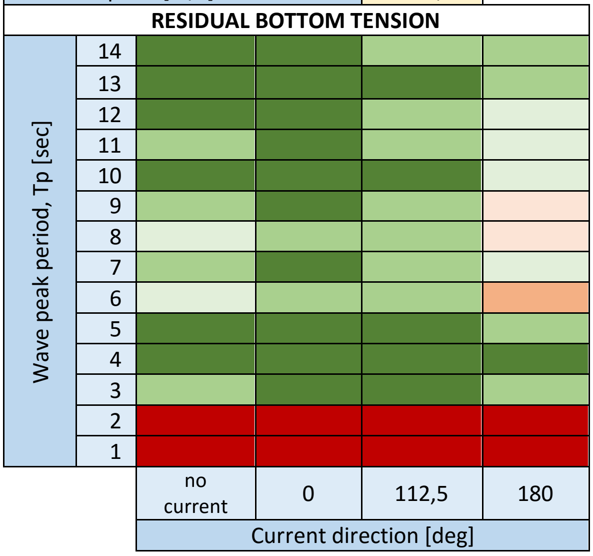
RESIDUAL BOTTOM TENSION				
Wave peak period, Tp [sec]	Current direction [deg]			
	no current	0	112,5	180
14	🟩	🟩	🟩	🟢
13	🟩	🟩	🟩	🟢
12	🟩	🟩	🟢	🟢
11	🟢	🟩	🟢	◽
10	🟩	🟩	🟩	🟢
9	🟢	🟢	◽	◽
8	◽	🟢	◽	◽
7	🟢	🟢	🟢	◽
6	◽	🟢	◽	◽
5	🟩	🟩	🟩	🟢
4	🟩	🟩	🟩	🟩
3	🟢	🟩	🟢	🟢
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥



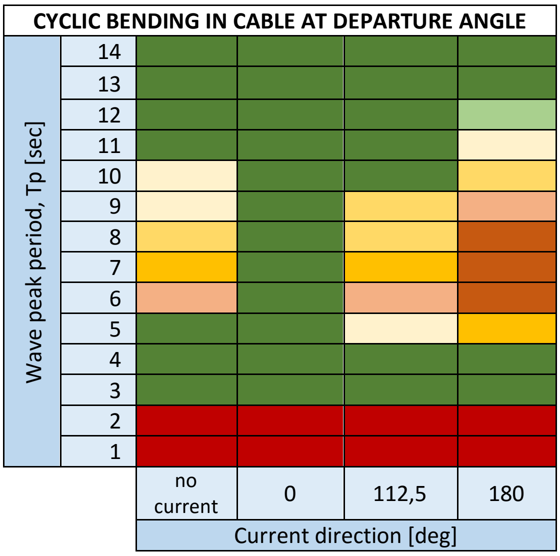
CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE				
Wave peak period, Tp [sec]	Current direction [deg]			
	no current	0	112,5	180
14	🟩	🟩	🟩	🟩
13	🟩	🟩	🟩	🟩
12	🟩	🟩	🟩	🟩
11	🟩	🟩	🟩	🟩
10	🟡	🟩	🟩	🟩
9	🟡	🟩	🟩	🟢
8	🟨	🟩	◽	🟨
7	🟧	🟨	🟧	🟧
6	🟠	🟨	🟨	🟧
5	🟩	🟩	🟢	🟢
4	🟩	🟩	🟩	🟩
3	🟩	🟩	🟩	🟩
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥

Table D-19: Residual tension and bending in cable at 300 m water depth when current forces at different directions are added.

Water depth [m]	300
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Significant wave height [m]	1,5
Wave direction [deg]	90
Current speed [m/s]	1,25



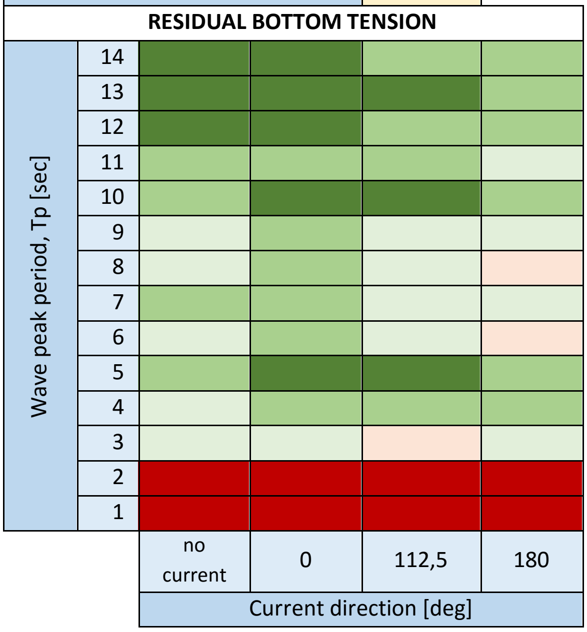
RESIDUAL BOTTOM TENSION				
Wave peak period, Tp [sec]	Current direction [deg]			
	no current	0	112,5	180
14	🟩	🟩	🟢	🟢
13	🟩	🟩	🟩	🟢
12	🟩	🟩	🟢	◽
11	🟢	🟩	🟢	◽
10	🟩	🟩	🟩	◽
9	🟢	🟩	🟢	◻
8	◽	🟢	🟢	◻
7	🟢	🟩	🟢	◽
6	◽	🟢	🟢	🟠
5	🟩	🟩	🟩	🟢
4	🟩	🟩	🟩	🟩
3	🟢	🟩	🟩	🟢
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥



CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE				
Wave peak period, Tp [sec]	Current direction [deg]			
	no current	0	112,5	180
14	🟩	🟩	🟩	🟩
13	🟩	🟩	🟩	🟩
12	🟩	🟩	🟩	🟢
11	🟩	🟩	🟩	🟡
10	🟡	🟩	🟩	🟨
9	🟡	🟩	🟨	🟠
8	🟨	🟩	🟨	🟫
7	🟧	🟩	🟧	🟫
6	🟠	🟩	🟠	🟫
5	🟩	🟩	🟡	🟧
4	🟩	🟩	🟩	🟩
3	🟩	🟩	🟩	🟩
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥

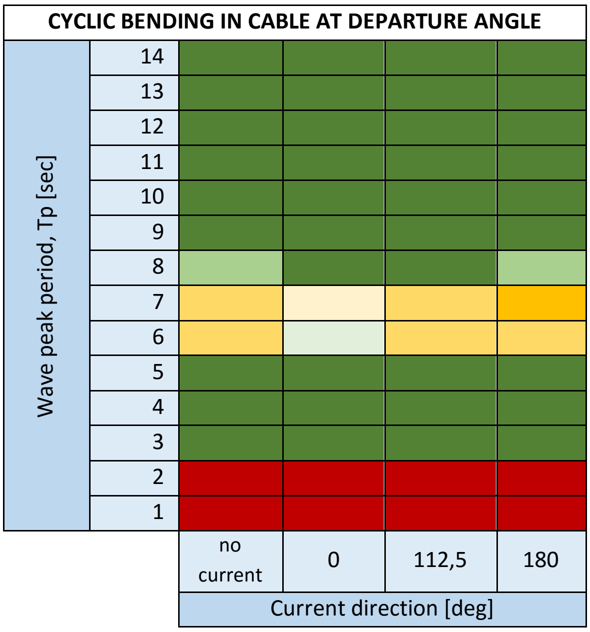
Table D-20: Residual tension and bending in cable at 700 m water depth when current forces at different directions are added.

Water depth [m]	700
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Significant wave height [m]	1,5
Wave direction [deg]	90
Current speed [m/s]	0,75



RESIDUAL BOTTOM TENSION

Wave peak period, Tp [sec]	no current	0	112,5	180
14	🟩	🟩	🟢	🟢
13	🟩	🟩	🟩	🟢
12	🟩	🟩	🟢	🟢
11	🟢	🟢	🟢	⬜
10	🟢	🟩	🟩	🟢
9	⬜	🟢	⬜	⬜
8	⬜	🟢	⬜	🔸
7	🟢	🟢	⬜	⬜
6	⬜	🟢	⬜	🔸
5	🟢	🟩	🟩	🟢
4	⬜	🟢	🟢	🟢
3	⬜	⬜	🔸	⬜
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥
	Current direction [deg]			

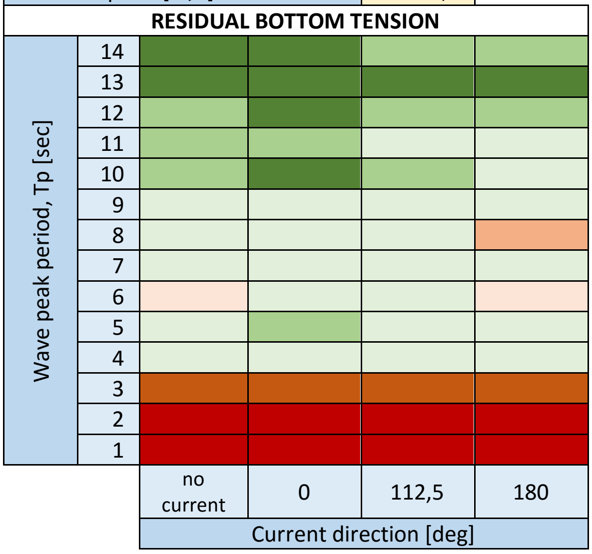


CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE

Wave peak period, Tp [sec]	no current	0	112,5	180
14	🟩	🟩	🟩	🟩
13	🟩	🟩	🟩	🟩
12	🟩	🟩	🟩	🟩
11	🟩	🟩	🟩	🟩
10	🟩	🟩	🟩	🟩
9	🟩	🟩	🟩	🟩
8	🟢	🟩	🟩	🟢
7	🟨	🟡	🟨	🟧
6	🟨	⬜	🟨	🟨
5	🟩	🟩	🟩	🟩
4	🟩	🟩	🟩	🟩
3	🟩	🟩	🟩	🟩
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥
	Current direction [deg]			

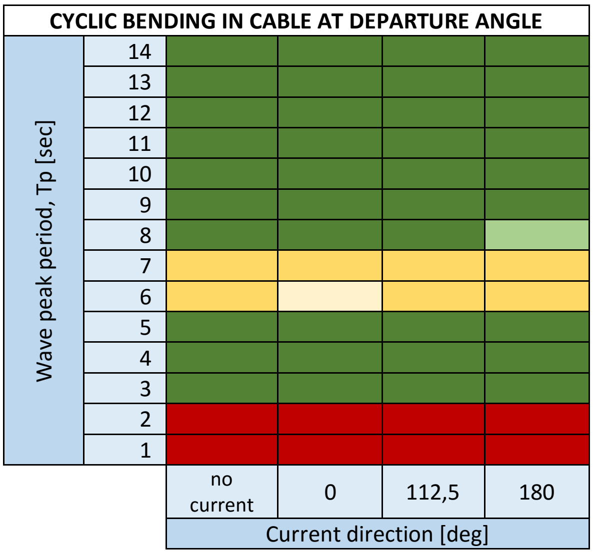
Table D-21: Residual tension and bending in cable at 1200 m water depth when current forces at different directions are added.

Water depth [m]	1200
Laying wheel location [m]	-5
Residual tension target [kg]	1000
Significant wave height [m]	1,5
Wave direction [deg]	90
Current speed [m/s]	0,5



RESIDUAL BOTTOM TENSION

Wave peak period, Tp [sec]	no current	0	112,5	180
14	🟩	🟩	🟢	🟢
13	🟩	🟩	🟩	🟩
12	🟢	🟩	🟢	🟢
11	🟢	🟢	⬜	⬜
10	🟢	🟩	🟢	⬜
9	⬜	⬜	⬜	⬜
8	⬜	⬜	⬜	🔶
7	⬜	⬜	⬜	⬜
6	🔸	⬜	⬜	🔸
5	⬜	🟢	⬜	⬜
4	⬜	⬜	⬜	⬜
3	🟧	🟧	🟧	🟧
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥
	Current direction [deg]			



CYCLIC BENDING IN CABLE AT DEPARTURE ANGLE

Wave peak period, Tp [sec]	no current	0	112,5	180
14	🟩	🟩	🟩	🟩
13	🟩	🟩	🟩	🟩
12	🟩	🟩	🟩	🟩
11	🟩	🟩	🟩	🟩
10	🟩	🟩	🟩	🟩
9	🟩	🟩	🟩	🟩
8	🟩	🟩	🟩	🟢
7	🟨	🟨	🟨	🟨
6	🟨	🟡	🟨	🟨
5	🟩	🟩	🟩	🟩
4	🟩	🟩	🟩	🟩
3	🟩	🟩	🟩	🟩
2	🟥	🟥	🟥	🟥
1	🟥	🟥	🟥	🟥
	Current direction [deg]			

Centralized Laying Wheel

Dynamic simulation results of jointing operation with wave present and moving the laying wheel to the center of the vessel stern. Legend in Table D-1 and Table D-2.

Table D-22: Residual tension and bending in cable at 700 m water depth when moving the laying wheel to the center of the stern.

Water depth [m]	700
Laying wheel location [m]	0
Residual tension target [kg]	1000
Wave direction [deg]	90

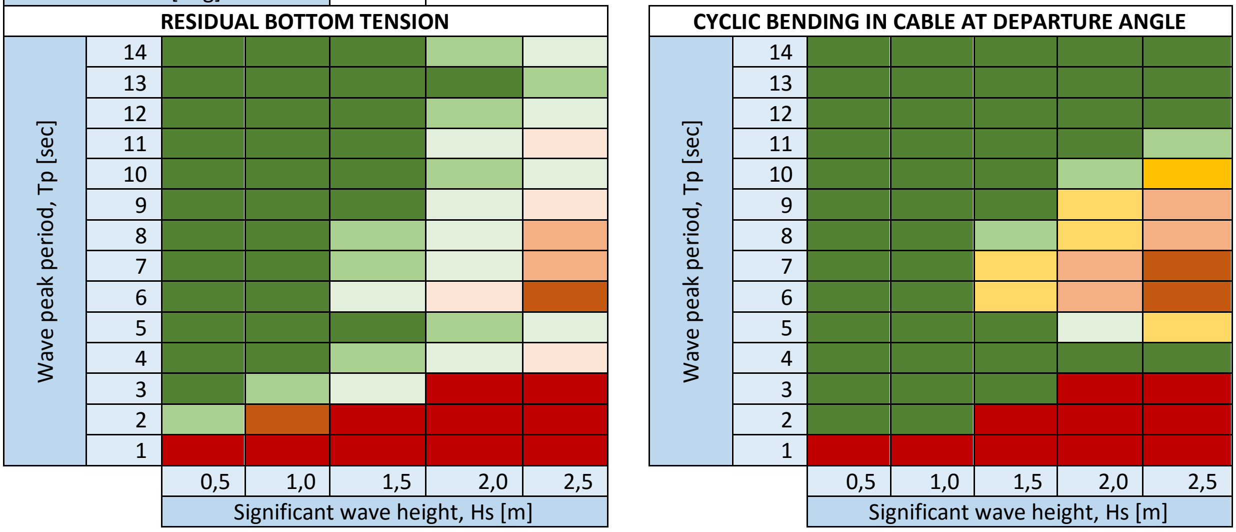


Table D-23: Residual tension and bending in cable at 1200 m water depth when moving the laying wheel to the center of the stern.

Water depth [m]	1200
Laying wheel location [m]	0
Residual tension target [kg]	1000
Wave direction [deg]	90