

Operability limits based on vessel motions for submarine power cable installation

Master thesis

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Preface

This master thesis concludes my education in becoming an offshore engineer. I am very grateful for the opportunity to perform my graduation at VBMS. I have had a great time working among enthusiastic and professional colleagues. And I am looking forwards for new projects to come.

Hereby, I would like to thank the members of my graduation committee for their support and sharing their knowledge. Special thanks go out to Ruud Beindorff for his seemingly unlimited amount of energy and optimism in guiding me.

On a personal note, I would also like to thank my family, girlfriend and close friends for their support. I could not have performed this well without them.

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Abstract

The increased demand for renewable energy has resulted in a growth of the offshore renewables market. Offshore wind farms grow in size and move further from shore and into greater water depths. This will increase the amount of wind energy that can be captured, but will also increase the environmental exposure on the vessels that install the submarine power cables. This increased exposure will result in reduced operability and thus increased costs for installation. In order to make offshore renewable energy competitive with land based alternatives, the installation costs of offshore wind parks need to be reduced. The improvement of operability of cable laying processes may be one of the factors in this undertaking.

Traditionally, operability in offshore construction is characterized by the significant wave height. Operable weather conditions are determined using a time-domain simulation of the laying process in parameterized sea-states. This results in a list of sea-states and vessel headings that are determined to be operable or non-operable. The crew on site has to interpret these weather limits with actual conditions at hand, which induces a need for pragmatic discretization of the sea-states. This discretization is a known source of operability loss. Whilst the interpretation of the wave conditions can also lead to lost operability. The exact losses are hard to measure as the human factor is quite large for this aspect. The wave conditions however, are not the direct cause of cable integrity infringement. The ship motions in combination with cable dynamics and environmental forces provide the loads on the cable that can require the operations to be halted.

The current method of analysis is based on a pragmatic method of time domain simulation. For the sea-states that the analysts are interested in, only a part of the 3-hour wave sequence is simulated. If the operational limits for the vessel and cable are not infringed for that part of the simulation, the sea-state is deemed workable. A sample of 27 full 3-hour time domain simulations has shown that this method underestimates the maximum cable loading by an average of 3%.

The focus of this thesis is to find a relation between vessel motions and response of submarine power cables that may be limiting operations. To reach this goal, the possible failure modes of submarine power cables have been investigated. It was concluded that compression in the cable near the touchdown zone is the main limiting factor. A quasi static analysis of a representative array cable led to a hypothesis that the velocity by which the chute of the vessel moves has a direct relation to cable compression. This hypothesis has been tested by means of regular and irregular vessel motions.

A model of the N-class cable laying vessel has been implemented in the proprietary analysis software: OrcaFlex. For regular motion analysis, surge and heave motions were imposed on the vessel model. From the time domain analysis, a strong relation has been found between chute velocities in the direction of the cable axis and tension loss. Where larger chute velocities even led to compression in the cable.

This same relation is observed by simulations of the N-class vessel in irregular sea-states. Regardless of wave height, period or direction. This relation can be used to form the basis for a new method of operability assessment. Vessel motions can be measured with a high degree of accuracy. Several industry-accepted systems have been developed that predict future vessel motions based on actual weather, weather forecast and the time history of vessel motion. These systems can provide the crew with assistance in decision making.

Direct wave loads have proven to add a significant amount of scatter to the otherwise near-perfect compression prediction based on vessel motions. Currently it is unclear how large the effect of wave shielding of the cable by the vessel is. This relation needs to be further researched to increase the accuracy of the model.

When further hurdles in finding relations between vessel motions and cable integrity are taken, operable conditions can be determined with reduced inaccuracies in modelling and observing sea-states. These new methods will also negate the need for pragmatic parameterization since critical vessel motions can serve as a direct input in the monitoring system, without human interaction.

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1 INTRODUCTION

1.1 BACKGROUND

The increased demand for renewable energy has resulted in a growth of the offshore renewable market. Offshore wind farms grow in size and move further offshore and into greater water depths. This will increase the amount of wind energy that can be captured, but will also increase the environmental loading on vessels and cables during installation. Which will result in reduced operability and thus increased costs.

In order to make offshore renewable energy competitive with land based alternatives, the installation costs of offshore wind parks need to be reduced. The improvement of operability of cable laying processes may be one of the factors in this undertaking.

1.2 OPERABILITY ASSESSMENT METHODS

Traditionally, operability in offshore construction is characterized by the significant wave height. Operable weather conditions are determined using a time-domain simulation of the laying process in parameterized sea-states. This results in a list of sea-states and vessel headings that are described as operable or non-operable. The crew on site has to interpret these weather limits with actual conditions at hand, which induces a need for pragmatic discretization of the sea-states. This discretization is a known source of operability loss.

The wave loads however, are not the direct cause of cable integrity infringement. The resulting ship motions in combination with cable dynamics provide the ultimate loading on the product that can halt the operations. If a direct relation between vessel motions and cable integrity can be found, operability can be defined as a set of limiting vessel motions.

Vessel motions can be measured with high accuracy. Several industry-accepted systems have been developed that predict future vessel motions based on actual weather, weather forecast, hydrodynamic databases and the time history of vessel motion. These systems could provide the crew with assistance in decision making.

1.3 PROBLEM DEFINITION

Before operability assessment based on vessel motions may become reality, it is imperative that a relation is found between vessel motions and operability criteria for cable installation. This leads to the main research question:

Can a direct relation between vessel motions and cable integrity limits be found?

To be able to answer this question, several sub questions are formulated:

- *What are the critical loadings on a submarine power cable during installation?*
- *Can a limiting motion be defined for sinusoidal vessel motions?*
- *Will such a limit be applicable to irregular vessel motions and sea states as well?*

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

- Literature study where the methods of operability analysis are described: chapter 1,2,3.
- Case study to evaluate sensitivities in the current operability assessment: chapter 4,5.
- Quasi static analysis to understand the governing mechanics in cable compression: chapter 6.
- Regular and irregular motion analysis to analyse vessel and cable response: chapter 7,8,9.

2 INTRODUCTION TO SUBMARINE POWER CABLE INSTALLATION

Submarine power cables are used for a wide range of applications. Array cables provide the connection between individual wind turbines and substations, whilst export cables transport the generated electricity to shore. Interconnectors are used to export energy in-between states, islands and continents. The oil & gas industry is also making increased use of submarine cables to provide energy for offshore platforms.

The installation of these cables is performed using cable laying vessels that range from multipurpose barges to designated cable laying vessels (CLV). This chapter describes the anatomy and mechanical properties of submarine power cables and the vessels and techniques that are commonly used.

2.1 PROPERTIES OF SUBMARINE POWER CABLES

Submarine power cables play a major part in the development of an offshore wind farm. The installed costs of the cables take up only 15% of the total costs for an offshore windfarm project. However, about 80% of all damage claim costs in offshore wind farms come from the cables as well, according to Lloyd Warwick & Codan (1). These claims can either originate from direct damage such as bad workmanship, fishery activity, anchoring and construction operations. Or over time due to fatigue, temperature loads and corresponding aging.

The challenging part for the installing companies comes fort from the fact that submarine power cables are primarily designed to transport electrical energy with minimal losses during their stationary lifetime in the seabed. The mechanical properties needed for smooth instalment operations are of secondary importance.

2.1.1 AC vs DC cables

The main distinction in the types of cable is whether alternating current (AC) or direct current (DC) is transported. DC cables will often be laid as a pair of separate cables, each with only one conductor. Whilst AC cables consist of 3 conductors within a cable, each transporting current at another phase. AC cables are the most common type of cables used in offshore wind energy production since power generation is performed with AC. DC cables will transport power with less losses but are used only when large amounts of energy need to be transported over large lengths to justify the expensive power conversion equipment. With future windfarms growing in capacity and moving further offshore, the amount of DC power solutions is expected to rise (2).



Figure 1 Example of high voltage 3 conductor AC cable

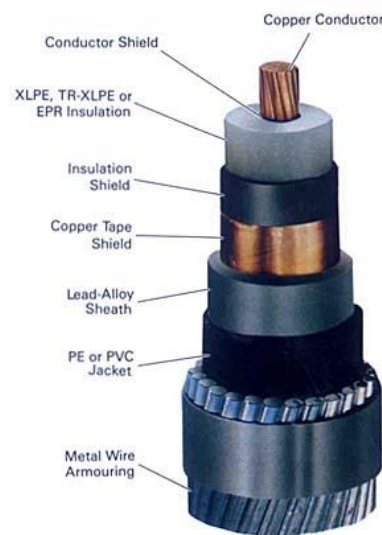


Figure 2 Example of high voltage DC cable

2.1.2 Cable anatomy

A submarine power cable is often designed specifically for an individual project. Examples of AC and DC cables with the individual layers are shown in Figure 1 and 2

The conductor(s) are either made out of copper or aluminium. Insulation is mostly made from cross-linked Poly Ethylene whilst the cable armour is made out of galvanized or stainless steel wires. There are several screens and layers to protect the insulation from water ingress. Metallic Layers are employed to reduce the emittance of electric fields and deny Teredo-worms. Metallic layers outside of the main insulation can also be used for testing the cable insulation properties. An important acceptance test that is often performed before, and after installation of the cable.

2.1.3 Axial stiffness

The axial stiffness of a cable can be predicted by looking at the conductors and armour wires. Unlike aluminium, copper displays a nonlinear stress-strain behaviour in the operating conditions (3). Predicting the stiffness contribution through internal friction between layers is a challenging part. Fortunately, the main contribution comes from the armour wires which can be modelled reasonably well.

The amount, diameter, Young's modulus, residual tension and pitch angle of the armour wires are the main parameters defining the stiffness of submarine power cables. Compression of the core and twisting of the cable also have influences on the axial stiffness. "Armoured cables can generally be assumed to behave linearly. Both measured cable behaviour and the nonlinear governing equations behave in a linear manner over small strains ($\epsilon_c < 1\%$) typical of most operating conditions." (3).

2.1.4 Bending stiffness

The bending stiffness of submarine power cables is non-linear and dominated by stick/slip hysteresis effects as shown in Figure 3.

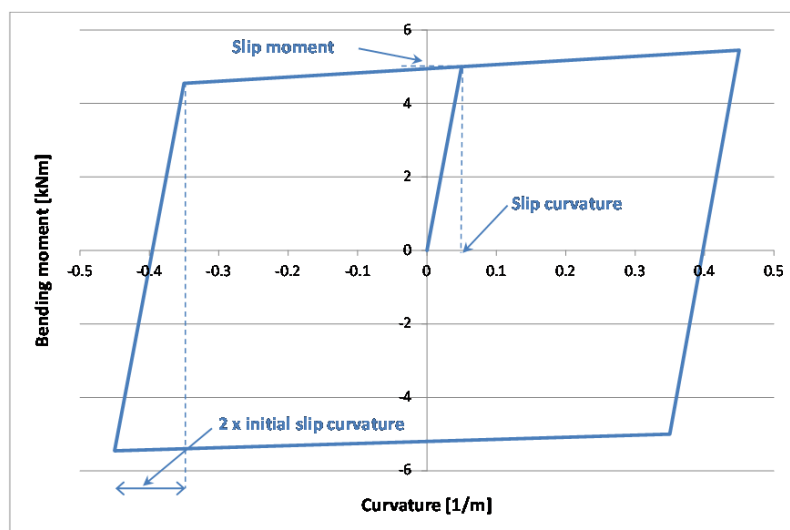


Figure 3 Typical Stick/Slip behaviour of submarine power cables (4).

The layers of which a cable exist are mainly un-bonded and have various elastic properties. When curvature is low, friction between the armour wires and adjacent layers is sufficient to resist tensile wire slippage, resulting in relatively stiff behaviour. However, as the curvature increases, a point is reached where the available friction is not enough to prevent the layers from slipping, reducing the further increase of bending stiffness (5).

The curvature at which the various layers of a product cross-section slip is a function of inter-layer contact and friction as well as the pitch length and pitch diameter of the layers (6). Inter-layer contact and friction are in

term a function of axial tension which implies that combined bending and tensile tests are needed to fully describe the bending stiffness of a submarine power cable.

Once all the layers in the cross-section slip, the bending stiffness is considerably reduced. These effects should be taken into account when performing dynamic analyses, since the cable is expected to surpass the stick-regime for most operations. Until now, most cable producers supplied only a constant or linear bending stiffness product specification. Only recently have some suppliers started to deliver non-linear bending curves based on product tests to improve the mathematical models of cable handling.

An example of the non-linear behaviour of cable bending stiffness is found in Figure 4. The measured force required to bend the cable decreases after the slip regime is reached. The small spikes in the force measurement are probably the result of the manual operation of the hydraulic pump instead of cable bending behaviour as shown in the test setup Figure 5.

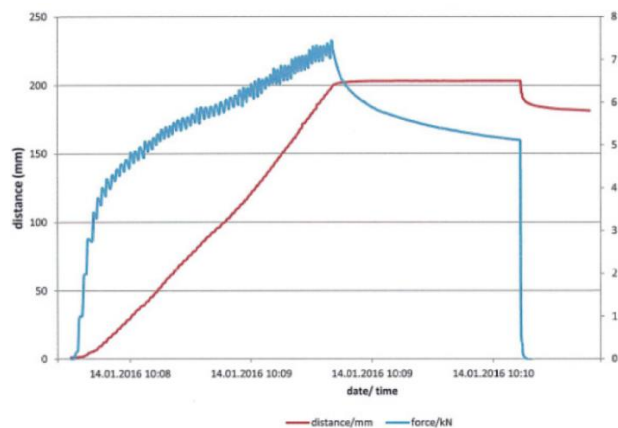


Figure 4 Non-linear bending stiffness of a submarine power cable (7)

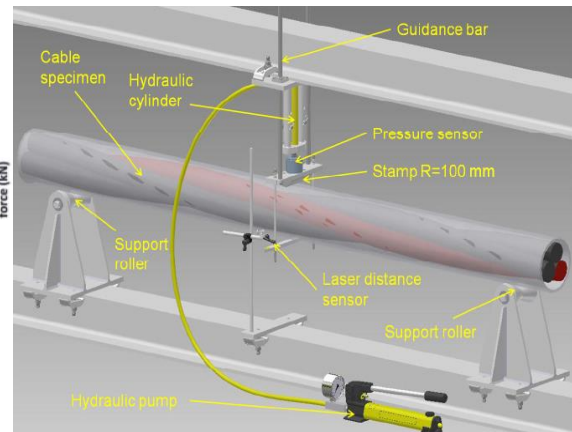


Figure 5 Setup for 3-point bending test (7)

2.1.5 Torsional stiffness of single-layer armoured cables

AC Submarine power cables generally consist of 3 cores that are helically wrapped around each other as seen in Figure 5. When a single layer of armour wires is applied for protection of the cable, as is generally the case for array cables, the armour wires will most often be wrapped in the same direction as the cores.

When torqued against the lay direction, the armour wires will open up which allows the cable to absorb a certain degree of twist. This is needed when the cable is stored in a static tank since every coil of cable in the tank will require a full rotation of the material to be absorbed in that coil. The opening of the armour wires makes this torque direction the least stiff of the two.

Torqueing the cable in the lay direction will make the armour wires compress the cores which leads to more stiff behaviour. Torsional stiffness in the lay direction can be around three times as large for array cables when compared to the counter-lay direction.

2.1.6 Torsional stiffness of double armoured cables

Submarine power cables may be fitted with double layers of armour for added protection or specifically to make them torque balanced. In the latter case, the armour layers are counter rotating to fulfil the condition of torque balance. Torque balance is a requirement which implies that much less torque will be developed in a cable that is loaded in tension and restrained from rotating in both ends (8).

2.2 CABLE HANDLING LIMITS

To reduce the risk of cable damages during installation, specific installation criteria are composed by the manufacturer for the installing company to apply. The mechanical limits that have the biggest impact on operability of the installation process are listed in this section.

2.2.1 Minimum bending radius

Bending of the cable will create axial stresses in the numerous layers of the cable. Excessive bending can lead to bird caging of the armour wires, buckling of metallic sheets, signal loss of optical cables, loss of insulation integrity, water ingress and many more faults. The minimum bending radius (MBR) will be determined by the manufacturer for each cable. The MBR's for a single cable are often variable depending on the applied tension and the operation at hand. Maintaining the MBR during cable installation is sometimes the limiting factor in operability.

2.2.2 Compression limit

Axial compression of the cable can lead to most of the same failure mechanisms as with the MBR. It also poses the risk of cable hockling. Single-wire armoured cables are not torsional balanced. Since there is a difference in the cable tension at the LCE (Linear Cable Engine) and the touch down point (TDP), there will be a resulting torsion in the cable as it is suspended in catenary. With high enough torque, sufficient length and a loss of tension, the cable can throw itself into a loop due to instability, called hockling (Figure 6). The hockling itself does not necessarily damage the cable, but when tension is restored, the MBR could be compromised.

Currently, there is no accepted industry standard for determination of compression limits in subsea power cables. The result is that most manufacturers specify that subsea cables are not allowed to be axially loaded in compression (9). This poses a problem for cable installation companies since compression can occur if the cable is heaved in a rapid motion. With the current installation methods, compression is often the limiting factor for operable conditions.

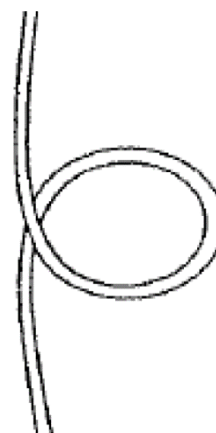


Figure 6 Hockle

2.2.3 Maximum tension

When the cable is tensioned, the armour wires will compress the cable core. When too much tension is applied, damage may occur for instance in the electrical insulation system or optical fibres. Therefore, a maximum safe working load far below the minimum breaking load of the cable will be defined.

2.2.4 Tension whilst bending

Within laying operations, a cable will be diverted several times with for example: a sheave, capstan or a bend in a J-tube. During such a bending motion, the tension in the cable will produce a side-wall pressure that tends to flatten the cable which could jeopardize the cable integrity. To regulate this effect, a maximum side-wall pressure is defined by the producer.

2.2.5 Crush load

When cables are stored in multiple layers or when traversing through a linear cable engine, significant crushing loads can be exerted. Cable manufacturers will supply a limiting pressure for the installing company to adhere to.

2.2.6 Coiling behaviour

Cables with a single armour layer can often be coiled for storage. Doing so may open up the armour wires slightly. Therefore, testing of the cable behaviour under coiling is recommended to ensure that no damage occurs (10).

2.3 BALANCE IN CABLE TENSION

During submarine cable installation, managing the tension in the cable is important to maintain cable integrity.

If the tension is too low, a sharp bend will occur near the TDP which could exceed the minimum bending radius, especially when dynamic excitation takes place. The risk for compression waves and cable hocking becomes also higher when low tension is applied during motions of the chute. The minimum tension that needs to be obtained during vessel motions is in practice most often the limiting criteria.

It is not always possible to reduce the risk of compression by increasing the tension. High tensions will increase the residual tension in the cable once it rests on the seabed, making post lay burial operations more difficult. High residual tension can also lead to a risk of cable free spans which are vulnerable to bottom instability and currents. Stability of the cable in a curve on the seabed can also be jeopardized by high laying tensions.

In extreme cases, high tension in combination with vessel motions could result in exceeding the maximum axial safe working load on the cable. This may also pose a threat to personnel and machinery. In practice however, the maximum axial safe working load is almost never the limiting operability factor for intermediate water cable laying.

2.4 CABLE LAYING VESSELS

Cable lay barges and vessels (CLV) are available in all sizes and with all kind of equipment. Main factors for selection of a cable laying platform are: load carrying capacity, manoeuvrability properties, deck space for handling equipment, accommodation and bollard pull. The bollard pull becomes important when a cable plough is to be utilized for cable burial.

Cables are typically stored in turntables (carousels), static coils or large drums. Static coils can only store cables that can be coiled, where the lay direction of the strands also needs to conform to the coiling direction. Torsional balanced cables cannot be coiled and therefore not stored in a static coil. When installing torsional balanced cables, a Carousel or a large drum will be needed. Drums are usually operated with their axis of rotation in the horizontal plane. This limits their size as the mass of the cable will influence the centre of gravity of the vessel severely. Carousels come with a challenge as well. Their size and weight provide a substantial momentum which can restrict the maximum cable pay-out and loading speed.

The dimensions of the required storage will be largely dependent on the cable properties and cable length. Export/shore connection cables are typically both the longest and heaviest cables to be installed in an offshore wind farm development. Currently, they can have lengths greater than 100km with an overall weight of 7,000t or more. A typical DP 2 class CLV with carousel is shown in Figure 7.

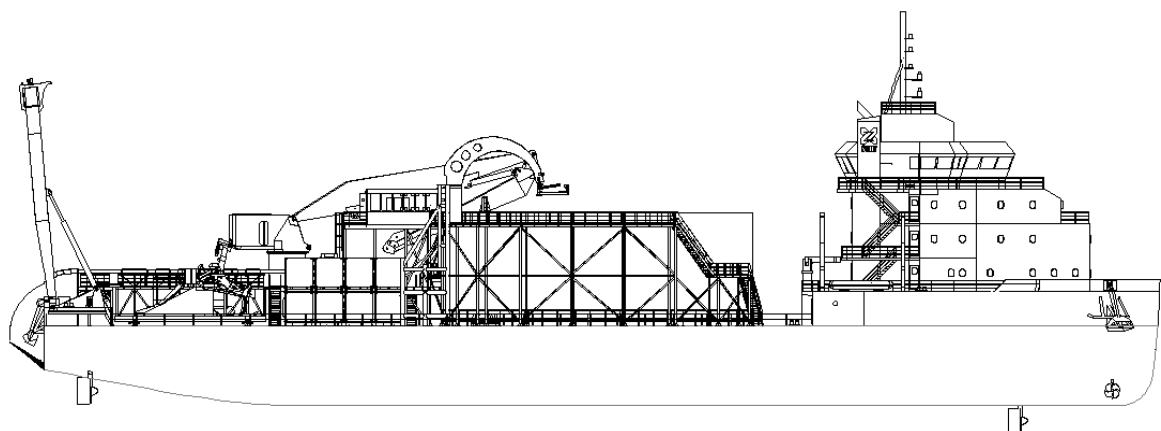


Figure 7 Cable laying vessel Ndurance

2.5 INSTALLATION TECHNIQUE

Submarine power cables can be installed in many ways and new methods are proposed even now. The most common methods for cable installation are discussed in this section.

When cable laying commences, the cable is guided out of the storage through a linear cable engine, capstan or similar device. The cable can enter the water in several ways: S-lay with a chute or stinger, J-lay over the side or through a moon pool.

The simplest installation method is by use of a chute, as visible in Figure 8. The chute is a rounded part of the stern of the vessel that guides the cable into the water. The chute will have a radius that is larger or equal to the MBR of the installed cable and poses no obstruction for the instalment of accessories or field joints. Most offshore power cables for wind energy are installed in this manner.

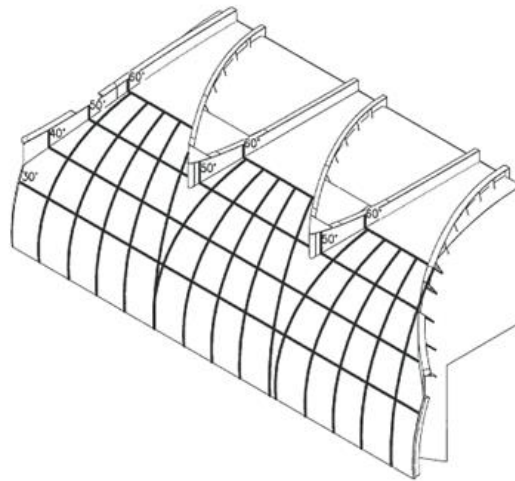


Figure 8 Isometric view of chute CLV Ndurance

When water depths become large and the side wall pressure becomes limited, S-lay may be performed by use of a stinger to support the cable over a larger length. See Figure 9.

Another way of laying cable is via the J-lay method. The cable will move through a vertical tensioner to cut out the over bend, making this method applicable for deeper waters. Another advantage of this method is the increased flexibility in placement of the tensioner. The cable can enter the water amidships through a moon pool to negate the effects of pitch and roll on cable dynamics. Possible disadvantages however, are that there will be a minimum water depth required for the sag bend and installation of accessories could become increasingly complex through the moon pool.

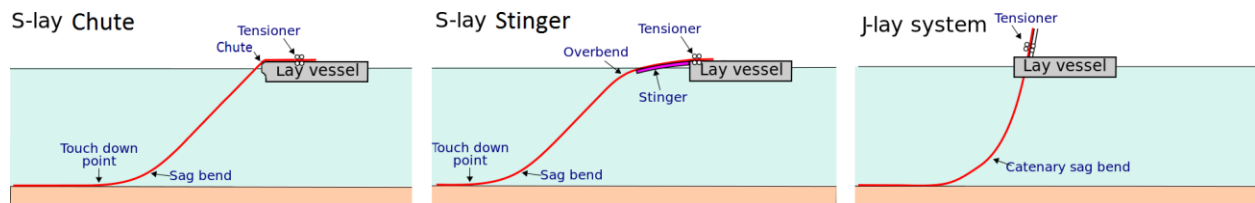


Figure 9 S-lay with Chute, S-lay with Stinger and J-lay

3 MODELLING OF CABLE LAYING

This chapter describes the method that is used to analyse cable behaviour under installation conditions. The general principle of the lumped mass method is explained. As well as the boundary conditions, the cable model, damping sensitivity analysis and the required segmentation length.

3.1 LUMPED MASS METHOD

The dynamic analysis of submarine cables is generally performed by numerical calculations in the time domain due to the non-linear effects of catenary shape, elasticity and drag. The lumped mass method was derived for predicting dynamic tension amplification in mooring systems (11). This method is also used in the numerical software package OrcaFlex© from Orcina to analyse the dynamics of flexibles in fluids.

The lumped mass method models a line as a series of lumps of mass joined together by massless springs, rather like beads on a necklace. The lumps of mass are called nodes and the springs joining them are called segments. Each segment represents a short piece of the cable, whose properties (mass, buoyancy, drag etc.) have been lumped at the nodes at its ends (12). An example of a 2D mass-spring system is illustrated in Figure 10.

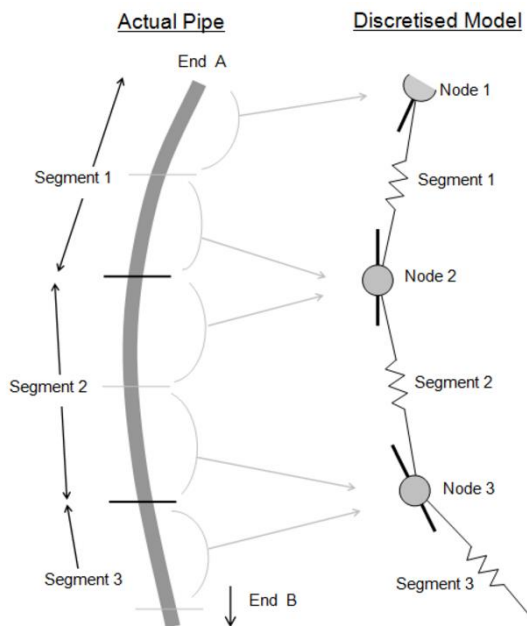


Figure 10 Lumped mass method in 2D

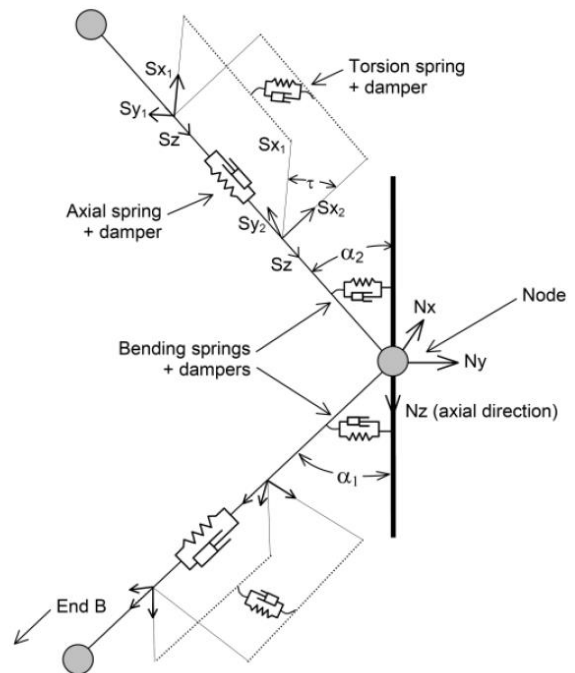


Figure 11 3D mass-spring-damper system used by OrcaFlex© (12)

The original model of Van den Boom for a mooring line does not allow for material damping, bending and torsional moments. It is however possible to include these effects by adding more dampers and springs as shown in Figure 11.

The equations of dynamic equilibrium are derived for each node to obtain a set of discrete equations of motion. These equations can be solved in the time domain using finite difference techniques resulting in time series for nodal displacement, forces and tensions that can be analysed to assess the cable integrity.

OrcaFlex© utilizes this improved lumped mass method and has been chosen as modelling software for this master thesis. Mainly because of the reputation the software has built up in the offshore engineering industry for modelling flexibles, as well as the vast amount of experience with this software within VBMS.

3.2 TIME INTEGRATION METHOD

OrcaFlex® allows two methods of time integration: the explicit and implicit integration scheme. Both have distinct advantages and disadvantages.

3.2.1 Explicit integration

The explicit integration scheme uses semi-implicit Euler with constant inner and outer time steps. Most calculations are performed for every inner time step. Some more slowly varying parameters such as wave particle motion and aerodynamic forces are evaluated in the outer time step only, decreasing simulation time.

The main advantage of the explicit integration scheme is that it is very accurate for rapid varying loads. It also allows the software to incorporate non-linear soil models for the seabed: Damping resistance during soil penetration and suction forces during cable uplift. These forces can reduce the compression loads in the cable, especially in clayey soils.

The method is conditionally stable when the time steps are small enough. The downside is that the required time steps are very short. The recommended inner step size is $1/10^{\text{th}}$ of the shortest natural nodal period in the system. For short cable segments, this can lead to time steps in the order of 10^{-5} seconds. This increases the simulation time significantly.

Another downside of the Explicit integration method in OrcaFlex® is that it does not allow for material or Rayleigh damping. This can be an important source of damping to reduce high frequency noise. See section 3.6.1.

3.2.2 Implicit integration

The implicit integration scheme uses the generalized- α method as described by Chung and Hulbert (13). This method calculates all forces in the same manner as with explicit integration. When all the forces for all the nodes are calculated, the whole system equation of motion is solved at the end of each time step. This is instead of iterating each node every time step separately.

Solving the entire system of equations in one step requires the inversion of large matrices. This makes the calculation of a single time step much slower than with the explicit method. The stability of the method however, is maintained for much larger time steps. Generally, in the order of 10^{-2} seconds. This makes the implicit integration method often faster than the explicit and is therefore the method of choice throughout the industry.

A disadvantage of the implicit integration scheme is the lack of damping in the soil model. This can partly be countered however, by introducing material or Rayleigh damping that cannot be modelled when using the explicit integration method. The choice can be made to include neither soil or material damping to take a conservative approach since both forms of damping generally decrease compression loads.

3.3 CABLE TYPE USED FOR MODELLING

For most of the simulations for this thesis, a typical array cable model with copper conductors has been utilized. The model assumes extruded XLPE isolators and a single layer of galvanized steel armour wires. Values of non-linear bending stiffness has been assumed based on comparable cables. The values for the linear and non-linear bend stiffness are plotted in Figure 13.

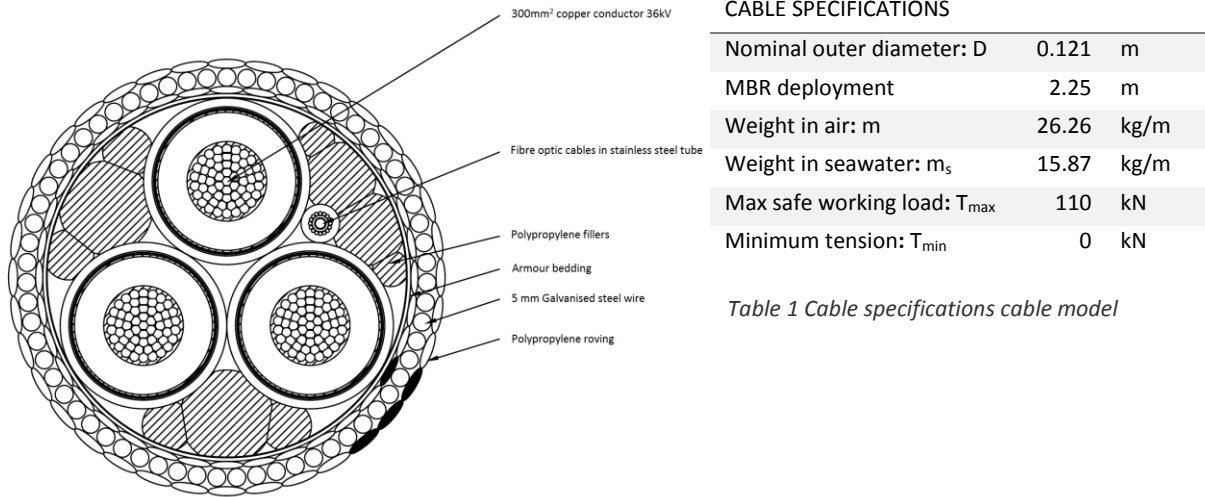


Figure 12 Cross section of cable model.

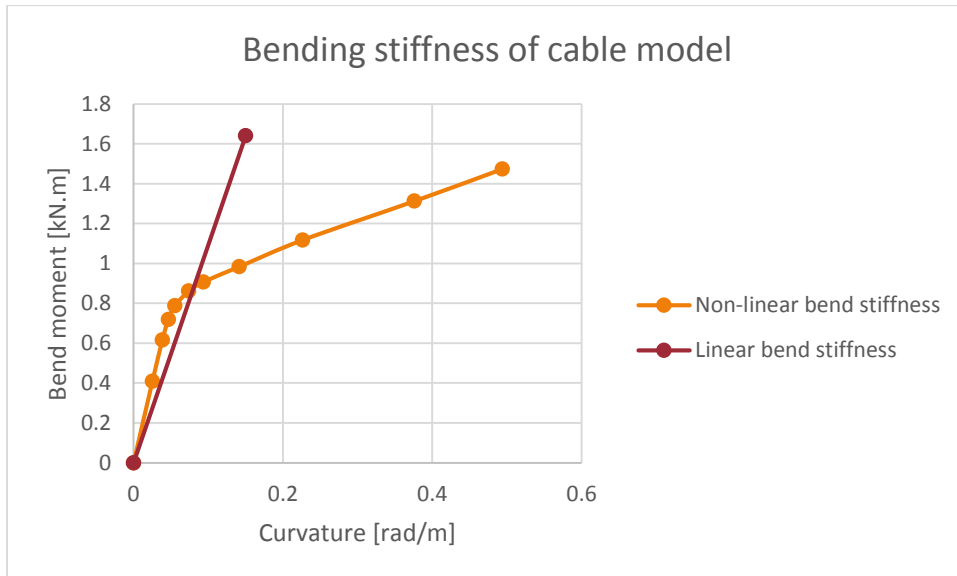


Figure 13 Bend stiffness for used cable model

3.4 BOUNDARY CONDITIONS

The suspended submarine cable is excited by both the vessel motions and environmental loads. The method by which these boundary conditions are implemented in the model is explained in this section.

3.4.1 Linear Cable Engine and Chute

In the simulations, one of the ends of the submarine power cable is clamped tight in the LCE, about 10m forwards of the chute. The exact location depends on the vessel configuration. For modelling purposes, it is assumed that this end is clamped with an axial stiffness equal to the cables own axial stiffness. The rotational and shear stiffness's are set to infinity to model the LCE.

The vessel is modelled as a rigid body with the chute attached to it. The chute supports the cable and makes sure that a certain radius is maintained where the cable is in contact with the vessel. The vessel motions are calculated by importing motion RAO's from an Ansys Aqwa diffraction model and combining these with the modelled wave trains. This provides the excitation of the cable as it is forced to follow the motions of the vessel and de chute.

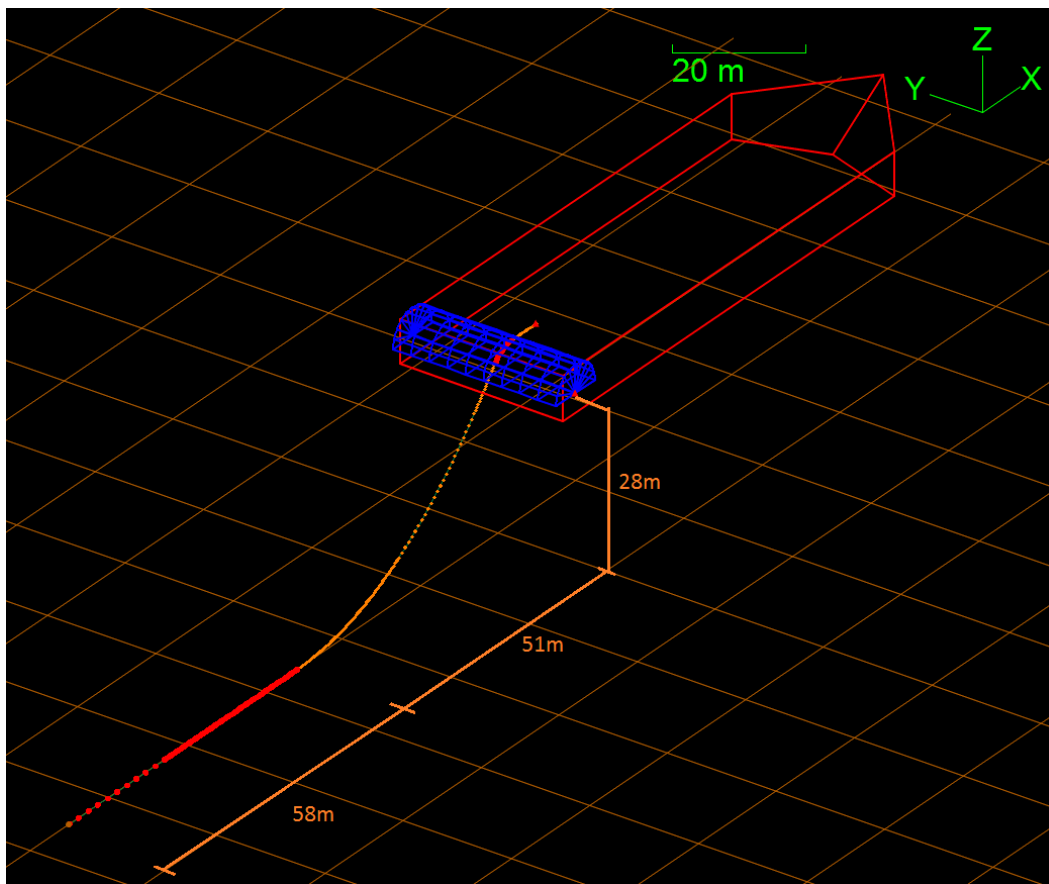


Figure 14 Isometric view of chute and cable N-class 28m water depth, 40-degree departure angle

3.4.2 Seabed interaction

The other end of the cable is anchored on the seabed. To make sure that there is no interference between the anchor point and the catenary behaviour, a length of at least 50 meters is maintained in between the anchor point and the TDP as shown in Figure 14.

The seabed plays an important role as an elastic solid for the cable to rest on. The seabed is modelled as an elastic distributed spring in both normal and shear direction. This gives the seabed a normal resistance that is proportional to the penetration depth. Whilst the lateral resistance is proportional to the displacement of the contact point (node) from its undisturbed position.

Seabed friction cannot be modelled by standard Coulomb friction since this would result in a discontinuous force/deflection relationship that would lead to dynamic instability for numerical software such as OrcaFlex®. To overcome this problem, the force is linearly built up over a critical displacement diameter (3.1), as visible in Figure 15.

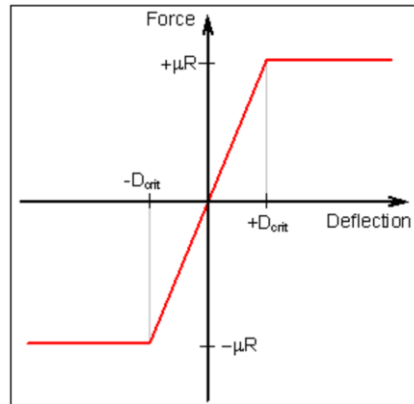


Figure 15 Modified Coulomb friction model (12)

The critical diameter D_{crit} is defined as follows:

$$D_{crit} = \frac{\mu_f R}{K_s A_c} \quad (3.1)$$

μ_f	=	Friction coefficient [-] 0.5 for axial motions, 1.0 for lateral to include bulldozing effect.
R	=	Contact reaction force [N]
K_s	=	Shear stiffness of the soil which is normally set to 100.000 [kN/m/m ²]
A_c	=	Contact area [m ²]

3.5 DAMPING IN THE NUMERICAL MODEL

Apart from the quadratic drag term, there are other sources of damping that can play a significant role in the dynamic behaviour of the cable model. OrcaFlex® models can show high frequency noise when the cable is compressed at the seabed. This can impair the accuracy of the model and may be damped by several methods. However, care must be taken to prevent too much damping of low frequency responses as this may also impair the accuracy of the results. The effects of various damping sources as well as other sensitivity studies are discussed in this section.

3.5.1 Damping through non-linear bend stiffness and hysteresis

Submarine power cables show non-linear bending stiffness behaviour. The main contributors to this behaviour are deformation of the materials and friction between the layers that slip whilst bending. Hysteresis effects in non-linear bend stiffness can provide a source of damping for the cable close to the TDP, where the cable is sequentially bent and straightened. The non-linear behaviour is not always known in the stage where the operable limits are determined. The industry will have to push on manufacturers to provide this data.

More details on non-linear bend stiffness can be found in section 2.1.4.

3.5.2 Rayleigh damping

Rayleigh damping is viscous damping that is widely used to model internal structural damping. Rayleigh damping may be set proportional to stiffness or a linear combination of mass and stiffness. Where the stiffness term provides damping linearly proportional to response frequency, and the mass term inversely proportional to response frequency (12).

Care must be taken that the damping ratio does not become too high in the response frequencies of interest as this may significantly impair the accuracy of the results. When low response frequencies are of great importance, it may be wise to consider stiffness proportional damping only.

Here follows an example of Rayleigh damping that has been applied in models used by VBMS. In this method, the Rayleigh coefficients were set to include mass and stiffness proportional terms that are equal to 2% of the critical damping in the response periods of 2 and 10 seconds as in Figure 16.

The critical damping is defined as:

$$C_{crit} = \sqrt{\frac{2mL_0}{EA}} \quad (3.2)$$

In which m is the mass of a cable segment, L_0 the un-stretched length and EA the young's modulus times cross sectional area.

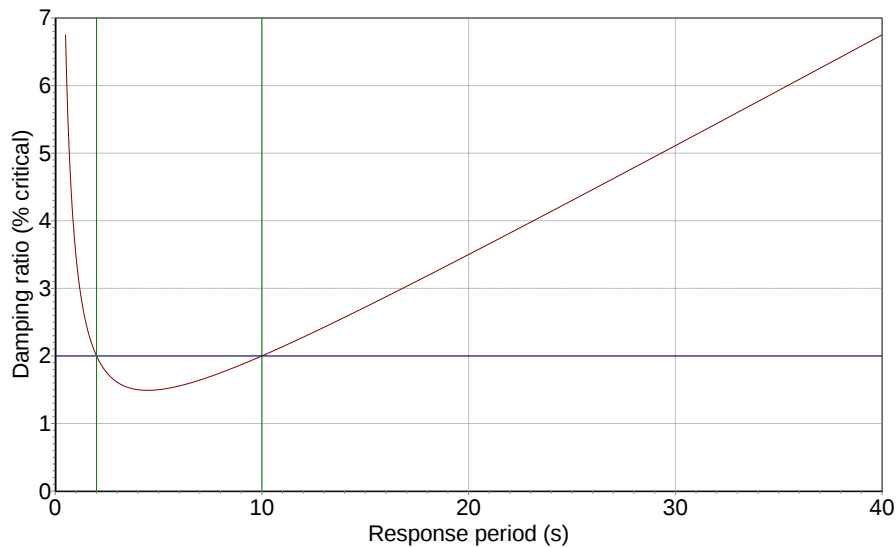


Figure 16 Example of Rayleigh line damping

3.5.3 Soil damping

The simplest model of the seabed used in OrcaFlex© is that of a linear distributed spring which can work effectively for sandy soils. The model can be upgraded to incorporate non-linear springs, dampers and also suction effects which can create a more realistic model for clay and mud. One big downside of soil damping is that it can only be implemented in OrcaFlex© when the explicit integration scheme is used. With the explicit method not being able to perform the required amount of simulations in the given time (section 3.2.1), the soil damping is often neglected in the VBMS methods of simulation and is excluded from this investigation.

3.6 DAMPING METHODS INVESTIGATION

To show the effects of these various methods of damping, an investigation has been undertaken. Six variants of the cable model have been attached to a model of the chute of the CLV Ndurance (Figure 7) in a water depth of 28 meters with a pre-tension of 12.95kN at the departure point. This results in a departure angle of 40 degrees from vertical. The cable variants comprise:

- Cable with constant bending stiffness, no damping.
- Cable with constant bending stiffness and 2% Rayleigh damping
- Cable with constant bending stiffness and 6% Rayleigh damping
- Cable with non-linear bending stiffness and hysteresis
- Cable with non-linear bending stiffness and hysteresis and 2% Rayleigh damping
- Cable with non-linear bending stiffness and hysteresis and 6% Rayleigh damping

To compare the various cable types for limiting installation conditions, a regular chute motion that is normally outside of the operability range is selected. The motion consists of a local heave amplitude of 3m and a surge amplitude of 0.4m. Both sinusoidal motions have a period of 9 seconds and are 180 degrees out of phase. The compression shapes of some of the steady state motions are shown in Figure 17 to Figure 19.

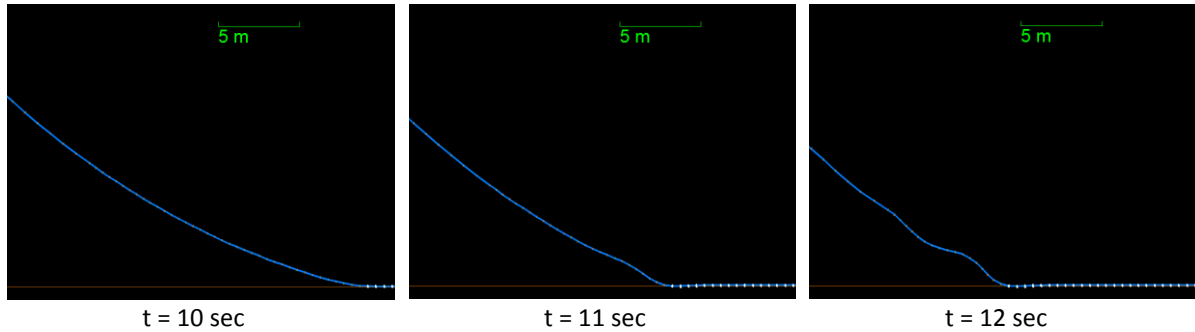


Figure 17 Compression shape of cable with linear bending stiffness

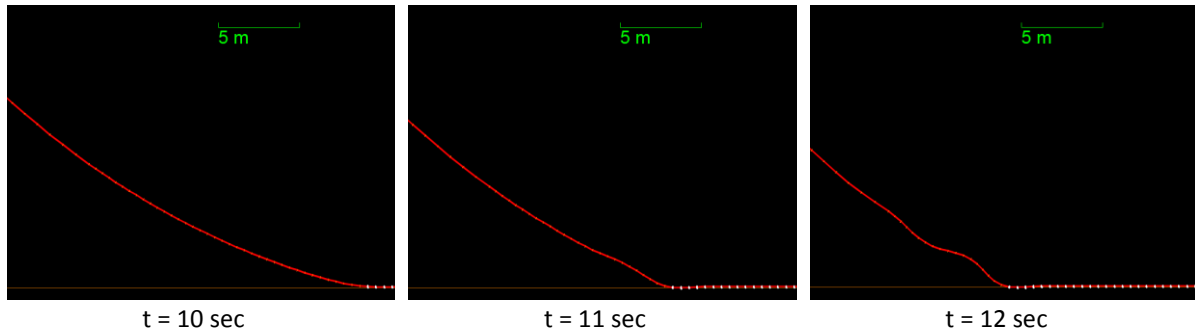


Figure 18 Compression shape of cable with linear bending stiffness, 6 % Rayleigh damping

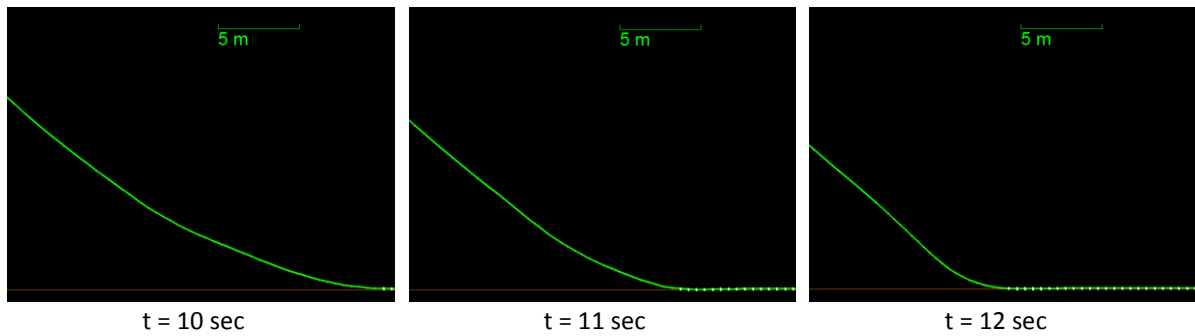


Figure 19 Compression shape of cable with non-linear bending stiffness

Figure 17 and Figure 18 show that the cables with linear bend stiffness behave similarly in compression. Both with and without Rayleigh damping, a double S bend occurs that travels up the cable with the receding TDP.

The cable with a non-linear bending stiffness shows no such sharp bending behaviour. There is an upward curvature to be seen at the 12 second mark, but not as severe as with the linear bend stiffness. This gentler curvature more closely resembles cable behaviour as may be observed by ROV's in the field. A problem when analysing the tension in the cable is the occurrence of high frequency response. When a cable is modelled without bending hysteresis or Rayleigh damping, high frequency compression and tension waves travel along the cable in the simulation. This jumping behaviour occurs from the moment the cable is compressed for the first time and makes it hard to obtain correct values for the minimum tension that occurs for a given motion. An example is shown in Figure 20.

In this figure, a time series is shown for the lower boundary condition of the cable where it is fixed on top of the seabed. The cable is exited in exactly the same manner as described earlier in this section. Note that the high frequency response has travelled at least 40-meters through cable that is resting on the seabed. With soil damping hard to model in the selected software and the axial hydrodynamic drag being low, the compression waves reach the cable end without losing much of their energy.

In Figure 21, a time series is shown for exactly the same cable loading parameters, only this time the cable is modelled with bending hysteresis and Rayleigh damping. The response before the first moment of compression is identical. And the response during and after compression is readily interpretable.

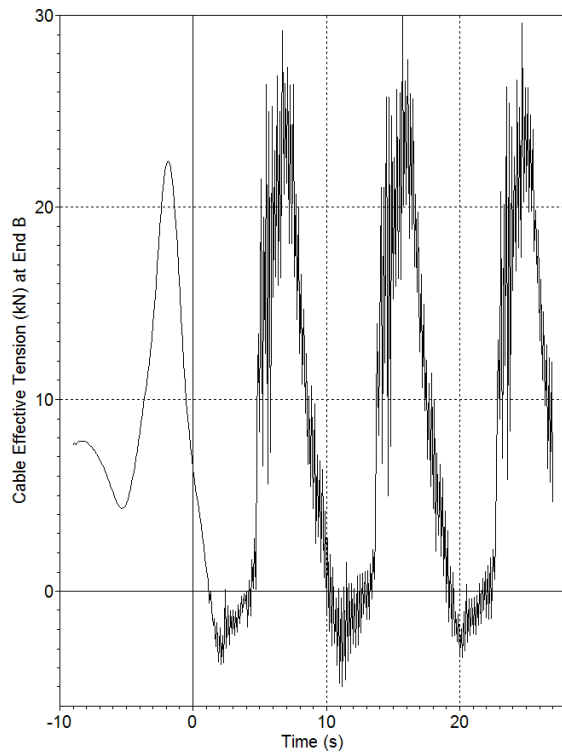


Figure 20 Tension in lower boundary without internal damping

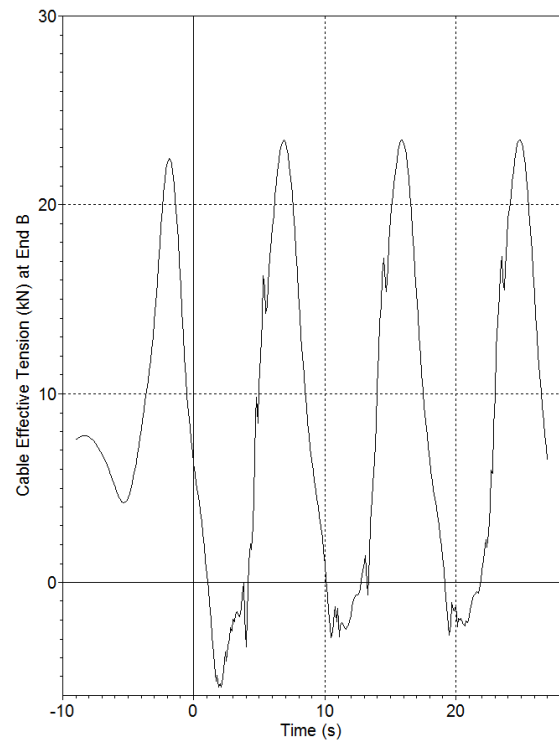


Figure 21 Tension in lower boundary with 2% Rayleigh damping and non-linear bend stiffness

To show the values of compression along the cable length, a range graph can be used. In Figure 22, a range graph is depicted for the 6 tested cable variants. In a range graph, a variable as for example: minimum tension, may be plotted against the range of cable elements. In other words, for each cable element, the minimum tension obtained during the full time domain will be plotted. Which shows quickly if a limit is exceeded and if so, at which section. The cable coordinate 0m is placed at the tensioner on deck. The cable departs from the chute at around 11 meters. The TDP is between 60 and 90m, and the cable end is anchored at 130m.

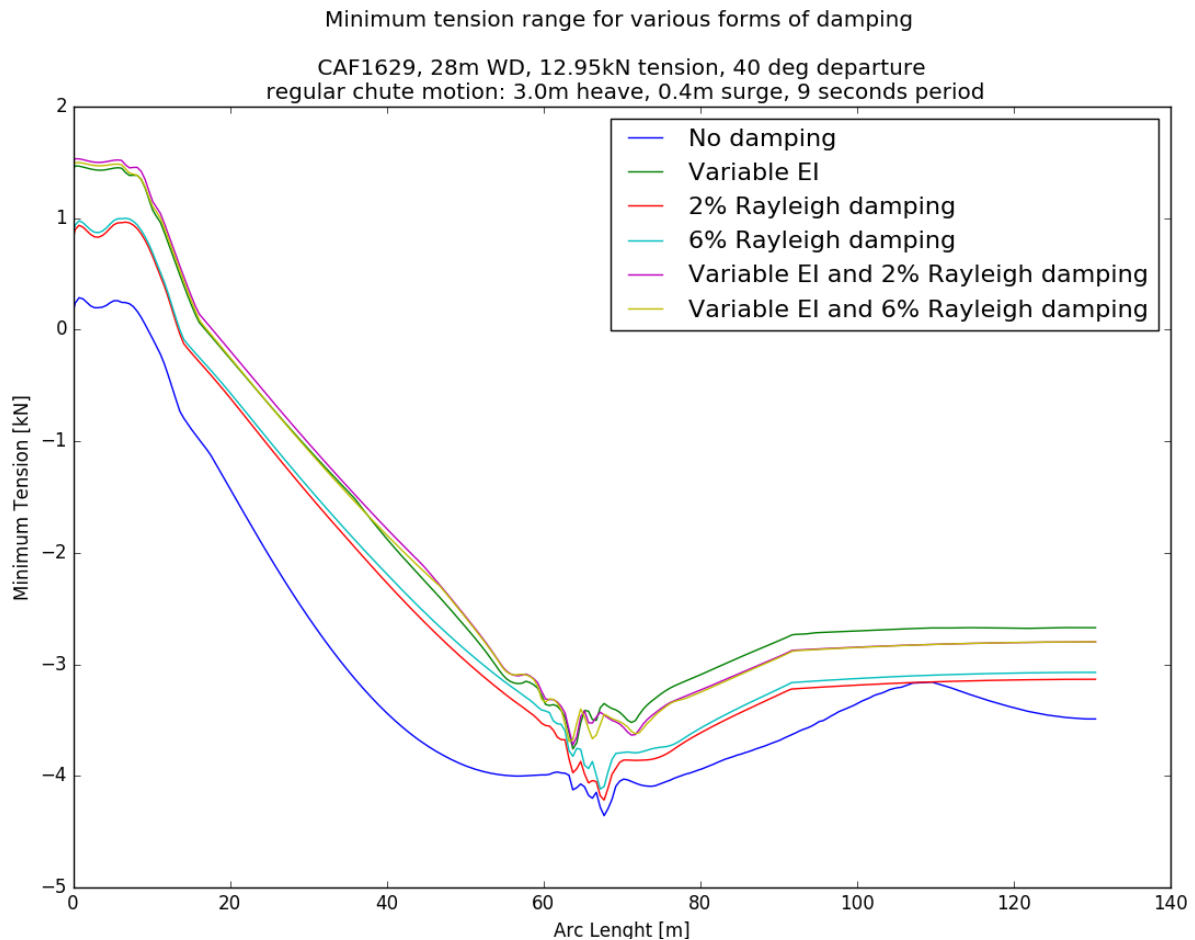


Figure 22 Minimum tensions of 6 variants of the model cable

Figure 22 shows that the various cable models have very comparable minimum tensions between the chute and the touchdown zone except for the undamped cable. From the touchdown zone and onwards along the sea floor the differences between the other cable types increases.

The cables modelled with a form of internal damping show a constant value of compression for the section of cable that is stationary on the seabed. This behaviour is expected since the compression that is generated in the touchdown zone will be passed on towards the boundary condition without much damping.

Since a range graph takes the absolute minimum value of tension for each segment, the high frequency peaks will be measured. This can lead to compression forces that may not be realistic. A compression peak of 4kN that only exists for a fraction of a second is not deemed realistic for the rather slow moving cable. This explains the main difference in minimum tension between the cable with and without internal damping in Figure 22.

Other observations that can be made from Figure 22, are the following:

- Adding Rayleigh damping reduces compression over the cable range but has small effects in the touchdown zone.
- The non-linear bend stiffness reduces the compression over the full length of the cable.
- When combining non-linear bend stiffness and Rayleigh damping, the differences between 2 and 6% damping are small.

3.6.1 Discussion of damping methods

The non-linear bending stiffness of the cable is a physical property of the real world cable and shows more realistic bending behaviour for compression is simulated at the TDP. Not all cables that are currently analysed within VBMS are supplied with a non-linear bending stiffness curve. However, as it is desired to become a standard practice in the future, the non-linear bending stiffness is applied in the modelling for this thesis research.

With this investigation focusing on the on the edge of operable conditions, it is important that compression is modelled accurately. Even for cases that would normally be discarded if the operational limits are exceeded. The addition of 2% Rayleigh damping is chosen since its suppression of high frequency noise negates the need for a post simulation filter. 2% can be justified with the knowledge that the cable consists of many un-bonded layers of various materials comprising both synthetics and metals. Therefore, all further simulations are performed with 2% Rayleigh damping included.

3.7 OPTIMAL SEGMENTATION LENGTH INVESTIGATION

For finite element methods, the discretization of elements plays a major role in the accuracy of the model. An investigation has been performed to find the optimal segment length that accurately models compression within reasonable computational time.

Segmentation sizes varying between 0.01 and 1 meter have been used in a typical load case for a general array cable in a water depth of 30m with 20kN of top tension. The top end of the cable was heaved with a sinusoidal motion for various amplitudes at a constant period of 9 seconds. Which generally coincides with the natural period of pitch for the N-class vessels. The minimum tension found in each simulation is plotted in the range graph of Figure 23.

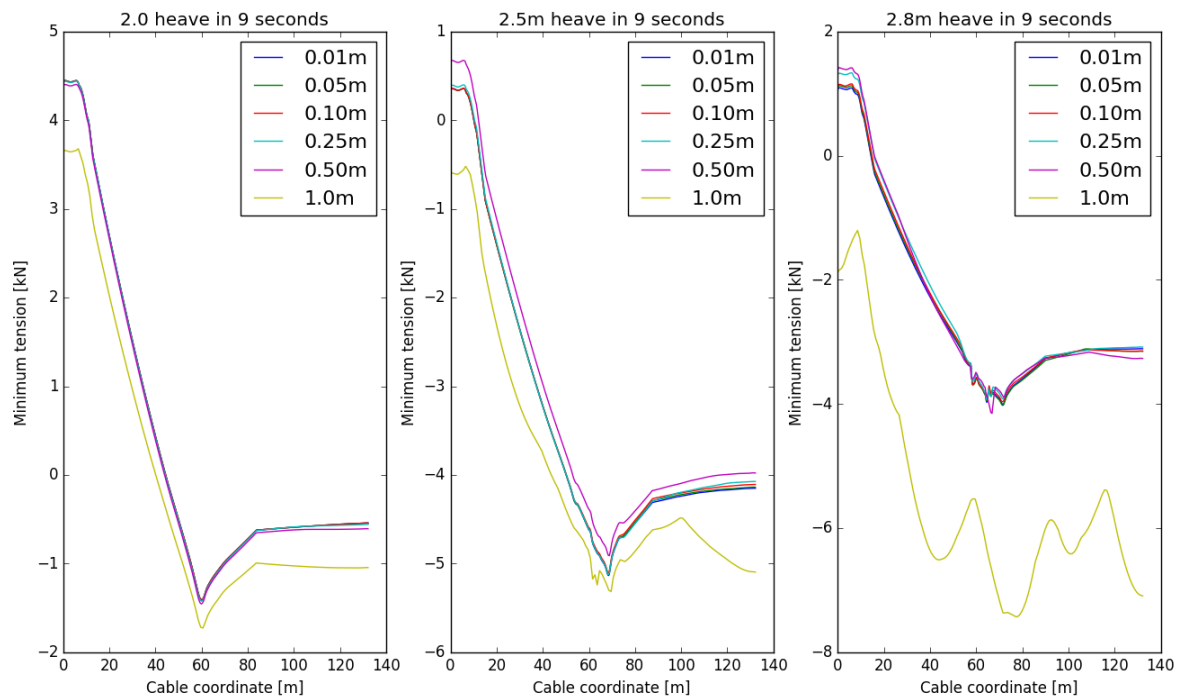


Figure 23 Segmentation size investigation cable with non-linear EI

As can be seen from the graph, a segmentation size of 1.0m shows a distinct difference when compared to the finer segmentation sizes. For the 0.5m segmentation, the difference in compression is slightly less than 2% for the most severe load case which is deemed acceptable. This makes the 0.5m segmentation a suitable segmentation length for future simulations.

4 CURRENT OPERABILITY ASSESSMENT METHOD

This chapter describes how the model from chapter 3 is utilized by VBMS to assess operable conditions for cable installation.

4.1 OPERABILITY ASSESSMENT PHILOSOPHY

Operability is the ability to keep an equipment, a system or a whole industrial installation in a safe and reliable functioning condition, according to pre-defined operational requirements.

The hydromechanics engineers of VBMS provided a method by testing various sea-states combined with various operational settings in time domain simulations. If the operational limits of the vessel and cable can be maintained in such a simulation for a certain amount of time, that combination of parameters is deemed operable.

This method results in a list of operable combinations of sea-states and operational settings that can advise the offshore construction manager during operations. The method of operability assessment may vary for every project due to the various working environments and installation tools that are used. The method will always have to be approved by a marine warranty surveyor before the project can be executed.

The following limit states are used to assess whether cable integrity is assured:

- Compression limit
- Maximum allowable tension
- MBR
- Side wall pressure
- Operational experience (for instance minimum layback of 10m)

4.2 SETTINGS OF CURRENT OPERABILITY SIMULATIONS

The accuracy of operability simulations is determined by the method of simulation as well as the chosen parameters that should mimic reality as close as possible. The most important settings that are characteristic for the VBMS approach to operability assessment are listed in this section. The amount of variables that are combined gives an insight in the required amount of simulations and hence the computational effort required. The validation of the use of a reduced time domain simulation scope requires special interest and is investigated in the next chapter.

4.2.1 Stationary vessel simulation

Most of the time, the vessel is modelled without forward speed. One reason for this is that the model of the cable would need to be very long to accommodate the vessel movement for an extended simulation time. Since the calculation time scales rapid with the amount of cable segments, modelling a stationary vessel is a pragmatic solution to this problem. An argument that can be given for this method is that the pay-out speed of the cable can match the vessel velocity. If the assumption is made that the velocities can always be matched, the resulting models would be very similar except for missing a portion of axial drag that originates from the cable sliding in de water. With the knowledge that the axial drag is two orders of magnitude smaller than lateral drag (Appendix E), it is deemed acceptable to neglect the axial drag all together and therefore allow zero forward motion to be used.

4.2.2 Chosen wave parameters

For each project, locally occurring significant wave heights, directions and periods are deduced from met-ocean studies. The irregular wave fields that occur on the project location can often be described by a JONSWAP spectrum. Significant wave heights are selected with corresponding peak periods. The values for the peak period of wind sea-states are often linearly interpolated between:

$$\sqrt{13H_s} < T_p < \sqrt{30H_s} \quad (4.1)$$

This is a simple method to model the most probable H_s , T_p combinations for most areas in the North Sea, which is approved by GL Noble Denton (14). Subsequently, peak-enhancement factors γ , can be used to describe young sea-states which are often part of the working environment for offshore windfarms (15).

$$\begin{aligned} \gamma &= 5 & \text{for } \frac{T_p}{\sqrt{H_s}} &\leq 3.6 \\ \gamma &= e^{(5.75 - 1.15 \frac{T_p}{\sqrt{H_s}})} & \text{for } 3.6 < \frac{T_p}{\sqrt{H_s}} < 5 \\ \gamma &= 1 & \text{for } 5 \leq \frac{T_p}{\sqrt{H_s}} \end{aligned} \quad (4.2)$$

Equations JONSWAP peak enhancement factors

These wave conditions are often simulated for multiple directions since this has a major influence on the response of the vessel. The wave directions are often distributed uniformly in 30° intervals to reduce the total amount of simulations.

For a single project, it is not uncommon to investigate 4 wave heights with each 4 peak periods in 12 wave directions. This already provides 192 combinations of sea-states which will later be multiplied by other variables. The goal of this distribution is to give a clear view of the influence of the waves, within reasonable CPU time.

4.2.3 Current modelling

Currents are taken into account for some projects where the tidal currents are strong. Current loading on the cable may induce offset that needs to be corrected. For other projects the current is often neglected under the assumption that current will dampen the dynamic system of waves and cable oscillations, resulting in a conservative model.

4.2.4 Seabed modelling

Experience based friction factors are applied for longitudinal and lateral motions of the cable over the seabed. The seabed is often modelled as a perfect horizontal plane unless, for example: a scour protection needs to be accounted for when pulling a cable in, or free span analysis needs to be carried out for laying on ridges and sand waves.

Often, different friction factors are applied for lateral and axial cable motions. The lateral friction factor is generally given a higher value to account for bulldozing of the soil by the cable.

4.2.5 Water depth

The water depth is very project specific. For an array project, water depths range often between 10 and 40m which can be discretized in a pragmatic amount of values. Export cables and umbilicals may be laid in much greater water depths and will generally contain a shore landing. When this happens, coarser depth discretization may be required or more simulations are needed. The decision for such problems lies with the analyst.

4.2.6 Cable types

During a single project, multiple cable types may need to be installed. When considering an array project, cables connecting a string of wind turbine generators (WTG) may have larger conductor cross-sections closer to the offshore substation to reduce the losses.

4.2.7 Top tension

For a catenary analysis: the top tension, bottom tension, departure angle, layback distance and water depth are the main parameters of interest. As long as the water depth, cable weight and one of the other variables is known, the catenary shape is defined.

Top tension is controllable on board the vessel and can therefore be used as the leading parameter for the analysis. Since the catenary shape is the governing variable for the criteria of MBR and compression limit, the

top tension is often discretized in a few values. For infield cables in intermediate water depths often between 5 and 40 kN.

4.2.8 Number of simulations

The total number of simulations, based on the different environmental conditions and tensions can be in the order of 10^4 . A typical example: $n_{H_s} \cdot n_{T_p} \cdot n_{\theta} \cdot n_d \cdot n_{\text{Tension}} \cdot n_{\text{cable}} = 4 \cdot 4 \cdot 12 \cdot 4 \cdot 8 \cdot 2 = 12288$ simulations. This visualizes the need for well thought off variables, since the required amount of simulations can increase rapidly.

The spread of the variables depends on the project at hand. An export cable for example can cross a larger variety of water depths, requiring a larger segmentation of the depth and tension parameters. Whilst a shore pull-in operation may require additional parameters such as currents and large departure angles.

4.2.9 Further refinement

When significant gaps appear in the operability, a more detailed investigation can be undertaken. Wave spreading can be used to go further in depth and perhaps provide a slightly less conservative approach. For some projects, a spreading coefficient of $n = 6$ is used in the $\cos^{2n} \theta$ relation, which according to DNV recommended practices (15) is within the allowable spreading coefficient band for wind seas.

Sometimes additional simulations are performed when specific combinations of H_s and θ give rise to unsatisfactory conditions after wave spreading is applied. In that case H_s will be lowered in small increments until all cable integrity test criteria are met for that specific simulation.

5 EFFECTS OF REDUCED TIME DOMAIN SIMULATION IN CURRENT METHOD

Operability is often defined as a 3-hour operable sea-state. It is however, not deemed feasible to simulate the vessel and cable for the full duration of such a wave train due to the severe computational effort involved. A pragmatic approach is needed. This chapter describes the method by which the simulation time can be reduced and explores the effects by comparing the results of this reduction to full time domain simulations.

5.1 REDUCED TIME DOMAIN METHOD

For each combination of wave height and peak period, a 3 to 10-hour irregular wave sequence is generated. From this sequence, the point in time where the largest waves occur are selected as the centre around which 250 seconds of simulation time are performed. The highest waves can be defined in two ways: By measuring the wave height between two zero upward crossings, as well as two zero downward crossings. These can analogous be called: Highest rise & highest fall as shown in the example of Figure 24.

The surface elevation is often assumed to be a Gaussian process, which has symmetrical statistic characteristics (16). Therefore, one could assume that it does not matter which definition of wave height is utilized. However, the cable response is not symmetrical as compression is related to downward chute motions only. Therefore, both wave height definitions are used to select the simulation intervals. These intervals may overlap, reducing the simulation time a little further.

In this manner, the required simulation time is reduced by a factor 21.6 or 72, depending on whether a 3 or 10-hour wave sequence was selected. Which is quite significant as nowadays still a few days' worth of computational time is needed to perform the needed simulations with time reduction applied.

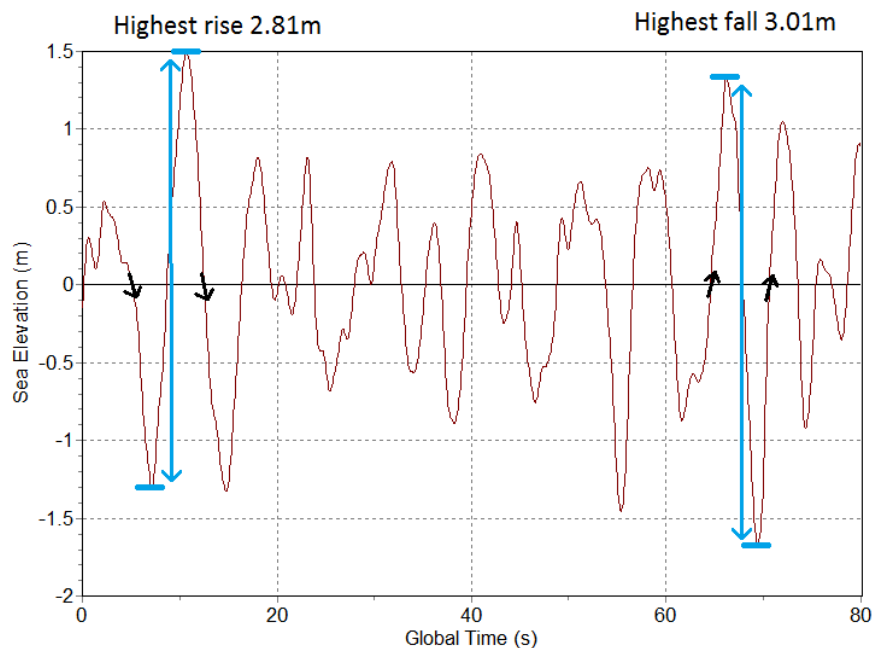


Figure 24 Example of hi rise & fall in 80 second JONSWAP wave train: 3m H_s , 7.87s T_p , 1.69 γ

5.2 INVESTIGATION SETUP OF REDUCED TIME SIMULATION

The reduction of simulation time is of interest since it cannot be concluded up front that the severest cable loads occur during the largest wave heights. Therefore, an investigation has been undertaken to assess the influence that the height of the waves has on cable compression.

To gain insight in the effectiveness of the reduced simulation time: a set of full 3-hour time domain simulations has been simulated. Parameters are chosen to represent a typical array cable laying operation, see Table 2. The cable as depicted in section 3.1 is selected and modelled. The CLV Ndurance is selected as installation vessel.

Table 2 Boundary conditions reduced simulation time investigation.

H	30m	Water depth
T _{Top}	20kN	Top tension
ϕ	40°	Departure angle

A set of JONSWAP irregular wave trains has been selected, each at a bow quartering direction of 135° from the stern and modelled without wave spreading. The selected wave trains comprise of 3 significant wave heights with each 3 peak periods that are determined again by equation (4.1). Each combination of H_s and T_p obtains a value of γ calculated by equation (4.2) For each set of wave parameters, 3 unique sea-states have been generated. Bringing the total amount to 27 simulations as depicted in Table 3.

Table 3 JONSWAP wave parameters for testing reduced simulation time.

CASE	1-3	4-6	7-9	10-12	13-15	16-18	19-21	22-24	25-27
H _s	1	1	1	1.5	1.5	1.5	2	2	2
T _p	3.61	4.54	5.48	4.42	5.56	6.71	5.1	6.42	7.75
γ	5	1.78	1	5	1.46	1	4.97	1.73	1

A full 3-hour time domain simulation has been performed for each case. To compare various cases, the maximum dynamic tension loss ΔT_D is introduced in equation (5.1) This is the difference between the static tension in the TDP (T₀) and the lowest tension found for all elements in the full simulation period (T_{min}). Since T_{min} may be negative when compression occurs, this conversion makes ΔT_D positive whether compression occurs or not and easy to compare for various sea-states with the same boundary conditions for the cable.

Similarly, $\Delta T_{D, Rise}$, $\Delta T_{D, Fall}$ are the tension losses found in each of the 250s simulated periods around the highest rise and fall respectively.

$$\Delta T_D = T_0 - T_{min} \quad (5.1)$$

$$\Delta T_{D, Found} = \frac{\Delta T_D}{\max\{D_{T, rise}, D_{T, fall}\}} \quad (5.2)$$

5.3 REDUCED SIMULATION TIME RESULTS

The following results were obtained in the reduced simulation time investigation:

- The T_{max} and MBR are within limits for all 27 simulations and are therefore not further investigated.
- The T_{min} of 0 kN allowable compression has been exceeded for a few cases leading to inoperable conditions.
- For 9 out of 27 simulations: D_{T, Found} = 1 which means that the minimum tension of the full 3-hour simulation was found within the highest rise & highest fall domains. This is the desired result.
- In 18 out of 27 cases, less tension loss was found then should be based on the full 3-hour simulation. Which is undesirable.

It can be concluded that for the majority of cases, the maximum tension loss is underestimated by this method. The size of the fault is further investigated:

- The average value for $D_{T, \text{Found}}$ over 27 sea-states = 0.97. So in average, the current method underestimates the loads by 3%.
- Standard deviation of $D_{T, \text{Found}}$ over all cases is equal to 0.04.

Within this example of 27 cases, case 22 has the smallest value of $D_{T, \text{Found}} = 0.817$. Meaning that the loading is underestimated by 18%. The current method found a minimum tension of 1.69kN which would be accepted as there is still some tension in the cable. The minimum tension in the full 3-hour wave sequence was found to be -1.03kN, meaning compression which is not acceptable.

Hence, one out of 27 cases from this study has been falsely accepted as operable using the current method.

The full results of this case study can be found in Appendix C Reduced simulation time validation. The implications of these results are discussed in the discussion: chapter 10.

5.4 OTHER RISKS IN CABLE ANALYSIS

The errors in the reduced time domain simulation are not the only risks incorporated in cable lay analysis. Models and assumptions are needed. When the choice is made to make a model of reality, inaccuracies and uncertainties will be introduced. These may impose risks that are important to take into account. The most important risks have been identified for the current and new method of cable lay analysis:

5.4.1 Idealization of a wave spectrum

The preferred wave spectrum used for simulations is the JONSWAP spectrum which stands for: Joint North Sea Wave Observation Project. This spectrum is equal to the Pierson-Moskowitz spectrum multiplied by a peak enhancement factor γ . This peak enhancement factor is designed to fit measurements of sea states that are not fully developed, as is generally the case in the North Sea (17). In spite of the extensive measurement campaign to improve the wave spectrum models, real wave conditions will never fully comply to an idealized spectrum and may therefore impose greater loads than modelled.

5.4.2 Discretization of wave spectra

One problem of using wave spectra to define the operable conditions, is the need for discretization. It is impractical to create a continuous distribution of operability across various parameters such as H_s , T_p , γ as this cannot be easily read by the crew of the vessel. The solution is to determine operability by discretized variables that can be looked up in a table. This discretization induces an error as the actual wave conditions will almost always differ from the discretized spectra. An example of discretisation that may be used in catenary analysis is the step size of 0.25m H_s . The effects of this step size are investigated by means of the highest expected wave crest.

If we look at the distribution of the maximum crest height per wave, and are interested in large crests, we can assume that these maxima are Rayleigh distributed (16). From the Rayleigh distribution follows that the most probable maximum crest height in a wave sequence is equal to:

$$mod(\eta_{max,crest}) \approx \sqrt{2 \ln N} \frac{H_s}{4} \quad (5.3)$$

Due to the square root and logarithm parts in the formula, the maximum expected crest height will grow slowly with an increasing amount of waves (N). However, due to the nature of the Rayleigh distribution, the chances of an actual wave condition that exceeds this expected maximum is equal to 0.63. Exceedances should not be large due to the narrowness of the spectrum. But still the chance of exceedance is large. Given this fact, it stands to reason that a small discretization step in significant wave height is not very useful as the maximum expected wave height in a sequence will never be determined with a large certainty.

5.4.3 Stationary wave spectrum

Wave spectrum analysis often assumes a stationary sea state. This is almost never true in nature. Some conservatism is often gained in assuming a stationary sea state as the highest expected sea state is often forecasted.

5.4.4 Accuracy of vessel hydrodynamic databases

The model of a vessel that is created to investigate how it responds to waves is often made by use of diffraction methods. These models have their own limitations such as: neglecting viscous effects and thruster wash. Part of these inaccuracies can be compensated by monitoring the wave loads and vessel response for a period of time. Several industry-accepted, self-learning software packages have been developed for this purpose.

5.4.5 Model errors

Modelling cable installation procedures in a software package also brings some limitations. Wave refraction on the hull of the vessel is often not taken into account. This will lead to larger direct wave loads as the cable cannot enjoy shielding from the vessel.

5.4.6 Soil interaction

Lots of uncertainties lie in the interaction between the cable and the seabed. The models that are often used assume a perfectly flat seabed that can be modelled as a distributed spring. In reality, the interaction between cable and soil is more complex whilst obstructions on the seabed such as boulders or recesses could lead to increased cable loads.

5.4.7 Cable properties

Not all (mechanical) properties of submarine power cables are tested in detail before the operability assessment is performed. Diameter, submerged weight, and surface roughness may be determined with a high degree of accuracy in the design phase based on the materials used. But other mechanical properties such as the bending stiffness and structural damping may in practice have an uncertainty as high as 50%.

Some tests that were published only recently have shown that the compression limits imposed by cable manufacturers may be very conservative (9). This is perceived to be one of the largest factors imposing conservatism in the system of cable installation analysis.

6 QUASI STATIC CABLE ANALYSIS

A submarine power cable suspended from the chute of an installation vessel will form a catenary shape due to its limited bending stiffness. The catenary shape together with the quadratic drag equations are important sources of non-linear cable response. This chapter explores the character of cable response based on quasi statics and drag. The insights gained will form the basis for compression limit theory, which is tested using numerical analysis in chapter 8.

6.1 CATENARY EQUATION

A geometric catenary is the curve that an idealized hanging cable assumes under its own weight when supported at its ends. The idealizations that are required for simplified analysis are:

- Zero bending stiffness
- Continuous homogenous material
- Zero elastic elongation

These idealizations are generally acceptable for submarine power cable installation. The elastic elongation is normally in the order of $\epsilon_c < 1\%$ (3). As high lay tensions are undesirable for cable burial. The homogeneousness of the material and the bending stiffness are also small factors compared to the scale of cable installation.

The catenary shape is described by the hyperbolic cosine as in equation (6.1). The shape is defined by the catenary shape parameter: a . The full derivation of the catenary equation based on force equilibrium with zero bending moment in the elements can be found in Appendix B. The definition of the axis system and other variables is depicted in Figure 25.

$$y = a \cosh\left(\frac{x}{a}\right) = \frac{a\left(e^{\frac{x}{a}} + e^{-\frac{x}{a}}\right)}{2} \quad (6.1)$$

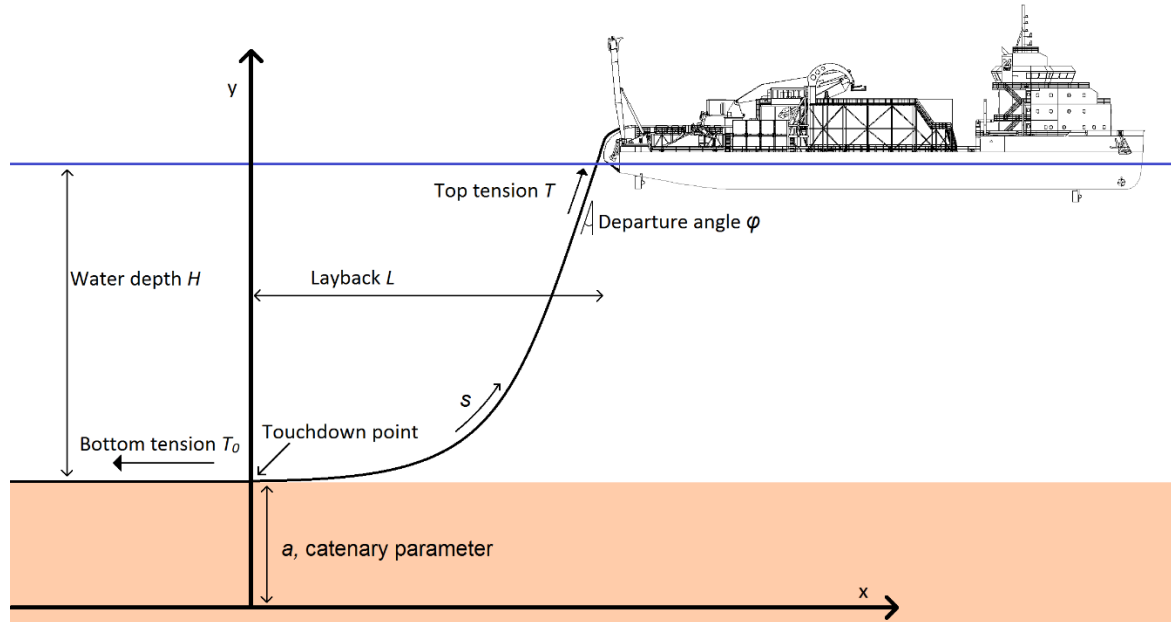


Figure 25 Catenary reference system

6.2 CATENARY EFFECTS

When the chute of the vessel moves in negative surge or heave direction, slackness is obtained in the cable. With enough time, the cable will sink towards the bottom. The tension will decrease, the TDP will move closer to the vessel and the balance of forces is restored.

With the catenary shape being described as a hyperbolic cosine, it is hard to obtain a deterministic function that shows the displacement of the catenary for a given displacement of the hang off point. Therefore, a case study is performed for a typical infield cable lay scenario. The parameters used to simulate the quasi static cable response to a chute excursion are shown in Table 4. The cable response in small steps is shown in Figure 26.

Table 4 Base case parameters chute excursion

CABLE CONFIGURATION	
WD	28m
T_{top}	12.95kN
T_0	8.0 kN
ϕ	38°
Excursion	2.8m

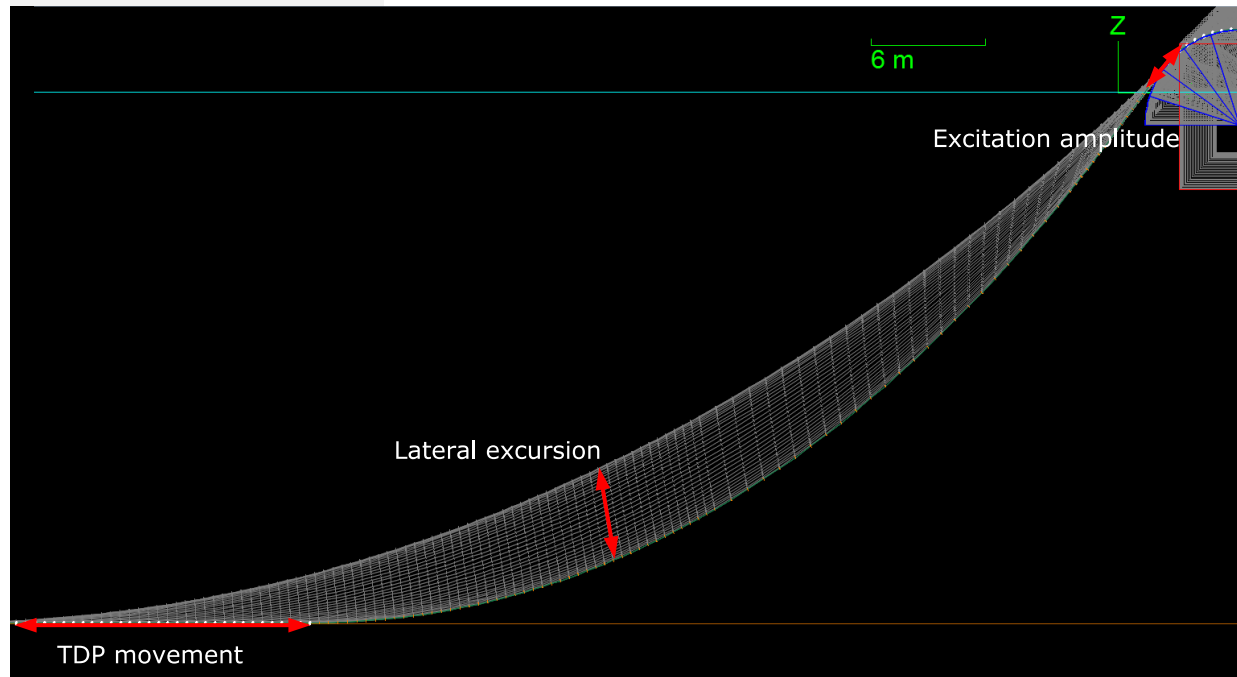


Figure 26 Example of 1.4m quasi static excursion in axial direction

In Figure 26 the non-linear catenary effects are clearly visible. Due to a chute excursion of 2.8 meters in the cable axial direction, a larger lateral excursion of 4.9m is obtained in the sag-bend. The TDP moves to an even greater extent: 15.3m for this example.

This non-linear behaviour of large lateral excursions and even larger TDP movements play an important role in the development of cable compression. The lateral excursion is resisted by drag and the TDP movement may be required to move faster than the transverse wave velocity will allow. Both effects are explained in their respective sections: 0, 6.5.

6.3 CABLE FREE FALL VELOCITY

Submarine power cables that are developed for offshore windfarms have a limited weight when compared to their diameter. In the previous section it is shown that a large lateral excursion follows from a small chute excursion. This relation implies that high chute velocities will need an even higher lateral cable velocity along the sag-bend in order for the catenary to maintain its shape. The maximum velocity which can be obtained is calculated in this section.

When a segment of cable is horizontally placed in water and let loose, an equilibrium will be formed where the gravitational pull cancels out with the hydrodynamic drag and buoyancy. For this equilibrium, it is assumed that the cable does not rotate and moves through the fluid at right angles to its longitudinal axis.

The vertical force equilibrium demands:

$$F = F_d - F_g = 0 \quad (6.2)$$

The drag force is equal to:

$$F_d = \frac{1}{2} \rho_w v_r^2 C_d D \quad (6.3)$$

The gravitational force is equal to:

$$F_g = m_s g \quad (6.4)$$

Note that the submerged weight is used and therefore the buoyancy is already incorporated.

The normal flow drag coefficient for circular cylinders is dependent on the Reynolds number and surface finish. For the model cable, with a surface roughness of 10^{-2} the drag coefficients profile is shown in Figure 27.

The Reynolds number can be calculated via:

$$Re = \frac{\rho_w v_r D}{\mu} \quad (6.5)$$

Iteration of the equations: 9 - 12 results in a terminal velocity of 1.48m/s at a Reynolds number of $3.9 \cdot 10^4$. The used parameters are listed in Table 5.

Table 5 Parameters for terminal velocity calculation

Symbol	Variable	Value	Unit
m_s	submerged weight	15.87	kg/m
g	gravity acceleration	9.81	m/s ²
D	diameter	0.121	m
ρ_w	seawater density	1025	kg/m ³
μ	kinematic viscosity (4°C)	0.00467	Ns/m ²
C_d	drag coefficient	1.143	-
v_r	velocity relative to water	1.48	m/s

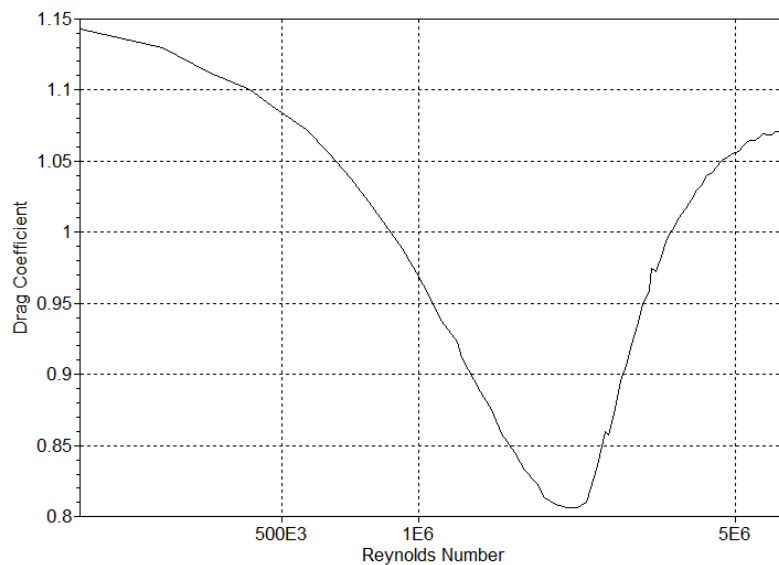


Figure 27 Drag coefficients of model cable

From the calculations it is concluded that the cable model cannot fall faster through the water in lateral direction than 1.48 m/s. Due to the catenary effect as described in section 0, a small excitation at the chute will lead to larger lateral excursions along the sag-bend. The same principle works for velocities. A small velocity of the chute in the axial direction of the cable, will lead to larger lateral velocities needed to maintain the catenary.

It is important to note that the selected cable is built with copper power cores. Similar size infield cables are often used with aluminium cores which reduces the submerged mass whilst maintaining similar drag forces. These cables will have an even lower free fall velocity, which may be reached by lower chute motions.

Other analyses such as: the derivation of drag dominance based on the Keulegan Carpenter number, the magnitude of the hydrodynamic damping and the magnitude of axial drag can be found in Appendix E.

6.4 TENSION LOSS AND COMPRESSION

When slackness is introduced in the cable, the cable sinks towards the seabed. Due to the large lateral drag component and the limited submerged weight, a significant portion of the cable weight will be “carried” by the drag. In other words, when the cable falls through the water, the drag will impose a tension loss along the cable.

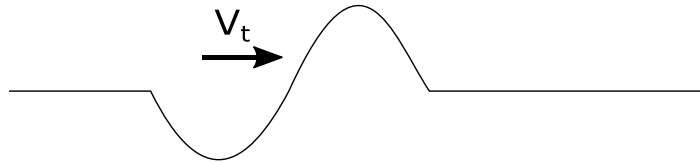
If the excitation of the cable is fast enough, the cable is no longer able to follow the catenary shape due to the drag forces and all tension may be lost. The cable will move towards the bottom with the lateral velocities governed by drag and the axial velocities governed by both inertia and the shape of the falling cable. When the free falling cable segments hit the bottom with a certain velocity, their momentum will create compression in the cable which is undesirable.

The shape of the falling cable is dependent on the drag forces, which in turn depends on the velocity and orientation of the cable segments. Therefore, it is impossible to find an analytical expression for the cable under (partial) free fall and compression. Hence numerical analysis in the time domain is needed to find the velocities by which the cable starts to compress.

6.5 EFFECTS OF TDP MOVEMENT

As shown in section 0, the displacement of the Touch Down Point will be a number of times larger than the excursion of the cable at the chute. For a relatively small axial velocity, the TDP will have to move at a significant speed to retain the catenary shape. This may be limited by the transverse wave velocity in the cable.

For a simplified analysis, the transverse wave velocity for a disturbance in a cable without bending stiffness is depicted in equation (6.6).



$$v_t = \sqrt{\frac{T_0}{m}} \quad (6.6)$$

Transverse wave velocity

Figure 28 Schematized transverse wave

It is important to note that the tension in the cable has a direct relation with the allowable wave velocity. Once the cable slackens and falls towards the bottom, tension is reduced and the transverse wave velocity therefore reduces as well. Due to the catenary shape, the TDP will have to move at great velocities to maintain the catenary shape. Due to the limited allowable transverse wave velocity, a “jump” may occur near the seabed (18) as seen in Figure 29. Whether or not this jump occurs depends on the catenary configuration and the velocity of excitation.

It is expected that the maximum amount of compression that can occur in a given catenary configuration with a given cable is limited. If the chute is excited by a motion fast enough for the whole suspended cable to reach free fall, the only governing force that is responsible is the inertia of the cable in axial direction. The magnitude of this inertia will be dependent on the cable mass, catenary length and orientation of the cable segments. Due to the effects of drag and transverse wave, further analysis is required to be performed in a time domain numerical simulation.

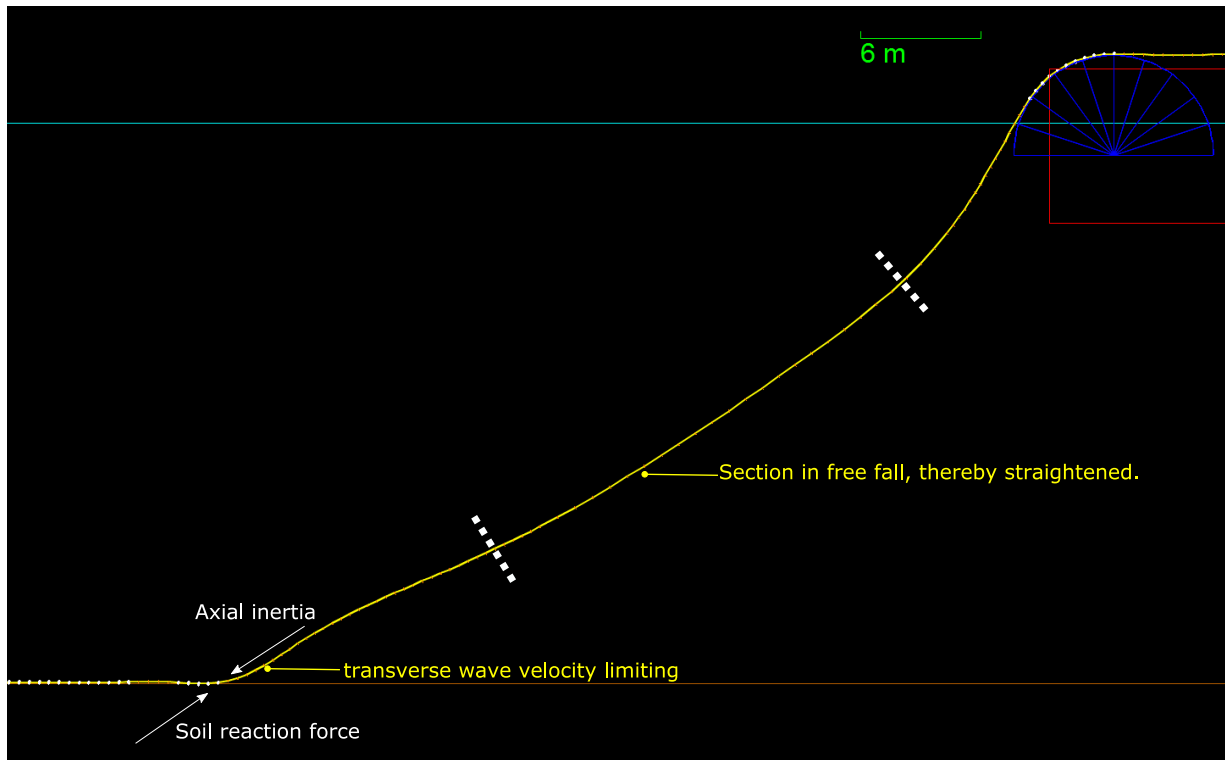


Figure 29 Cable in compression 1.6m chute excursion with 8 second period.

7 VESSEL MOTION ANALYSIS IN FREQUENCY DOMAIN

The installation vessel that is modelled for this thesis is one of the N-class vessels of VBMS. It is important to quantify the motions that the chute of the vessel is likely to make. Therefore, a series of time domain motion responses of the chute of the vessel have been calculated. These vessels have the following dimensions:

Table 6 Dimensions of N-class VBMS vessels

Length	99m
Breadth	30m
Design draught	4,7m
Displacement	12.285t

In practice, the upper limit of wave conditions in which cable installation operations may be performed is in the order of $H_s = 2\text{m}$ with a strong dependence on wave direction and period. To gain insight in realistic load cases that will often cause the operational limits to be surpassed, vessel motions in sea-states with $H_s = 2.5\text{m}$ have been analysed.

A diffraction model of the N-class vessels is used to obtain a set of displacement RAO's that are valid for the design draught of 4.7m. The RAO model is then exposed to a 3-hour JONSWAP wave train with $H_s = 2.5\text{m}$, three peak periods linearly interpolated between the boundaries of equation (4.1) in section 4.2.2. With corresponding peak enhancement factors based on equation (4.2). The RAO model is subjected to these three wave trains from the 0° to 180° wave direction in 30° intervals. The motions of the chute in the X-Z plane for these 3-hours are plotted in Figure 30.

Analysis of the chute motion time series has shown that the maximum excursions take place with a motion period of around 9 seconds. This is equal to the natural pitch period of the N-class vessels. The results from this analysis give chute motions that are realistic for the N-class vessels.

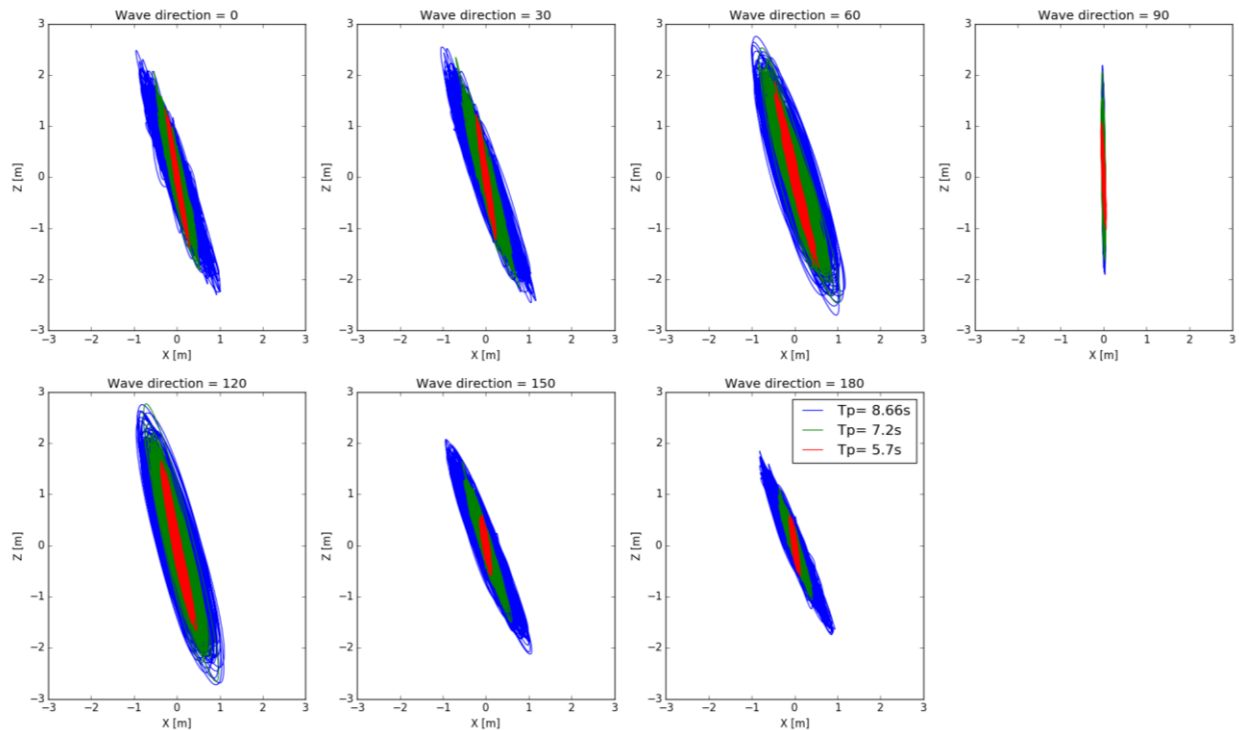


Figure 30 Chute motions in XZ plane CLV Ndurance in 3-hour JONSWAP 2.5m H_s

8 CABLE RESPONSE TO REGULAR VESSEL MOTIONS

In chapter 6, the governing mechanics for compression during submarine power cable installation were explored in theory. In this chapter, the assumption that cable compression is limited by the excitation velocity at the top is tested by numerical simulations in the time domain. For simplicity, sinusoidal motions of a vessel are created without applying waves or currents in the model.

8.1 STEADY STATE OF REGULAR MOTION SIMULATION

In order to remove any transient effects in a regular motion analysis, it is important to know the amount of cycles required to obtain steady state behaviour. This section discusses the factors that influence the transient period and determines the length of the transient behaviour period.

8.1.1 Dynamic build-up in simulations

OrcaFlex© provides the use of a dynamic build-up period before the main simulation begins. During this build-up period, which is usually taken as one wave-period, the wave and vessel motions are linearly ramped up from zero to full size. This provides a gentle start which improves stability and helps to reduce transients that are generated by the change from statics to full dynamics. To make a clear distinction between the build-up period and the main simulation, the zero point in time loss is placed in between the two periods.

8.1.2 Steady state investigation

A sinusoidal motion simulation has been performed on the modeled cable in the following configuration: $WD=30\text{m}$, $\phi=45^\circ$, $T_{\text{Top}}=15.8\text{kN}$. The applied vessel motion comprises an excursion of the chute of 2m in the axial direction of the cable. The motion return period is 9 seconds which is around the natural period for pitch of the N-class vessels.

To allow the assumption that the motions of the vessel and the cables are uncoupled, it is assumed that the cable loading is too small to have a significant influence on the vessel motions. The calculation supporting this statement can be found in Appendix D.

For each cable segment, the effective tension extremes for the whole simulation time of 10 motion periods is plotted in a range graph: Figure 31. The largest compression is found at $x_c=83.2\text{m}$, which coincides with the static TDP of the cable. For this point along the cable, a 45s time series of effective tension is shown in Figure 32.

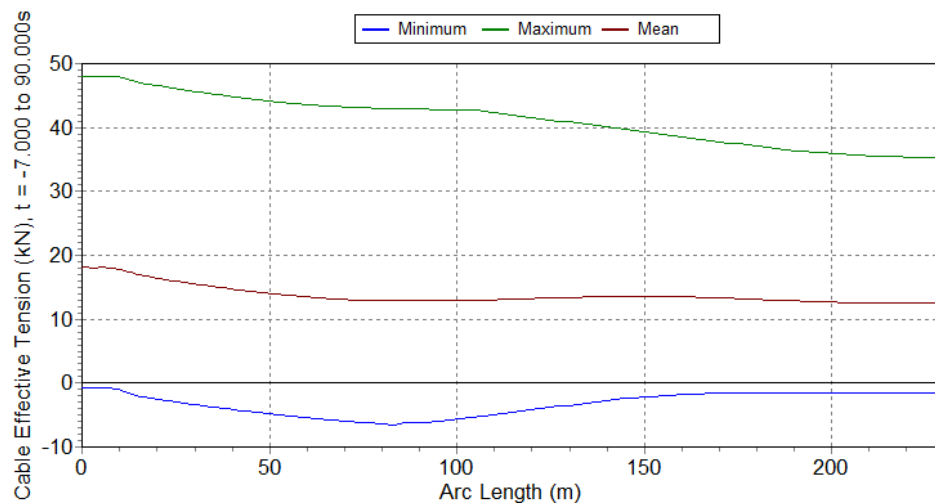


Figure 31 Range graph of minimum tensions per cable segment over 5 motion periods

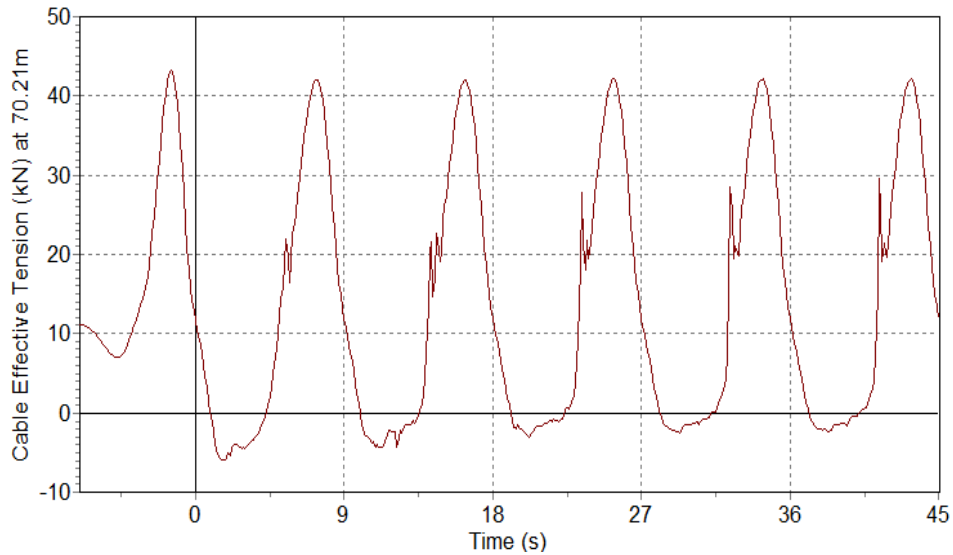


Figure 32 Effective tension time series at 83.2m arc length

The example in Figure 32 shows that the forces reach the steady state regime after the first motion cycle which is characteristic of heavy damped systems. There is a small reduction in the maximum compression value for the following few motions. This may be credited to the hysteresis effect in the non-linear bending stiffness. Each time the cable is bent in the touch down zone, the cable “remembers” this moment and will provide less resistance to bending in the next motion cycle leading to an increased curvature that is better able to absorb axial loads and hence reduces compression.

To show the progressive bending effect, snapshots of the cable during the first three motion cycles are shown in Figure 33. Each snapshot is taken at the point in time where the chute velocity is maximal for that cycle. Respectively: $t=2.2$, 11.2 and 20.2 seconds.

The progressive bending of the cable over multiple load cycles is not limited to the vertical plane. The cable starts to bend in the horizontal plane as well from the second motion cycle and onwards. The progressive bending of the cable allows compression loads to be absorbed in a bending motion, reducing the compression peak. This reduction is mainly apparent for the first three periods.

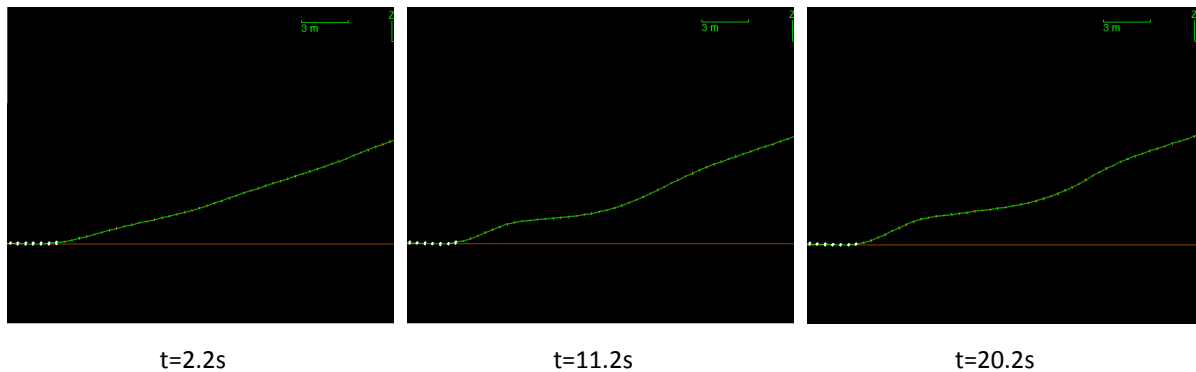


Figure 33 Progressive bending near touchdown zone with non-linear bending stiffness cable

8.1.3 Effect of lay rate on steady state simulation

To couple the effect of progressive bending to realistic installation scenario's, the time a cable segment spends in the touchdown zone becomes needs to be determined.

The time a cable segment spends in the touchdown zone is dependent on the extent that the TDP moves as well as the lay rate of the cable vessel. Typical lay rates for the N-class vessels range from 0.1 to 0.18m/s. These rates are limited by the maximum velocity of the carousel and tensioner which are in the order of 12 meters a minute. Whether these maximum lay velocities are obtained depends mainly on whether the cable is simultaneously buried, the soil type, and weather conditions.

For the base case scenario of $H=28\text{m}$, $\phi=40^\circ$ with the modeled cable, the TDP can move up to 27 meters when the chute is moved with the largest excursions found in chapter 7. These excursions comprise a heave motion of 2.8m and surge of 0.8m at the chute. Both with a period of 9 seconds and 180 degrees out of phase.

This means that a minimum of three successive motions for a cable segment in the touch down zone is reasonable. Also, the cable will have residual bending moments from being transported across the chute. These two factors make it acceptable to take the full reduction of compression due to progressive bending into account. And hence the steady state is defined from the third motion onwards.

8.2 AXIAL CABLE MOTIONS SETUP

The influences that excursion, velocity and acceleration of the chute have on cable compression are investigated. It is assumed that excursions of the chute in the direction of the cable axis give the greatest response since the most cable slack will be obtained in this direction. Vessel motions are often close to sinusoidal, therefore the motions in cable axial direction are simulated as sines as well.

To simulate pure axial motions, the model of the N-class vessels is forced in a prescribed sinusoidal motion in still water. The used axis system is shown in Figure 34 with the equations and variables shown below:

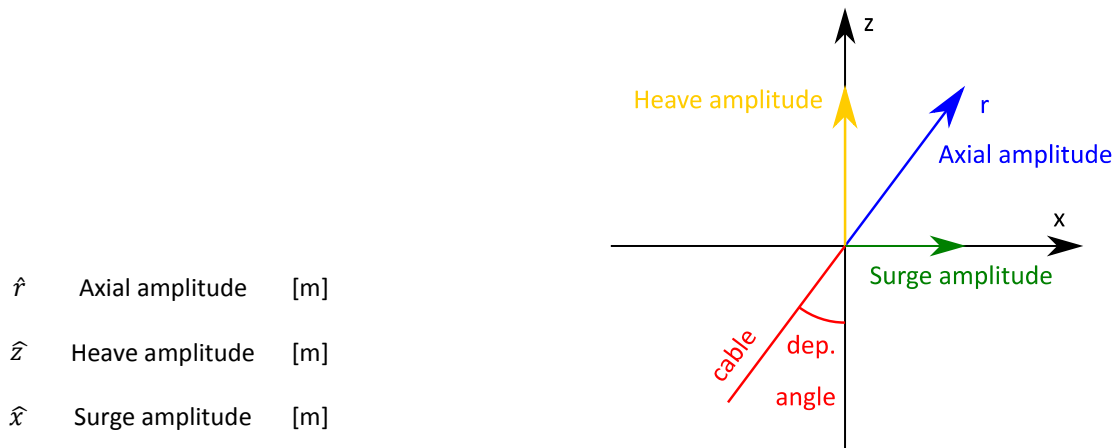


Figure 34 Cable axial direction

The required axial motion is described by:

$$r(t) = \hat{r} \sin(\omega t) \quad (8.1)$$

The velocity in r direction is obtained by the first time derivative and renamed v_a for axial velocity. Since OrcaFlex requires superimposed motion input for heave & surge separately, the amplitudes are calculated as a function of φ :

$$\begin{aligned} x(t) &= \hat{x} \sin(\omega t), \text{ with } \hat{x} = r \sin(\varphi) \\ z(t) &= \hat{z} \sin(\omega t), \text{ with } \hat{z} = r \cos(\varphi) \end{aligned} \quad (8.2)$$

A range of axial motions is simulated that may be found as a component in moderate sea-states to severe weather conditions that are outside of the normal operability range. Excursions range r ranges from 0.5 to 2.5m with 0.1m interval. Motion periods p are: 6,7,8,9,10 seconds. The axial velocity amplitude is equal to:

$$\widehat{v}_a = \omega \hat{r} = \frac{2\pi}{p} \hat{r} \quad (8.3)$$

For each combination of amplitude & period, a time domain analysis of the cable is performed. Each simulation is run for a duration of 3 motion periods in which the third motion is analysed for the maximum dynamic tension loss: ΔT_D as explained in Section 5.2.

8.3 AXIAL MOTION RESULTS

The obtained values ΔT_D are plotted against the velocity amplitude that is imposed on the chute. The results of axial motion simulations for a departure angle ϕ of 40 degrees in 28m water depth are shown in Figure 35.

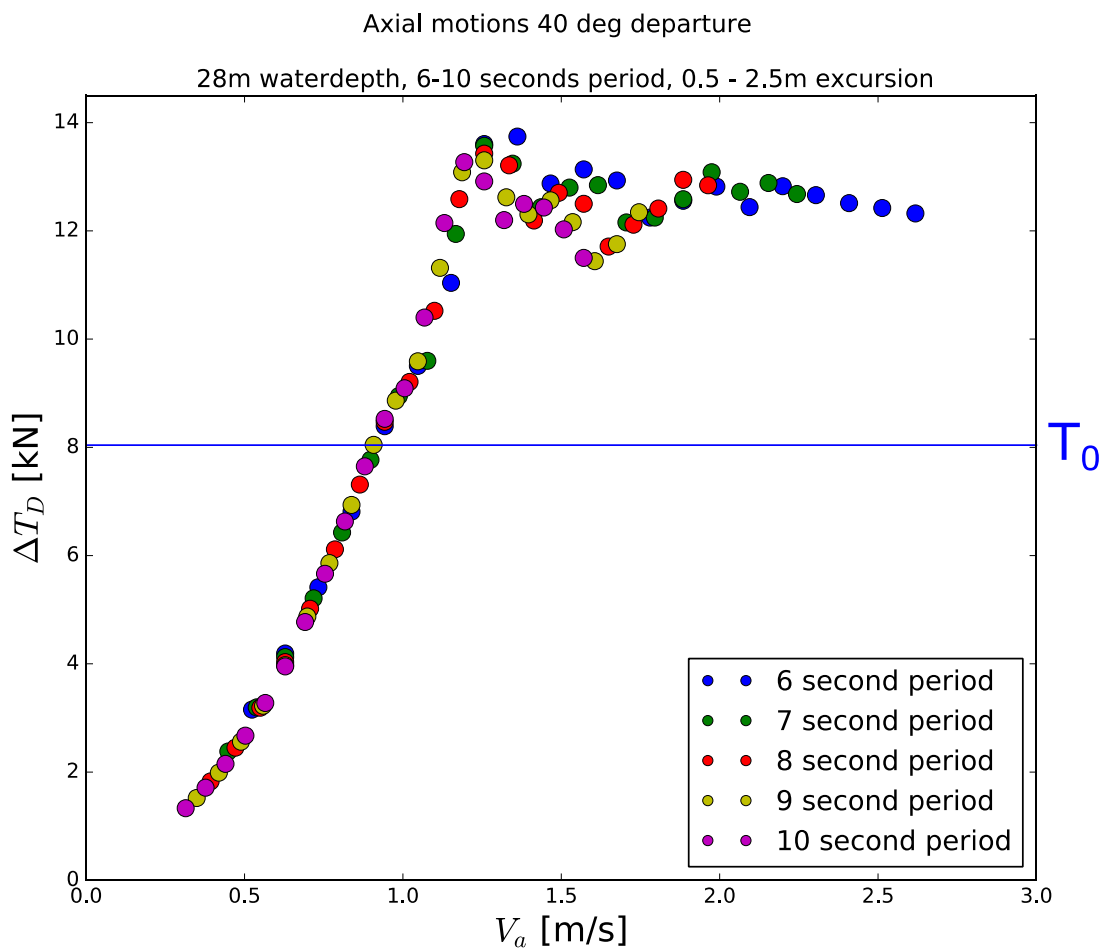


Figure 35 Results of axial cable motions at a 40-degree departure angle in 28m water depth

From Figure 35, the following can be observed:

- The simulation results closely resemble a line up to $v_a = 1.2$ m/s. From that point onwards, ΔT_D no longer grows and the spreading increases.
- $\Delta T_D = T_0$ for $v_a = 0.907$ m/s. This means that for $v_a \geq 0.907$ m/s will impose compression in the cable.
- There seems to be a limit to the amount of compression that can occur. From $v_a \geq 1.2$ m/s, the dynamic tension loss no longer increases and various combinations of excursion and period with the same velocity may have different values for the dynamic tension loss.

As the data points fall onto a single line, it can be concluded that it does not matter whether a short period with short amplitude or a long period with a long amplitude is used. As long as the resulting maximum velocity is equal, the dynamic tension loss will be of a comparable value. The hypothesis that compression in the cable is governed by the velocity of excitation at the chute: v_a is thereby confirmed.

The second hypothesis, that there is a limiting amount of compression, is also confirmed. As ΔT_D no longer grows from a certain value of v_a .

8.4 RESULTS OF REGULAR MOTIONS OTHER THAN AXIAL

Up to now, simulations only included excitation in the cable axial direction. The axial direction is perceived to be the most critical based on two assumptions:

- The catenary shape will be altered to the greatest extent whilst an excursion is performed in axial direction.
- Excursions in the direction perpendicular to the cable axis will be damped by the high lateral drag forces. These excursions will therefore mobilize a smaller section of the cable, leading to less tension loss and compression.

To test these theories, the cable has been excited by regular motions in directions close to cable axial. The chosen directions are: 30, 35, 45 and 50°. Both 5 and 10 degrees below and above the axial direction. The results of this analysis are shown in Figure 36.

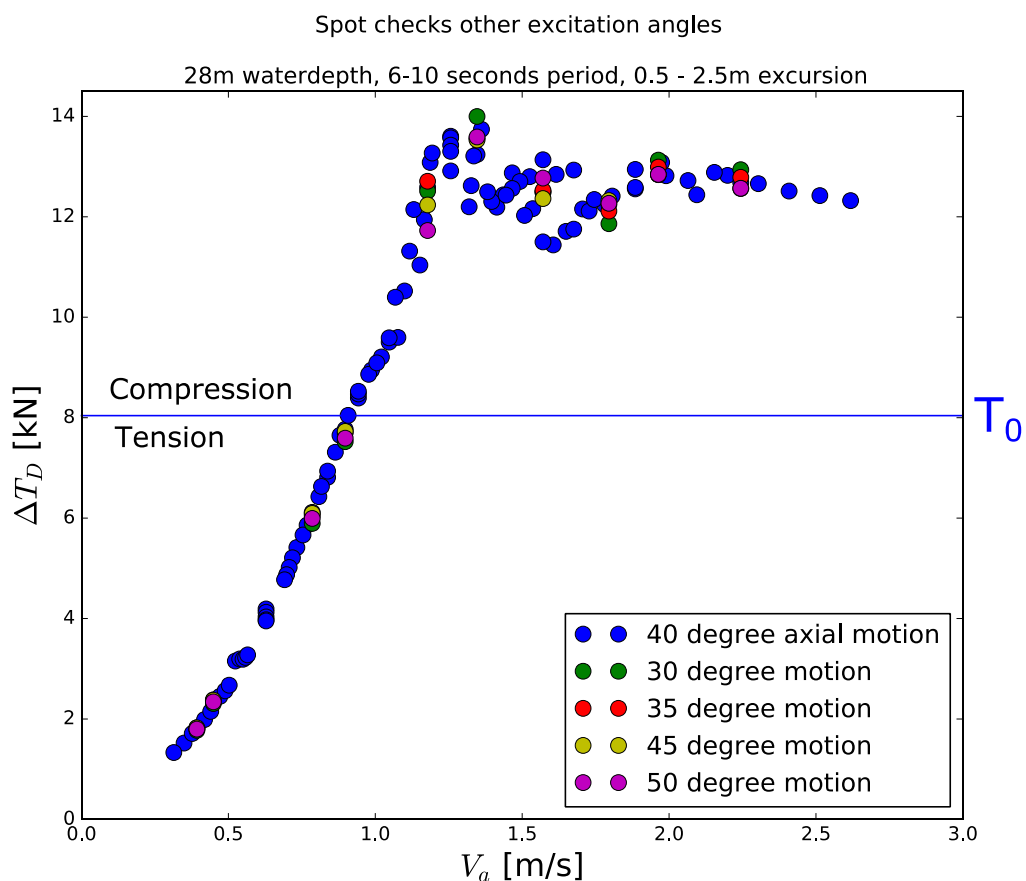


Figure 36 Results of regular chute motions close to axial

From Figure 36, the following can be observed:

Up to the velocity by which compression no longer increases, all angles other than cable axial show less tension loss. Only for velocities where maximum tension loss is obtained are there a few data points exceeding the axial tension loss results.

For the motions of interest, the values below maximum tension loss, it can be concluded that excitation in cable axial direction is governing.

8.5 ADDITIONAL AXIAL SIMULATIONS RESULTS

In the previous section, the conclusion was drawn that chute velocities in the cable axial direction are governing for compression. This is based on only one type of cable and one catenary shape. Additional simulations are needed to see if these trends hold for other configurations as well.

The data from the previous section ($\phi=40^\circ$) has been compared to two other configurations:

- The same cable, but departure angle $\phi=30^\circ$. This is obtained by reducing the static tension.
- A copy of the cable with twice the mass per segment, maintaining the same drag parameters. $\phi=40^\circ$.

For each cable configuration, the same combinations of motion period and excursion amplitude from the previous section are used. Whilst changing the mass and pre-tension, the static TDP tension (T_0) changes as well.

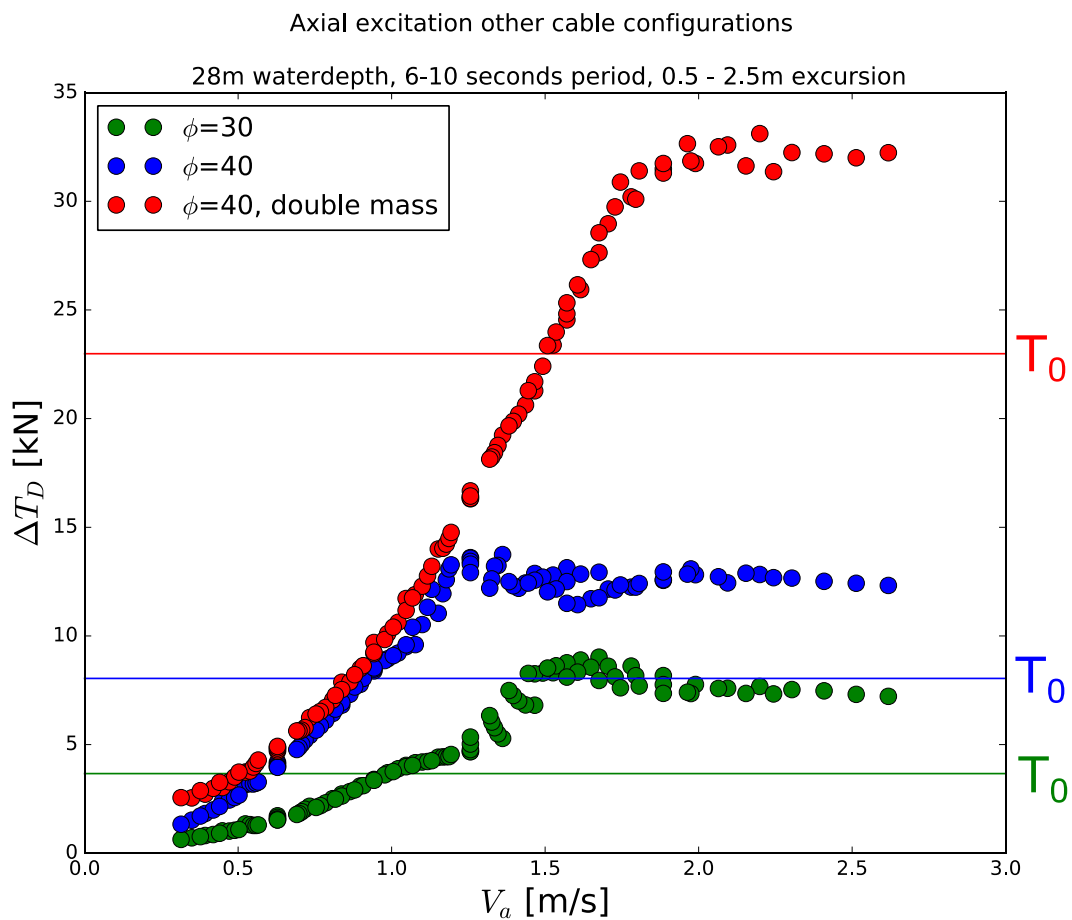


Figure 37 Axial motions of various cable configurations, $p = 6, 7, 8, 9, 10$ s $r = 0.5, 0.6 \dots 2.5$ m

When comparing the original data (blue) with the new data formed by double mass and $\phi=30^\circ$ in Figure 37, the following observations can be made:

- Each cable configuration has the data points lying on a line. With a similar shape.
- All three configurations have a maximum for ΔT_D .
- The cable with double the mass can follow considerably larger velocities of the chute before reaching compression when compared to the other cases.

The results are discussed in the discussion section.

9 CABLE RESPONSE TO IRREGULAR VESSEL MOTIONS

In reality, the vessel will have to cope with irregular sea-states and therefore irregular motions of the vessel. To see whether the chute velocity in axial cable direction is still dominant for irregular motions, irregular sea-states are simulated. It is important to notice that not only will the effect of irregular motions be analysed, the direct effect of waves on the cable will also be simulated. To make a distinction between these two effects, irregular vessel motions are also simulated without the instigating irregular waves.

9.1 MODELLING OF IRREGULAR VESSEL MOTIONS

The same operational settings apply as with the regular motion analysis: An N-class vessel deploys the modelled cable in 28-meter water depth. The static tension at the departure point is equal to 12.95kN which sets $\phi=40^\circ$. For visualization, see Figure 14 on page 11.

An arbitrary JONSWAP wave condition has been chosen that exceeds the current operability limits to great extent. This will make sure that a significant amount of wave conditions will show up that would normally result in a non-operable case. The vessel is exposed to three hours of irregular waves and a full time domain simulation of vessel and cable is performed. The following environmental parameters are chosen:

Table 7 Settings for chute motion-compression analysis irregular waves

Wave type:	JONSWAP
Hs:	4 m
Tp:	9.1 s
γ :	1.7
Direction:	150°
Current:	0 m/s
Wind:	0 m/s

The vessel responds to these wave trains with the motion RAO's that are obtained from a diffraction model. The time series of the chute motions as well as the minimum tension in the cable during each time-step are extracted from the simulation files. These time series are processed in Python. The processing steps are described below and the intermediate results are shown in Figure 38.

First, the time series of the heave and surge velocity are selected for the point of departure of the cable (top graph of Figure 38). These velocities are projected on the axis of the cable in the following manner:

$$v_a = \dot{x} \sin(\phi) + \dot{z} \cos(\phi) \quad (9.1)$$

$$v_l = -\dot{x} \cos(\phi) + \dot{z} \sin(\phi) \quad (9.2)$$

The resulting projected axial and lateral chute velocities are depicted in the second graph of Figure 38. The time series of the minimum tension in the cable are shown in the third graph of Figure 38. Note that the axial and lateral velocity are well in phase with the cable tension.

The maximum compression will occur close to the moment of minimum axial velocity. To cope with this phase difference that may be positive and negative, the chute motions are analysed in segments. The individual motion cycles are isolated. The axial velocity time series are cut into segments separated by each zero crossing. The interest lies only in the negative axial velocities as these are associated with compression. Therefore, the average velocity of each segment is calculated and all segments with a positive average axial velocity are discarded.

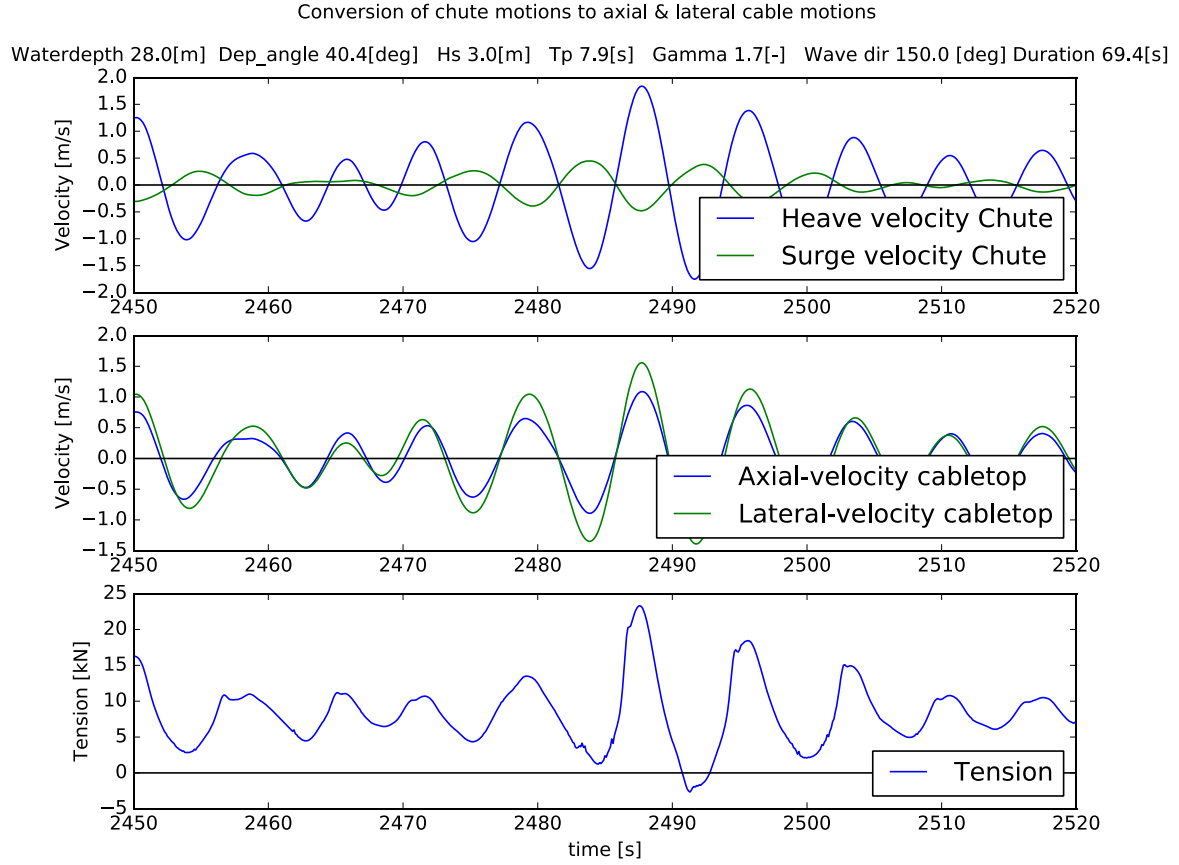


Figure 38 An example of 70 seconds conversion of chute motions to axial & lateral motions.

For the remaining segments, the minimum tension and minimum (most negative) axial velocity are determined. These combinations of maximum tension loss and maximum downwards axial velocity are plotted as a data point for each negative axial motion. The results for this 70 seconds example in Figure 38 are shown in Figure 39 for validation purposes.

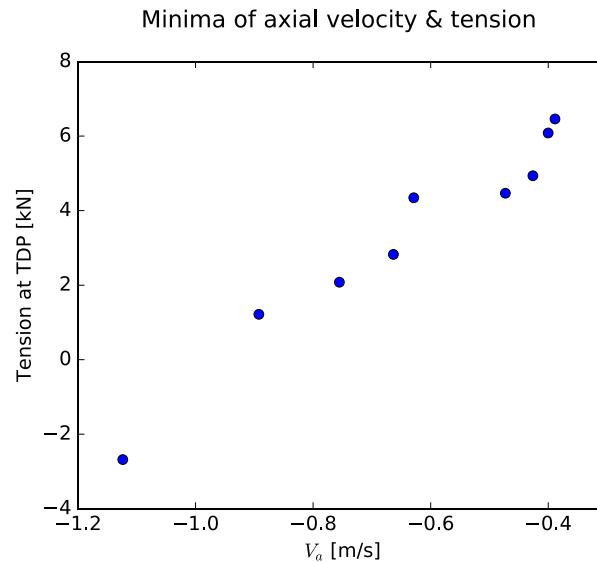


Figure 39 Example of 70 seconds of minima for individual motion cycles for validation

Figure 39 shows the minimum tension from each motion cycle plotted against the largest axial velocity in the downward direction. The results hint towards a positive correlation between axial velocity and tension in the cable, even when irregular motions and direct wave loads are applied.

Next, this analysis method is applied to the full three hours of data. The results of this irregular motion are normalized for compression to be able to compare various cable configurations with variable static tensions (9.3). Note that values of $C \geq 1$ indicate cable compression.

$$C = \frac{\Delta T_D}{T_0} \quad (9.3)$$

This value C is used to compare the results from a full 3-hour irregular waves sequence with the results of axial regular motion analysis. In Figure 40 the results of one of the simulations is shown.

9.1.1 Method for irregular motions without waves

Both irregular vessel motions and the direct wave loading have effects on cable response. To make a distinction between the two effects, the same irregular vessel motions have been simulated, without the waves that instigated the irregular vessel motions.

The simulation method is simple to set up: The time series of the vessel motions obtained in the irregular wave analysis, are used as a superimposed motion for the vessel in still water. In this manner, all the motions of the vessel due to the irregular waves are precisely replicated. Without the direct wave loads on the cable.

The analysis of the data is performed in the same manner as with the irregular waves: for each motion period, the maximum axial velocity is plotted against the normalized tension loss. Results are discussed in the next section.

9.2 ANALYSIS OF IRREGULAR MOTION RESULTS

The first results that are discussed are those from a 3-hour wave train hitting the vessel at 150 degrees from the stern. These results include direct wave loading on the cable.

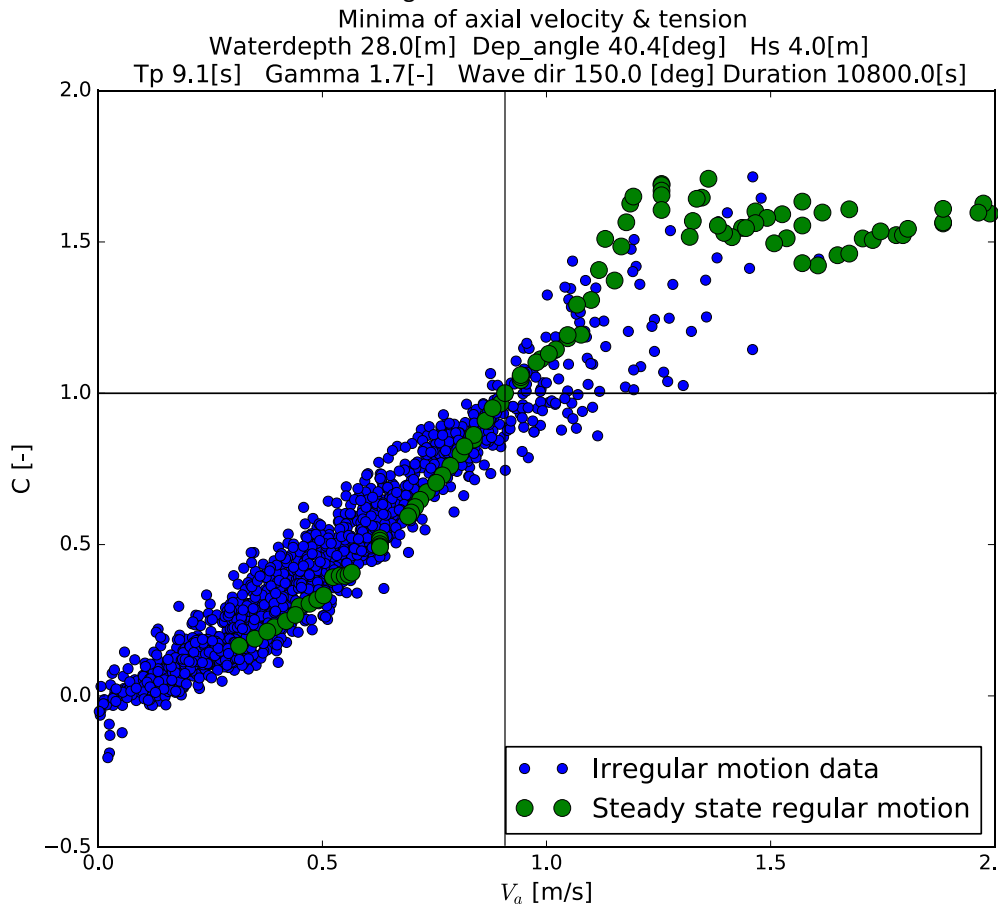


Figure 40 Comparison between normalized regular and irregular motion analysis.

The following can be observed from Figure 40:

- A positive correlation between maximum axial velocity and minimum tension in the cable is observed.
- The regular motion data seems to underestimate the tension loss for low axial velocities and seems to overestimate the tension loss when compression occurs which is conservative. The crossover point of underestimation and overestimation is around the onset of compression.
- The maximum compression that was predicted using axial regular motions is not exceeded by the irregular chute motions.

In Figure 40, a vertical line is drawn where the regular motion analysis predicts the onset of compression: $v_a = 0.907\text{m/s}$. This partitions the data in 4 parts: In this realization of a sea-state hitting the vessel at $\theta=150^\circ$, there are only a few realizations of $C \geq 1$ for $v_a \leq 0.907\text{m/s}$ which would have led to falsely accepted chute motions. There are some falsely rejected motions where $v_a \geq 0.907\text{m/s}$ and no compression is formed. But as those results are conservative and not a large majority, this is not seen as a problem.

It is interesting to compare the case from Figure 40, with the next case: the same irregular vessel motions but now without the direct wave loading on the cable as shown in Figure 41. The following observations are made:

- The spreading of the irregular data has severely reduced when compared to the case with waves. Especially for velocities where $C \leq 1$.
- The data for $C \geq 1$ does not seem to be altered much.
- The regular motion data is now the conservative side of the irregular data, even for the smaller velocities.

From these observations, the following conclusions are drawn:

- Direct wave loading has a significant influence on dynamic tension loss for the lower chute velocities.
- For higher chute velocities where compression becomes of influence, the wave loads have a less profound effect but are still increasing compression.

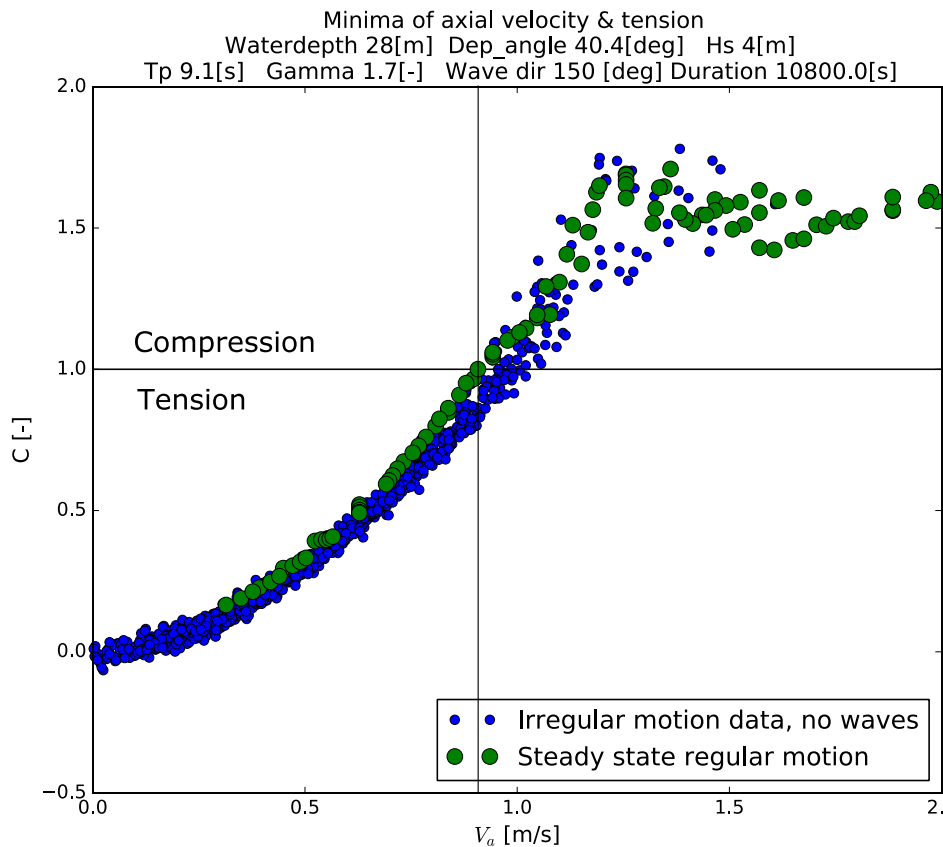


Figure 41 Comparison irregular motion without waves and regular axial motion

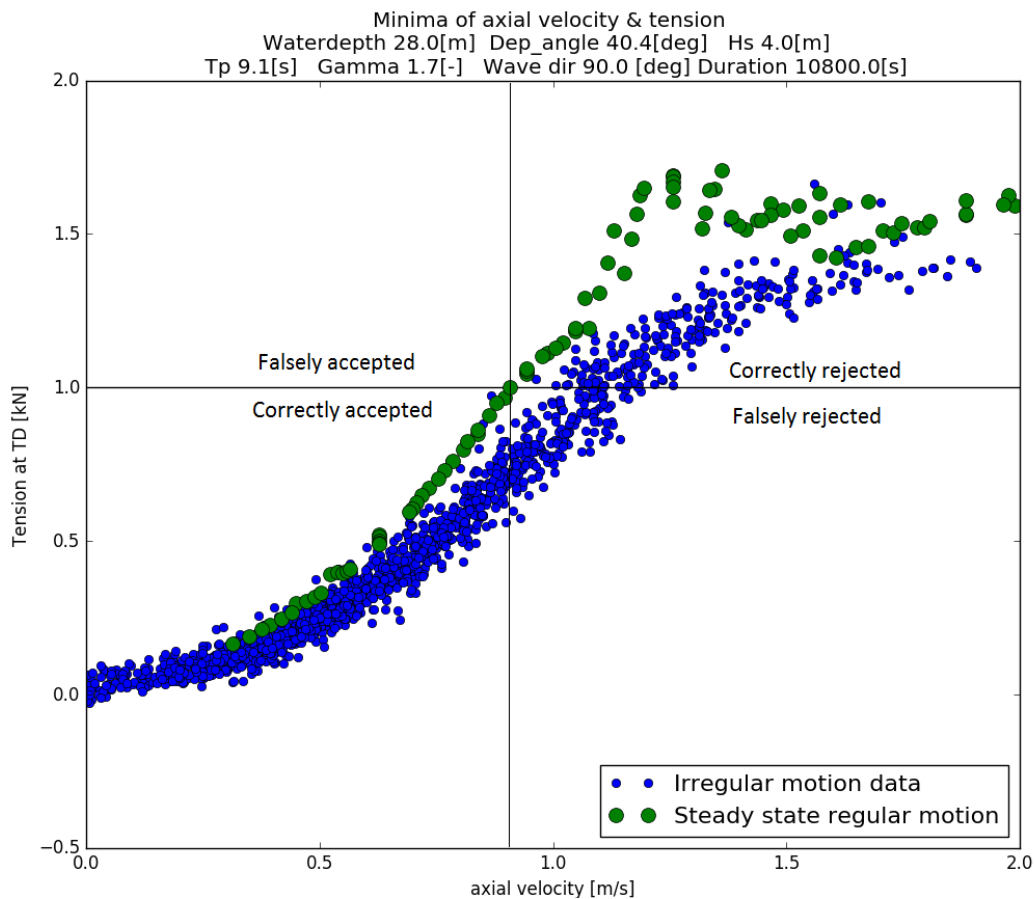


Figure 42 Comparison between normalized regular and irregular motion analysis. Beam waves.

Another interesting load case is when beam on waves are simulated with wave loads included. In Figure 42, the same wave sequence as from Figure 40 is analysed. But now for beam on wave conditions: $\theta=90^\circ$. The following observations are made:

- The same wave sequence shows less spreading in the relation between the compression number C and axial velocity v_a when directed beam on.
- The scatter plot shows more quadratic behaviour instead of the mostly linear correlation from Figure 40.
- The regular motion analysis consequently overestimates the compression for a given v_a .

It is interesting to see that the regular motion analysis overestimates the compression as obtained in the irregular motions. One explanation for this is that in beam on waves: the pitch motion will be much smaller whilst the sway motion of the chute will be significant. Therefore, the departure point of the cable will have larger lateral motions than axial in comparison to bow quartering waves. As concluded in section 8.4, excursions perpendicular to the cable axis tempt to dampen the compression response.

The underestimation of compression is not seen as a large problem. The correlation between v_a and C clearly still exist and the underestimation leads to a more conservative prediction. Perhaps a scaling factor can be implemented combining both lateral and axial velocities of the chute to predict compression. But as the majority of cable laying operations will be performed with the vessel turned to weather, it may not be a necessity to scale the predictions.

All in all, the expected minimum velocity for compression fits the irregular motion data well for $C \geq 1$. Therefore, it can be stated that the presence of compression can be predicted with some degree of accuracy based on chute velocities. How accurately exactly will be explained in section 9.3.

9.3 LINEAR REGRESSION ANALYSIS OF IRREGULAR MOTIONS

This section quantifies the strength of the relation between v_a and C . Analysis is performed by means of the Pearson correlation coefficient and regression analysis. The linear regression is used to calculate a certainty interval for compression based on regular chute motions.

9.3.1 Pearson correlation coefficient

The strength of correlation between two variables can be expressed by the Pearson correlation coefficient ρ (19). For the data in Figure 40, the parameter is calculated in equation (9.4).

$$\rho(V_a, C) = \frac{E[(v_a - \bar{v}_a)(C - \bar{C})]}{\sqrt{\text{var}(v_a) \text{var}(\sigma C)}} \quad (9.4)$$

Where E is the expected value and $\bar{v}_a$, $\bar{C}$ represent the averages of the data. The resulting correlation coefficient ρ for the given case is equal to 0.961 which indicates a high degree of correlation when compared to a perfect linear relation for which ρ is equal to 1.

9.3.2 Linear and quadratic regression

To further quantify the relation between axial chute velocities and cable compression, regression models are used. A linear and quadratic regression model have been made based on the least squares method (9.5). Where S is the sum of the squared residuals that is minimized. And β_0 , and β_1 are the parameters that define the linear regression line.

$$S = \sum_{i=1}^n \left(C_i - (\beta_0 + \beta_1 v_{a,i}) \right)^2 \quad (9.5)$$

The standard error of the estimate is equal to:

$$s_{C|v_a} = \sqrt{\frac{\sum_{i=1}^n (C_i - \bar{C})^2}{n - 2}} \quad (9.6)$$

In which n is equal to the amount of samples.

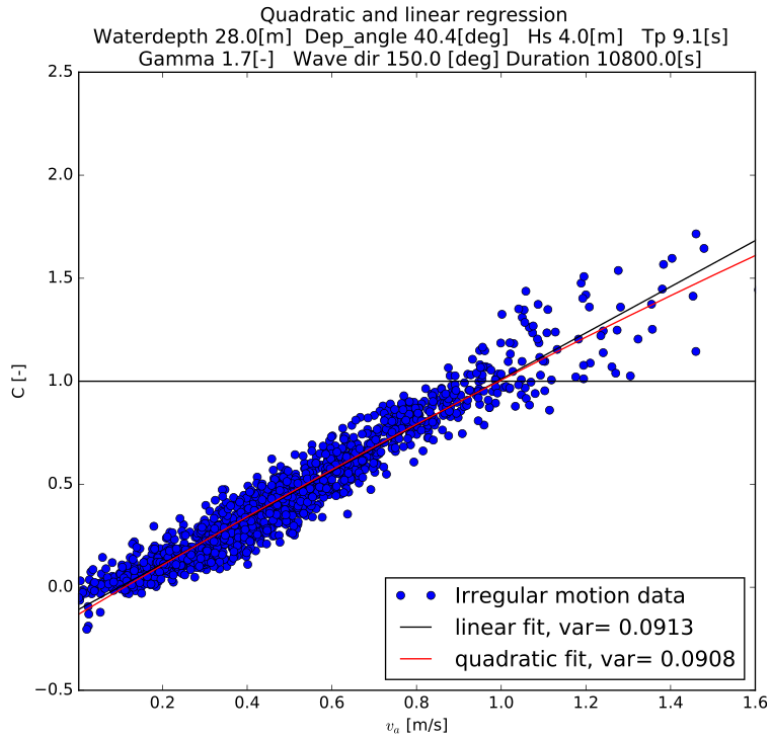


Figure 43 Linear and quadratic regression of axial chute velocity versus compression number C .

The resulting linear and quadratic regression lines in Figure 43 are very close together. As shown in the legend, both regression lines have a standard error of less than 0.1, showing a good fit. With the quadratic regression having a slightly better value.

9.3.3 Confidence interval and prediction interval of linear regression

A linear regression model, although slightly less accurate, is chosen to establish confidence and prediction intervals as these can give a clear indication of the distribution of the data. This simplification to a linear relation is deemed acceptable with ρ being close to 1 and the difference in standard errors small between linear and quadratic regressions.

A confidence interval for the true regression line can be constructed in the following manner:

$$\bar{C} \pm t_{v=n-2, \alpha/2} s_{\bar{C}} \quad (9.7)$$

Where $s_{\bar{C}}$ is equal to:

$$s_{\bar{C}} = s_C |v_a| \sqrt{\frac{1}{n} + \frac{(v_a - \bar{v}_a)^2}{\sum_{i=1}^n (v_{ai} - \bar{v}_a)^2}} \quad (9.8)$$

And t is the standard normal distribution and α the confidence interval.

The 95% confidence interval can be seen as the light grey area around the regression line in Figure 44. This interval shows the area in which the true regression line of the data will be with a probability of 0.95. The area is centred around the average of the data. But due to the strong correlation, the confidence interval is still rather small around the point where compression occurs: $C=1$.

The second set of limits that is shown in Figure 44 is the prediction interval. This interval does not scale up further from the average value of the data, as this interval is based on the assumption that the relation between C and v_a is perfectly linear. The 95% prediction interval states that 95% of the realizations will be within these bands when the distribution is resampled. The prediction band is calculated with the standard normal distribution: t . For the 95% prediction interval the following formula is used:

$$95\% \text{ pred. interval} = \beta_0 + \beta_1 v_{a,i} \pm t_{df}(0.975) s_{C|v_a} \quad (9.9)$$

Since the data looks symmetric, a statement can be made that that an equal amount of realizations should fall on both the lower and upper side of the 95% prediction interval. The conclusion can be drawn that the chance of exceedance of C above the selected interval is only equal to half the probability of the prediction interval.

A table with examples of prediction values is shown in Table 8.

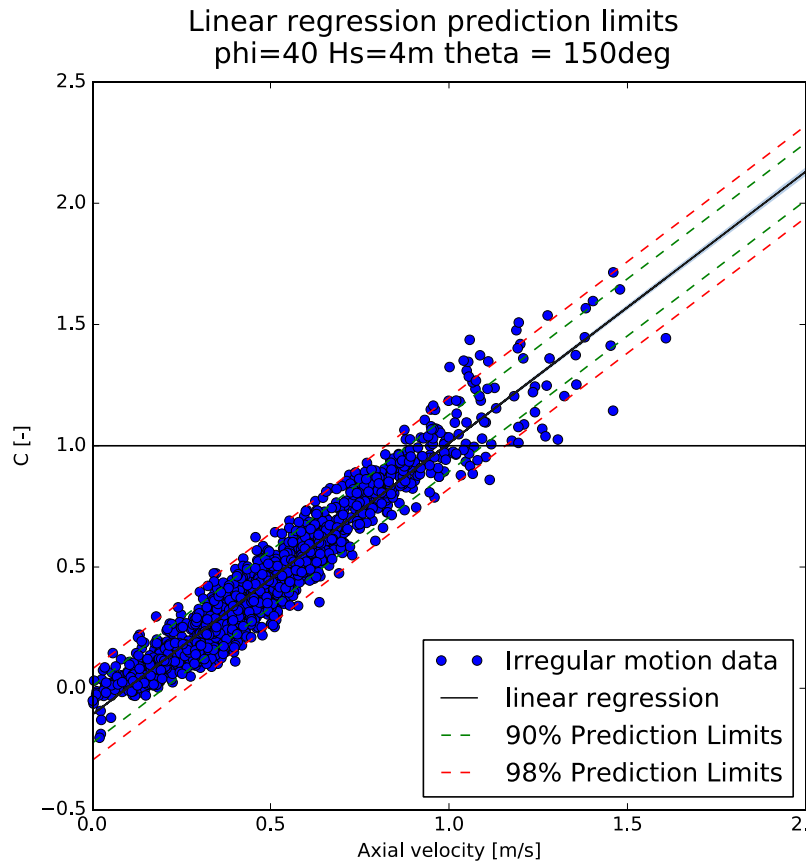


Figure 44 Confidence and prediction intervals.

Table 8 Prediction limits of v_a for onset of compression

Compression	Max v_a
Regression line	0.99m/s
5% risk	0.89m/s
1% risk	0.82m/s

One last note on these prediction intervals: These prediction intervals show the chance of exceedance along the full length of the prediction interval. When for instance the 1% risk interval is exceeded by a single vessel motion, that data point will still have to be above $C = 1$ to cause a problem. As the majority of the data will always be around the smaller values for v_a and C , the actual chance of underestimating the load in this manner is much smaller than 1%.

10 DISCUSSION

The current method of operability determination needs improvement. Analysis may take too large amounts of time even whilst using modern computers. In practice only limited combinations of wind seas, currents and swell are analysed as the required computational time will grow exponentially with a growing amount of variables present. Hence, during cable installation work, the real environmental loading will be compared to discretized load cases. Leading to a loss of workability.

The current method of simulating a 3-hour wave sequence for operability assessment uses the following assumption: the highest waves, either highest rise or highest fall, will result in the largest cable loading. This assumption is made to reduce computational time. The choice is made to simulate only 250 seconds around each definition of highest wave, instead of the full 3-hours.

In section 5 it is shown that for the case study 18 out of 27 simulations the maximum cable loading did not take place within the 250 second intervals around both definitions of the highest wave. This results in an average underestimation of the dynamic tension loss (ΔT_D) of 3%. For one of the 27 cases, 18% of the maximum ΔT_D was not found in the simulation leading to an accepted load case that should have been rejected. There is no standard for compensation of these underestimations. Therefore, it is uncertain whether these underestimations are always countered correctly by a safety margin.

There are three proposed solutions to obtain a larger certainty in cable analysis:

- One way to create some conservatism, which is sometimes used, is to lengthen the wave sequences. This will lead to a higher maximum wave as the maximum expected wave height is related to the amount of observed waves in a sequence. This will probably not be a straightforward success as it is made apparent that the highest wave is often not responsible for the most severe loading.
- The second method is to increase the minimum tension threshold. Since the results show that the current method has an average underestimation of ΔT_D of 3%, it could be advisable to raise the minimum tension requirement by at least an equal amount to incorporate some conservatism.

Both proposed solutions will lead to stricter operable conditions and hence loss of workability. Which is undesirable. Still there is an alternative:

- Operable limits may possibly be based on a variable that could have a stronger correlation with the dynamic tension loss: the motions of the chute of the vessel. If this method is found to be reliable, it would certainly be a lot more flexible and faster method of analysis. As vessel motions can be calculated in the frequency domain.

In chapter 6, it is shown that the maximum free fall velocity of a submarine power cable is governed by drag. The drag force is proportional to the squared velocity of the fluid moving around the cable. The maximum free fall velocity of the cable in normal direction is calculated. For the catenary shape to be maintained, the sag bend will have to make much larger excursions than the top of the catenary. This originates from the geometry of the catenary: the hyperbolic cosine. The same relation applies to velocities. A small velocity in axial direction at the chute of the vessel, will impose large normal velocities along the sag bend of the cable.

This geometric non-linearity is of great importance as free falling velocities of the cable can be reached for small velocities of the chute. When a cable free falls through the water, the drag force will be in equilibrium with the gravitational pull. In this force equilibrium, all tension in the cable is lost as the mass is “carried” by the water. When the cable elements start to reach the bottom, the elements are stopped. Here the inertia of the cable can cause compression.

From this reasoning, it can be assumed that the velocity by which the cable is excited at the top of the vessel is governing for the dynamic tension loss and hence compression. In section 8.2 this hypothesis is tested by simulating sinusoidal chute motions in the direction of the cable departure angle (v_a). The results in Figure 35 show that it does not matter whether a large excursion with large period is used or smaller excursions with

shorter periods. It is shown that the resulting maximum velocity of the chute dictates the dynamic tension loss and hence, compression.

In section 8.4, the effects of chute motions in directions other than the cable axis have been investigated. It is assumed that chute velocities in the cable axial direction are governing for two reasons:

- A catenary line will experience the largest excursions from excitation at the top if this happens in the direction of the departure angle.
- Excitations other than cable axial, will have a cable lateral component. These motion components will be quickly dampened through the high lateral drag. Leading to a smaller cable response.

This hypothesis has been tested by performing excitations in directions close to cable axial. These motions have shown consistently less dynamic tension loss when compared to cable axial. Thereby, the conclusion is drawn that the most limiting excitation of the cable from the chute comes through the axial direction.

From this conclusion, the hypothesis is made that chute motions in the axial direction of the cable may also be governing in irregular sea-states. Simulating irregular sea-states in OrcaFlex is distinctly different for 3 reasons when compared to the regular motion analysis from chapter 8:

- The vessel is no longer moved by an imposed motion. Instead, JONSWAP wave spectra are generated that move the model of the vessel according to its diffraction RAO model. With the waves being distributed with a random phase, the vessel will no longer be responding in regular sinusoidal motions.
- The second key difference is that the regular motion analysis was performed in the vessel's x-z plane. When simulating irregular sea-states from various angles, the chute of the vessel will also move in the vessel's y-direction. It is expected that this will dampen the axial motions of the cable just as with the results from 7.3. However, this cannot be concluded beforehand.
- The third difference between the regular and irregular motion analysis is the direct effect that surface waves have on the cable.

To see whether the velocity of the chute in axial cable direction is a good predictor of cable compression in irregular wave fields, a total of seven time-domain analyses has been performed. These wave conditions comprised various significant wave heights and cable departure angles. Each significant wave height has a corresponding peak period for young sea-states. Various wave directions have also been applied. For each of these cases, including one with a cross swell, a high correlation between chute velocity and tension loss is observed. The high correlation makes it plausible to utilize the chute velocity as a design limit for operability.

The chances of exceeding the compression prediction based on regular chute motions, have been modelled by use of regression analysis. Due to the variation in the data, an allowable value of $v_a = 0.82$ should be used to reduce the risk of exceeding the linear trend of $v_a = 0.99$ to 1%. It should be noted however that this is a very conservative assumption as an exceedance of the prediction interval does not necessarily have to occur for values of C above 1. There is a larger probability that an exceedance of the interval takes place for sub critical compression numbers.

In section 9.2 the results of one irregular motion analysis without direct wave loads show a very promising picture. Without the direct wave loads, the regular motion analysis performs as a near perfect prediction of compression. This is promising for the future as the cable often enjoys shielding from waves, since most cable installation work is performed with bow on wave conditions. The interaction between waves, vessel and shielding of the cable is however regrettably not part of this thesis.

Another remark on direct wave loads is that in order to find lots of data points on the edge of operability, sea states were used that are normally far from workable. It may be possible that for the more moderate sea states in which cable installation is normally performed, the direct effects that the waves have on the cable are less profound.

With the precise benefit of shielding unknown, a large safety factor in the allowable axial velocity is needed. Further research is needed to find these interactions as well as to find motion based limits for other limiting load cases.

If these interactions can be quantified well, the method of determining operability based on vessel motions may have the following advantages:

- Effectively, with a found relation between vessel motions and cable loading: The cable configuration is now decoupled from the wave loading. This makes it possible to compare various vessels for a given project rather quickly. As only the vessel response needs to be analysed, which can be performed in the frequency domain.
- Another major benefit is the possibility to assess the operability live whilst in the field. Motion response data of the vessel can be used direct without the need for parameterized sea-states or estimation of the wave characteristics by the crew.

There are also some possible drawbacks to the proposed method of operability assessment:

- Out of plane motions of the chute lead to a large overestimate of the compression. This is not considered to be a major problem as it is conservative and the vessel is often loaded with bow on conditions. However, it is still a loss of operability. Further research on the effects of out of plane motions may be needed to refine the model.
- The proposed method has only been tested for a limited amount of load cases. The accuracy may differ for other cables, water depths and pre-tensions.

Despite these possible drawbacks, the found relation between vessel motions and cable compression may prove to be a valuable tool in the near future. It is in the best interest to the industry to further investigate this relation. As in the end, a better understanding of cable response, especially live in the field, will result in less cable damage and a higher workability rate.

11 CONCLUSIONS & RECOMMENDATIONS

The following conclusions have been drawn in the scope of this thesis:

Current method of operability analysis:

- The most limiting cable integrity check is the minimum tension. Although it is not always clear how much submarine power cables can be compressed before their integrity is compromised, cable manufacturers are often reluctant to allow significant cable compression.
- The assumption that the largest cable loads are always present during the highest waves is not true.
- It is shown that cable loading is underestimated by simulating only a part of the 3-hour sea-states. Errors may arrive that are unacceptable. Although one could argue that this is countered by other assumptions such as the idealization and stationarity of the sea states. No direct safety factor is applied to cover this known fault.

Relation between vessel motions and cable integrity:

- The vessel and cable dynamics are uncoupled. The effect that the cable has on vessel motions is negligible.
- It is concluded that the dynamics of submarine power cables are governed by drag.
- Tension loss in the cable originates from fluid drag. Depending on the velocity that the cable obtains through the water, free falling may occur in which the weight of the cable is carried by the drag. Resulting in loss of tension.
- Cable compression is a result of both fluid-drag and cable-inertia. When sufficient slack is introduced, parts of the cable sink towards the seabed. When the seabed stops the cable, compression occurs. This effect is more profound when a larger segment of cable reaches free fall velocity. For this to occur, the chute of the vessel must also have a large downward velocity.
- For regular vessel motions it is shown that the velocity by which the chute moves in the axial direction of the cable, has a direct relation with the amount of tension loss. And hence with cable integrity when compression is a concern.
- There is a maximum amount of compression that can occur for a given cable configuration. This is dependent on the catenary configuration and the mass of the cable.
- The relation between chute velocities and tension loss also holds for irregular vessel motions resulting from irregular wave spectra, although direct wave loads have a severe influence on the accuracy.
- With an appropriate safety margin, it is possible to predict cable compression based on vessel motions for shallow water cable installation.
- Operability limits based on vessel motions have two distinct advantages:
 - Real time operability assessment can be performed in the field, supporting the crew in decision making.
 - Flexibility in analysis is obtained since the cable response becomes independent of vessel and sea-state. Being able to perform operability assessment studies in the frequency domain will make a significant difference for cable installation analysis.

The following recommendations are made:

To improve the current method of operability analysis:

- In the near future, cable manufacturers may start to increase the compression limits on their cables as efficiency can be gained through increased understanding of this phenomena. If over conservatism is thereby removed, it may be imperative to look critically at the faults in reduced time domain simulation.
- A combined operability assessment method based on chute motions and wave spectrum analysis can be beneficial. A few regular motion simulations can quickly give an estimate of the allowable vessel motions. When this is followed up by a series of vessel motion analyses in the frequency domain, the edge of the operable limits is quickly found. The precise limits can then be assessed with fewer time domain simulations. Reducing computational time.

Further research is encouraged for the following topics:

- The proposed method of operability assessment based on vessel motions uses only a single variable: The velocity of the chute in direction of the cable axis. It has been shown that motions of the chute normal to the cable axis have a damping effect on cable compression. Therefore, it may be possible to refine the model further by incorporating the normal velocities as well. This may reduce the overestimation of compression that is found in beam on waves.
- The effects of direct wave loading are significant. Understanding the mechanics of this interaction as well as how the vessel may shield the cable can be a decisive factor for implementing operability limits based on vessel motions.
- Current loads have not been taken into account for this thesis. In general, currents are expected to dampen cable dynamics due to the increased drag. Whether this will always have a positive effect on the risk of compression could be subject to further research.
- Only a limited amount of cable configurations is modelled for this thesis. For very shallow or deep waters, other loading criteria will certainly gain influence. These effects may need to be investigated as well.
- Relationships between vessel motions and other cable limits such as: maximum tension, minimum bending radius or sidewall pressure have not been investigated. Before operability assessments based on vessel motions can be implemented, design limit motions for these and other cable integrity checks will need to be investigated.

12 REFERENCES

1. **VBMS.** *Galloper Offshore Windfarm* . 2014.
2. **European wind energy association.** *The European offshore wind industry key trends and statistics 2015*. 2016.
3. **Kurt, J. P.** *Empirical Factors in the Prediction of Helically Armored Cable Axial Stiffness*. s.l. : ASME, 1984.
4. **DNV GL.** *Guideline for Installation of Rigid and Flexible Pipelines, Umbilicals and Subsea Power Cables – Analyses*. 2015.
5. **Zhimin Tan, Peter Quiggin, Terry Sheldrake.** *Time Domain Simulation of the 3D Bending Hysteresis Behavior of an Unbonded Flexible Riser*. s.l. : ASME, 2009.
6. **DNV GL.** *Guideline for installation of rigid and flexible pipelines, umbilicals and subsea power cables_ Limit state criteria*. 2015.
7. **VBMS & NKT cables.** *Test methodology bending stiffness test*. 2016.
8. **Shibu G, Parthasarathy N.S.** *An insight of torque and stress balance behaviour of a contrahelically armored cable*. London : World Congress on Engineering, 2008.
9. **Ahmed M. Reda, et al.** *Compression limit state of HVAC submarine cables*. s.l. : Applied ocean research, 2016.
10. **Cigré.** *Recommendations for mechanical testing of submarine cables*. 216. ISBN 978-2-85873-326-2.
11. **Boom, H.J.J. van den.** *Dynamic behaviour of mooring lines*. 1985.
12. **Orcina.** *OrcaFlex Manual*. version 10.b 16-06-2016. www.orcina.com.
13. **M., Chung J. and Hulbert G.** *A time integration algorithm for structural dynamics with improved numerical dissipation: The generalized alpha method*. s.l. : ASME Journal of Applied Mechanics, 1993.
14. **GL Noble Denton.** *General Guidelines for Marine Projects 0001/ND*. 2014.
15. **DNV GL.** *Environmental conditions and environmental loads*. 2014. DNV-RP-C205.
16. **Holthuijsen, L. H.** *Waves in oceanic and coastal waters*. 2007. ISBN 978-0-521-12995-4.
17. **al., Hasselmann et.** *Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP)*. 1973.
18. **J.I.Gobat.** *The dynamics of geometrically compliant mooring systems*. 200.
19. **F.M. Dekking, C. Kraaikamp, H.P. Lopuhaa, L.E. Meester.** *A modern introduction to probability and statistics*. s.l. : Springer, 2005.
20. **Morison J R, O'Brien M D, Johnson J W, and Schaaf S A.** *The force exerted by surface waves on piles*. s.l. : AIME Petrol Trans, 1950.
21. **Keulegan, G.H. Carpenter, L.H.** *Forces on Cylinders and Plates in an Oscillating fluid*. s.l. : Journal of Research of the National Bureau of Standards, 1985.
22. **Journee, J.M.J. Massie, W.W.** *Offshore Hydromechanics First Edition*. s.l. : Delft University of Technology, 2001.
23. **Polderdijk, S.H.** *Response of Anchor Lines to Excitation at the top*. Amsterdam : Elsevier, 1985.
24. **Engineering Toolbox.** [Online] 28 November 2016. http://www.engineeringtoolbox.com/sea-water-properties-d_840.html.

25. ESDU. *ESDU 80025: Mean forces, pressures and flow field velocities for circular cylindrical structures: Single cylinder with tow dimensional flow*. London : s.n.

APPENDIX A GLOSSARY OF TERMS

AC	Alternating current
CLV	Cable Laying Vessel
CFD	Computational Fluid Dynamics
DC	Direct current
Hockle	To damage cordage by twisting against the lay
MBR	Minimum bending radius
LCE	Linear Cable Engine
RAO	Response Amplitude Operator
VBMS	VolkerWessels Boskalis Marine Services
RAO	Response Amplitude Operator
ROV	Remotely Operated Vehicle
TDP	Touch Down Point

Appendix B Nomenclature

A	Cable cross-sectional area	[m ²]
a	Catenary shape parameter	[-]
A _c	Contact area	[m ²]
a _f	Local fluid acceleration with respect to the earth reference system	[m/s ²]
a _r	Fluid acceleration relative to the cable segment	[m/s ²]
C	Compression number	[-]
C _{crit}	Critical damping	[Ns/m]
C _a	Added mass coefficient for the cable segment	[-]
C _d	Drag coefficient for normal motion of the cable segment	[-]
D	Diameter of the cable	[m]
D _{crit}	Critical cable diameter for bottom friction	[m]
E	Young's modulus	[N/m ²]
F	Total force applied on a cable segment at a given time	[N/m]
F _b	Buoyancy force per meter cable	[N/m]
F _d	Fluid drag force per meter cable	[N/m]
F _g	Gravitational pull per meter cable	[N/m]
g	Gravitational constant 9.81 m/s ²	[m/s ²]
H	Water depth	[m]
H _s	Significant wave height	[m]
K _s	Shear stiffness of the soil which is normally set to 100.000	[kN/m/m ²]
L	Suspended line length	[m]
L ₀	Un-stretched length of catenary	[m]
m	Dry cable mass per meter	[kg]
m _s	Weight in seawater	[kg]
r	Motion amplitude	[m]
p	Motion period	[s]
R	Contact reaction force	[N]
T _{max}	Max safe working tension	[kN]
T _{min}	Minimum tension	[kN]
T ₀	Static touchdown tension	[kN]
T _p	Peak period	[s]
T _{top}	Top tension	[kN]
u	Magnitude normal displacement	[m]
v	Order of normal velocities	[m/s]
v _a	Chute velocity in cable axial direction	[m/s]
v _l	Chute velocity in lateral cable	[m/s]
v _r	Fluid velocity relative to the body	[m/s]
v _t	Transverse wave velocity	[m/s]
y _c	Local movement of cable element in the cable's y axis	[m]
γ	Peak enhancement factor for JONSWAP wave spectra	[-]
Δ	Mass of displaced fluid by the cable	[kg]
ΔT _D	Dynamic tension loss	[kN]
ΔT _{D,Fall}	Dynamic tension loss found in highest fall interval	[kN]
ΔT _{D,Rise}	Dynamic tension loss found in highest rise interval	[kN]
ε _c	Cable axial strain	[-]
θ	Wave direction	[deg]
μ	Kinematic viscosity (4°C)	Ns/m ²]
μ _f	Friction coefficient 0.5 for axial motions, 1.0 for lateral to include bulldozing effect.	[-]
ρ _w	Sea water density	[kg/m ³]
ω	Frequency	[rad/s]
φ	Cable departure angle measured from vertical	[deg]

APPENDIX C DERIVATION OF CATENARY EQUATIONS

The coordinate system from Figure 45 is used to derive the necessary equations that will define the catenary shape.

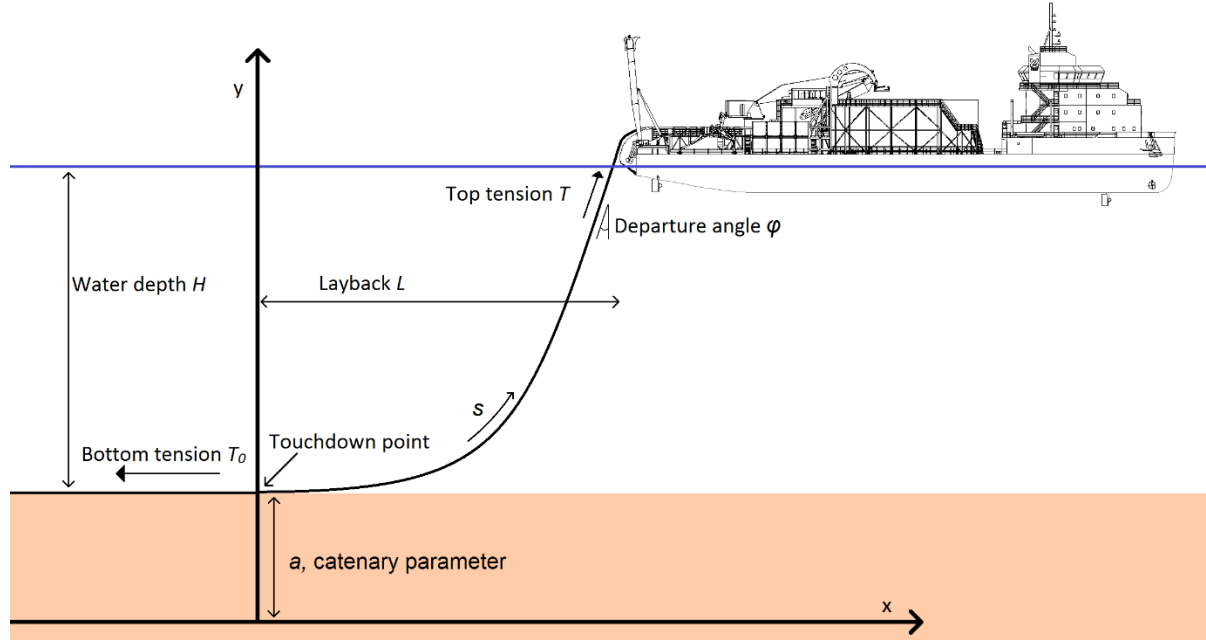


Figure 45 Catenary shape

In the stationary regime, there must be an equilibrium of forces. The sum of the horizontal forces gives us:

$$T \cos(\varphi) = T_0 \quad (C.1)$$

The vertical force equilibrium is obtained by substituting λg as the submerged weight of the cable:

$$T \sin(\varphi) = \lambda g s \quad (C.1)$$

Dividing these equations gives us:

$$\frac{dy}{dx} = \tan(\varphi) = \frac{\lambda g s}{T_0} \quad (C.2)$$

Here a is defined as the catenary shape parameter.

$$\frac{dy}{dx} = \frac{s}{a} \quad \text{with: } a = \frac{T_0}{\lambda g} \quad (C.3)$$

The formula for arc length is:

$$\frac{ds}{dx} = \sqrt{\left(\frac{dy}{dx}\right)^2 + 1} = \frac{\sqrt{a^2 + s^2}}{a} \quad (C.4)$$

Which allows:

$$\frac{dy}{ds} = \frac{dy}{dx} \frac{dx}{ds} = \frac{s}{a} \frac{a}{\sqrt{a^2 + s^2}} = \frac{s}{\sqrt{a^2 + s^2}} \quad (C.5)$$

This differential equation can be integrated to:

$$y = \sqrt{a^2 + s^2} + \beta \quad (\text{C.6})$$

For which β can be set to 0 by shifting the origin of the x-axis.

(C.4) is integrated with respect to s, to obtain:

$$x = a \sinh\left(\frac{s}{a}\right) + \alpha \quad (\text{C.7})$$

Where again, α can be set to 0 by shifting the y-axis, obtaining:

$$x = a \sinh\left(\frac{s}{a}\right), s = a \sinh\left(\frac{x}{a}\right) \quad (\text{C.8})$$

Equation (C.6) and (C.8) combined result in:

$$y = a \cosh\left(\frac{x}{a}\right) \quad (\text{C.9})$$

The catenary is now expressed by the hyperbolic cosine and catenary shape parameter: a .

APPENDIX C REDUCED SIMULATION TIME VALIDATION

The following table contains the full results of the reduced simulation time validation. The percentages show the percentage of missing in the used simulation interval for each individual case. A [-] means that the maximum was found which means that the selected interval contained the maximum ΔT_D was found.

Case	ΔT_D	Hi rise	Hi fall	Chute rise	Chute fall	Chute RV	Chute FV	Hi/Lo Rise	Hi/Lo Chute	Chute V
1	8.21	-	-	-	-	-	-	-	-	-
2	8.12	0.8%	1.4%	0.8%	1.4%	1.4%	1.4%	0.8%	0.8%	1.4%
3	8.13	1.6%	0.7%	1.1%	1.1%	0.8%	0.8%	0.7%	1.1%	0.8%
4	8.21	1.4%	1.4%	1.4%	3.6%	-	-	1.4%	1.4%	-
5	8.22	2.9%	2.9%	1.4%	2.0%	2.0%	2.0%	2.9%	1.4%	2.0%
6	8.12	0.8%	1.2%	1.0%	1.0%	1.0%	1.0%	0.8%	1.0%	1.0%
7	8.32	2.2%	1.3%	1.3%	-	1.3%	1.3%	1.3%	-	1.3%
8	8.29	6.4%	3.9%	3.2%	0.5%	0.5%	0.5%	3.9%	0.5%	0.5%
9	8.33	1.0%	4.3%	1.2%	1.2%	1.2%	1.2%	1.0%	1.2%	1.2%
10	8.40	5.6%	-	3.0%	3.0%	4.2%	4.2%	0.0%	3.0%	4.2%
11	8.30	4.0%	2.4%	0.7%	0.7%	0.7%	0.7%	2.4%	0.7%	0.7%
12	8.40	-	2.9%	-	3.0%	-	-	-	-	-
13	8.41	7.1%	7.1%	0.5%	0.5%	2.6%	2.6%	7.1%	0.5%	2.6%
14	8.81	-	9.3%	3.5%	3.5%	3.5%	3.5%	-	3.5%	3.5%
15	8.76	5.5%	-	6.6%	1.8%	1.8%	1.8%	-	1.8%	1.8%
16	13.09	2.1%	55.9%	-	-	-	-	2.1%	-	-
17	10.84	-	9.6%	16.5%	16.5%	16.5%	16.5%	0.0%	16.5%	16.5%
18	10.88	1.4%	1.4%	-	11.7%	3.3%	3.3%	1.4%	-	3.3%
19	8.56	2.8%	2.8%	7.9%	6.0%	-	-	2.8%	6.0%	-
20	8.67	10.0%	10.0%	-	8.2%	-	-	10.0%	-	-
21	8.72	1.7%	10.0%	-	-	-	-	1.7%	-	-
22	14.89	18.3%	36.7%	-	12.5%	12.5%	12.5%	18.3%	-	12.5%
23	16.77	38.6%	-	-	-	-	-	-	-	-
24	15.63	7.3%	-	7.3%	7.3%	7.3%	7.3%	-	7.3%	7.3%
25	15.90	7.0%	3.5%	4.5%	4.5%	3.3%	3.3%	3.5%	4.5%	3.3%
26	16.40	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%
27	16.58	-	9.3%	-	-	-	-	-	-	-

average:

2.5%	2.1%	2.6%
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compression cases

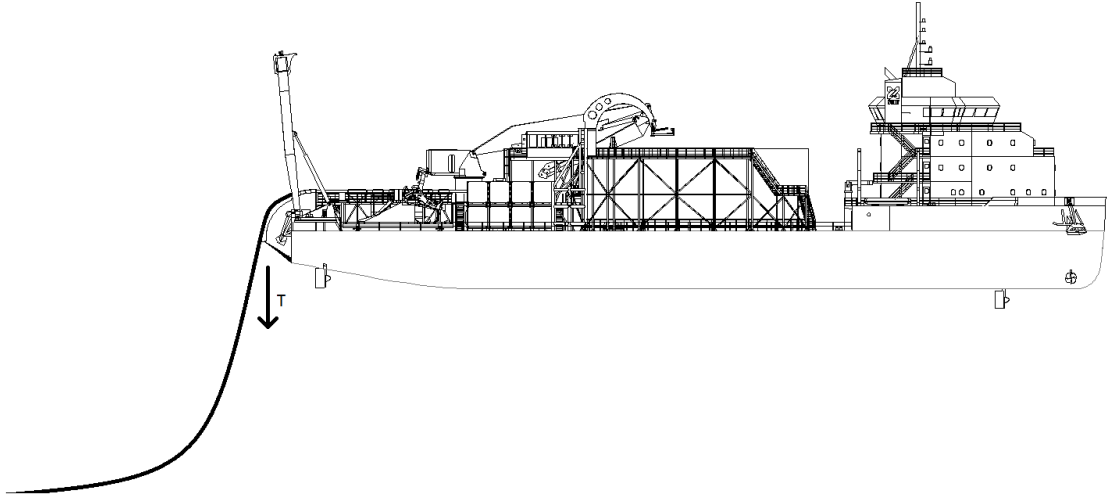
4.6%	3%	5%
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standard deviation

4.0%	3.6%	4.0%
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APPENDIX D VESSEL MOTION INDEPENDENCE

To allow decoupling of vessel and cable motions, it must be proven that the forces in the cable do not significantly influence the motions of the vessel. To compare the orders of magnitude, the vessel moment of inertia in the pitch direction is compared to the maximum moment that the cable can apply.



To simplify the calculation, the ship is modelled as a rod with equal mass distribution over its length.

$$I_{ship} = \frac{1}{12}ml^2 = \frac{9.81 * 12285000 * 44.5^2}{12}$$

$$I_{ship} \approx 1.98 * 10^{10} [kgm^2]$$

Length over all	99 m
Breadth	30 m
Design draught	4.8 m
Displacement	12.285 tons
Cable max safe working load	12 tons

$$I_{cable} = mr^2 = 12 * 9.81 * 1000 * 44.5^2 \approx 2.33 * 10^8 [kgm^2]$$

It is shown that the moment of inertia that the cable provides around the centre of the ship's mass is about 36 times smaller than the ships own moment of inertia. It is therefore safe to say that the motion of the ship is not significantly influenced by the cable tension.

APPENDIX E OTHER HYDRODYNAMIC PARAMETERS

Normal Hydrodynamic loading

The combinations of cable motion, wave particle velocity and currents create water velocities relative to the cable. These can be split into velocities normal and parallel to the axis of the cable. The forces that these relative velocities exert on the normal direction of a stationary cylinder can be described by the semi empirical Morison equation (E.1) ref: (20) .

$$F = \rho C_m V \dot{v} + \frac{1}{2} \rho C_d A v |v| \quad (E.1)$$

OrcaFlex© uses a modified Morison equation (E.2) ref: (12) to incorporate the local motions of the cable segments as well. This equation is used to calculate the hydrodynamic loads on each cable node for every time step.

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

The parameters are:

F	=	total force applied on a cable segment at a given time [N/m]
Δ	=	mass of displaced fluid by the cable [kg]
a_f	=	local fluid acceleration with respect to the earth reference system [m/s ²]
C_a	=	added mass coefficient for the cable segment [-]
a_r	=	fluid acceleration relative to the cable segment [m/s ²]
ρ_w	=	the water density in [kg/m ³]
C_d	=	drag coefficient for the cable segment [-]
A	=	drag area or displaced volume per m length [m ²]
v_r	=	fluid velocity relative to the body [m/s]

Normal drag dominance

The Morison equation consist of two parts: The inertia forces that are imposed by the mass of the displaced fluid plus the added mass. And the drag forces which are proportional to the velocity squared. The relative importance of the drag and inertia terms can be quantified by use of the dimensionless Keulegan Carpenter number (21) (E.3) In which y_c is the cable displacement amplitude and D the diameter of the cable.

$$KC = 2\pi \frac{y_c}{D} \quad (E.3)$$

As an estimate of the cable displacement amplitude, the maximum lateral displacement of the sag bend from section 0 of $y_c = 1.9\text{m}$ is taken. The chosen cable has a diameter of 0.121m which results in a KC value of:

$$KC = 2\pi \frac{1.9}{0.121} = 98.66 [-] \quad (E.4)$$

With the drag force being dominant for KC values greater than 45, (22) it is safe to conclude that the normal hydrodynamic loads on the cable are dominated by drag when the excursions are 1.9m.

Magnitude of hydrodynamic damping forces

A dimensionless length κ can be calculated to indicate the magnitude of the damping forces (23). When κ is larger than unity, the damping forces are relatively large and the response is of a heavily damped dynamic character. In the following example, the same typical cable configuration is used: $H=28\text{m}$, $\phi=40^\circ$.

$$\kappa = \frac{L}{\lambda} \quad \text{with } \lambda = \sqrt{\frac{T_{top}}{k_d u \omega^2}} \quad (\text{E.5})$$

$$k_d = \frac{1}{2} \rho D C_d \quad (\text{E.6})$$

L	=	suspended line length	60 m
T _{top}	=	top tension	13 kN
u	=	magnitude normal displacement	2m
ω	=	frequency	0.7 rad/s
ρ_w	=	density of surrounding fluid	1025 kg/m ³
D	=	diameter of the cable	0.121m
C _d	=	drag coefficient of the cable	0.99 [-]
v	=	order of normal velocities	1.5 m/s
μ	=	kinematic viscosity (4°C)	0.00467 Ns/m ² (24)

The example parameters lead to a κ value of 4.09 [-], which shows that the expected dynamic cable response is indeed of a heavily damped character for normal motions.

Axial Hydrodynamic loading

The axial hydrodynamic loading is much less significant when compared to lateral loading. As the cable is continuously prismatic, the added mass in axial direction can be set to zero. The axial hydrodynamic loading therefore exists from skin friction only.

OrcaFlex© advises the following values for axial drag: for subcritical flow ($Re < 3.8E5$), the axial drag coefficient for a smooth cylinder is 0.008 [-]. Whilst for a rough cylinder it can be set as 0.011[-]. These values are obtained from the database of the ESDU (25).

The axial velocity of the cable is expected to be a significant contributor to compression in the touchdown area. Therefore, it is conservative to take a lower value of axial drag. The value for a smooth cylinder of 0.008[-] is used for further simulations.

APPENDIX F FULL RESULTS OF IRREGULAR VESSEL MOTION ANALYSIS

The following combinations of cable departure angle and irregular sea-state have been investigated:

ϕ	H_s	θ	page:
40°	4m	180°	61
40°	4m	150°	62
40°	4m	90°	63
40°	3m	150°	64
30°	4m	150°	65
30°	3m	150°	66
30°	3m + Gaussian cross swell	150°	67

