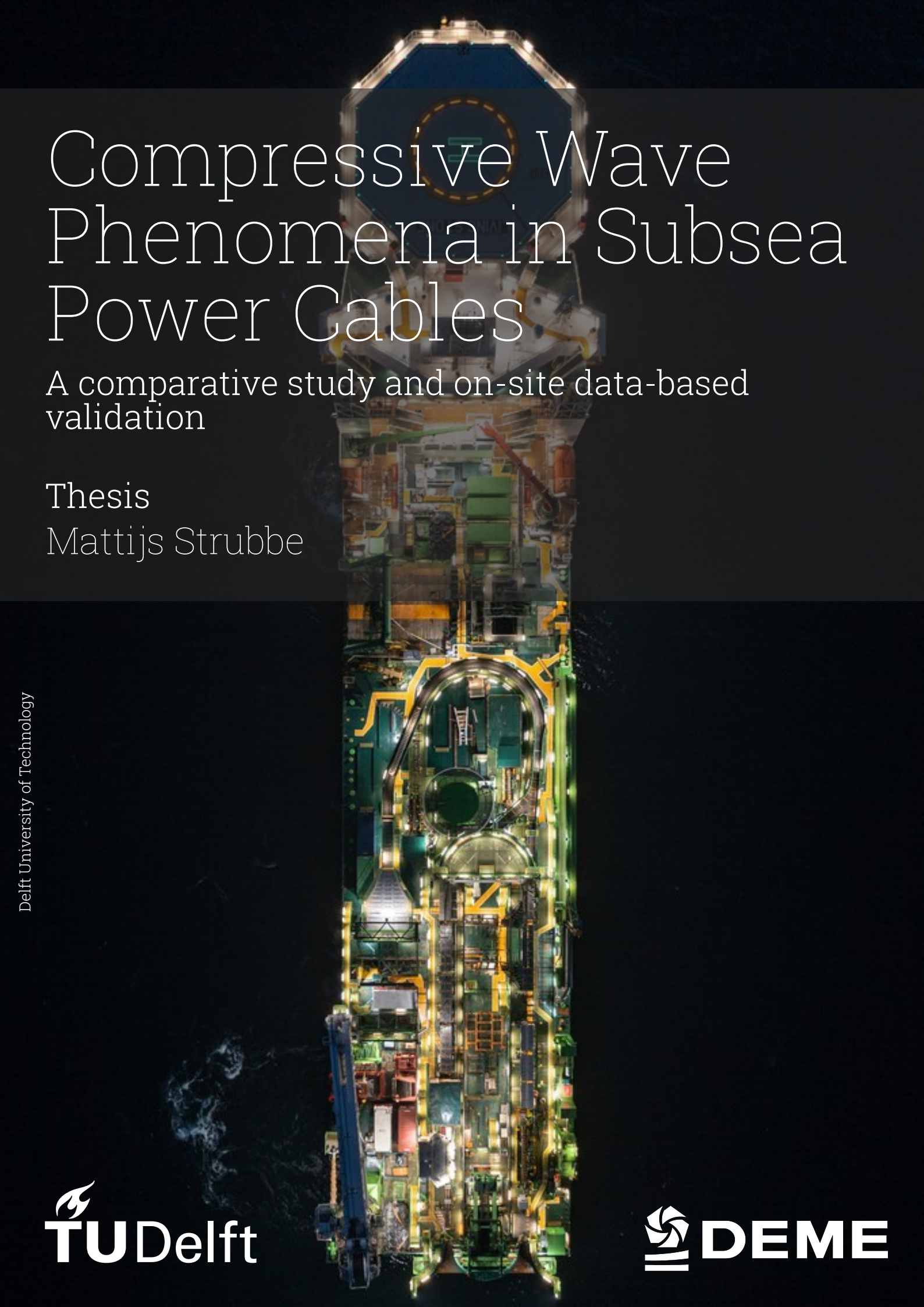




Compressive Wave Phenomena in Subsea Power Cables

A comparative study and on-site data-based validation

Thesis

Mattijs Strubbe

Thesis for the degree of MSc in Marine Technology in the specialisation
of Ship and Offshore Structures

Compressive Wave Phenomena in Subsea Power Cables

By

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Abstract

This thesis examines the occurrence and interpretation of compressive wave phenomena in subsea power cables during normal lay operations, with a focus on addressing a central uncertainty in the field. In current industry practice, the compressive behaviour predicted by numerical cable-lay simulations is frequently regarded as a limiting factor for installation, however, a significant research gap remains regarding whether these compressive waves correspond to actual physical cable responses or are merely artefacts of modelling assumptions. Accordingly, the primary aim of this research is to clarify this gap by evaluating whether the compressive waves observed in OrcaFlex simulations can be substantiated as phenomena that occur during normal lay operations.

To address this question, a comparative modelling, verification, and field-data assessment approach is adopted. First, the theoretical possibility of axial compression is demonstrated using a simplified Kirchhoff rod formulation, showing that time-dependent transverse excitation can induce compressive forces near the touchdown region. Subsequently, a Python-based finite element model is developed to capture both static and dynamic cable responses and is compared with OrcaFlex simulations. The validation strategy proceeds stepwise: starting with analytical catenary theory, followed by static verification across multiple cable types, and finally dynamic comparison using measured operational input data.

This thesis investigates the occurrence and interpretation of compressive wave phenomena in subsea power cables during installation operations. In industry practice, the compressive behaviour predicted by numerical cable-lay simulations is often treated as a limiting factor, although it remains unclear whether these compression waves reflect a physical cable response or are partly due to modelling assumptions. The objective of this research is therefore to assess whether the compressive waves observed in OrcaFlex simulations correspond to phenomena that can occur during normal lay operations.

To address this question, a comparative modelling, verification, and field-data assessment approach is adopted. First, the theoretical possibility of axial compression is demonstrated using a simplified Kirchhoff rod formulation, showing that time-dependent transverse excitation can induce compressive forces near the touchdown region. Subsequently, a Python-based finite element model is developed for both static and dynamic cable response and is compared with OrcaFlex simulations. The verification strategy proceeds stepwise: starting with analytical catenary theory, followed by static validation across multiple cable types, and finally dynamic comparison using measured operational input data.

The simulations are driven by manufacturer cable data and operational data obtained from DEME's cable-lay vessel Living Stone, including vessel motion data from Grafana and onboard sources, as well as ROV observations of the touchdown region. Within the simplified Python model, vessel motions are translated into chute boundary motions, allowing measured operational data to be applied to the cable model in a controlled manner. And the touchdown point is added as an extra boundary condition to verify the catenary shape.

However, an important limitation of this approach is that no sufficiently complete dynamic field dataset was available for the specific severe conditions in which compressive waves are observed in OrcaFlex. As a result, the Python model could only be verified for relatively mild or near-static conditions, and not for a measured case in which the suspected compressive-wave behaviour occurred. Consequently, the combined Python model and vessel data approach is not sufficient on its own to fully answer the main research question.

For that reason, an additional tension analysis is carried out using recorded cable-lay data. Time periods corresponding to normal lay operations are selected and screened based on the availability of reliable tensioner measurements. Particular attention is given to tension peaks, irregularities, and intervals in which negative tension values are observed, as these may indicate conditions relevant to compressive behaviour. These selected cases are subsequently analysed in OrcaFlex using the appropriate vessel motions and cable properties, while the corresponding ROV footage is reviewed in parallel to investigate whether any visually observable compressive behaviour can be identified.

The tensioner-selected cases did not show clear travelling compressive waves in the corresponding OrcaFlex simulations. Although several cases contained irregular or negative tensioner readings, these did not develop into sustained regions of axial compression near the touchdown point. This indicates that negative tensioner values should not be interpreted directly as evidence of compressive-wave behaviour in the suspended cable span, since the tensioner measurement represents a differential force across the onboard tensioner system rather than the true top tension of the free-hanging cable.

Because the project-data-based cases did not reproduce compressive waves, an additional parameter-variation study was conducted. The bending stiffness, touchdown point location, and imposed chute motion were varied to investigate which factors can trigger the phenomenon. The results show that changing the bending stiffness or touchdown point location mainly influences the local cable response but does not, in itself, generate travelling compressive waves. The imposed chute motion, and especially the resulting chute velocity, was found to be the dominant trigger. Compressive waves were only reproduced when the imposed boundary motion became sufficiently dynamic.

The thesis, therefore, combines theoretical analysis, numerical model development, validation, tensioner-based case selection, and parameter variation to investigate compression in subsea power cables from multiple perspectives. The results show that compressive waves were not observed in the analysed normal lay operations. However, the phenomenon cannot be entirely ruled out as physically possible under more severe dynamic excitation. The main conclusion is that the available project data were not dynamic enough to reproduce compressive waves. At the same time, the numerical parameter study indicates that sufficiently high chute velocity can trigger the phenomenon. Further validation requires complete operational datasets from more dynamically severe installation conditions.

Preface

I have not failed. I've just found 10,000 ways that won't work.

- Thomas A. Edison -

Although this project did not result in the solution I initially expected, it provided something equally valuable: a deeper understanding of the problem itself. Along the way, I learned that not every question leads to a clear answer and that challenging assumptions can be as important as finding solutions. This experience has strengthened my approach to tackling complex problems and taught me to value the insights gained throughout the process, regardless of the outcome.

I can extend this conclusion to my studies in Delft. I have tried out a lot of things and discovered what suits me and what doesn't. And it is with this mindset that I intend to approach my studies in the coming year.

During my Master's studies, many people have contributed to this journey, and I am deeply grateful to all of them. If you are reading this, there is a good chance that you are one of those people. Nevertheless, I would like to mention a few in particular.

First, I would like to thank my fellow students, who not only listened to my occasional complaints but also reminded me that the challenges and uncertainties of the graduation process are shared by everyone. Knowing that others were facing similar struggles provided both comfort and perspective.

I am also grateful to my family, who always believed in me. This gave me the confidence to keep going, and to my friends, who encouraged me to get out and enjoy life whenever I needed it most.

I would like to thank my colleagues at DEME for their support, insights, and good company throughout my internship. Our discussions provided many enjoyable breaks and a welcome reminder that, regardless of where we come from, there truly is no place like home.

Finally, I would like to express my sincere gratitude to my supervisors for their guidance, constructive feedback, and valuable insights throughout this project.

Mattijs Strubbe
Delft, July 2026

Summary

Subsea power cables are a critical part of offshore wind farm infrastructure. During installation, these cables are exposed to a combination of static and dynamic loads, including submerged weight, bending, seabed contact, hydrodynamic loading, and vessel-induced motion. In cable-lay simulations, axial compression is sometimes predicted near the touchdown point. In some cases, this compression appears as a travelling compressive wave. Since compression may become a limiting factor in project workability assessments, it is important to understand whether these waves represent real cable behaviour during normal lay operations or whether they are mainly caused by modelling assumptions in numerical simulations.

The objective of this thesis is to investigate whether compressive waves observed in OrcaFlex simulations can also be related to realistic cable behaviour during normal subsea power cable installation. To address this question, the research independently develops and applies a comprehensive methodology, including original theoretical analysis, the construction of a tailored numerical model, verification against OrcaFlex benchmarks, project-data-driven dynamic simulations, targeted tensioner data analysis, and an in-depth parameter variation study.

First, the theoretical possibility of axial compression in a cable-like structure is investigated. A simplified Kirchhoff rod formulation is used to show that time-dependent transverse excitation can introduce axial compression when the deformation is constrained. This result demonstrates that compression is mechanically possible and should not be dismissed beforehand. However, the theoretical proof only shows that compression can occur under simplified conditions. It does not prove that the compressive waves observed in cable-lay simulations also occur during real installation operations.

A Python finite element model is then developed to provide an independent modelling framework next to OrcaFlex. The model is built in two stages. The static model calculates the equilibrium cable shape under submerged weight, axial stiffness, bending stiffness, and seabed interaction. This static configuration is then used as the initial condition for the dynamic model, which includes inertia, hydrodynamic drag, added mass, seabed contact, and prescribed boundary motion at the chute.

The static Python model is first verified against an analytical catenary solution. Under simplified conditions, with negligible bending stiffness and high axial stiffness, the finite element model reproduces the analytical catenary shape. After this, the model is compared with OrcaFlex for realistic static cable configurations. The reference comparison shows good agreement in global cable shape, with an RMSE of 0.185 m and a maximum deviation of 0.282 m. Additional cable types are also evaluated to assess the robustness of the static model. These comparisons show that the Python model is suitable for representing the global static cable configuration, although its accuracy decreases for cases where local bending and contact behaviour become more dominant.

The dynamic model is subsequently used to investigate time-dependent cable response. Instead of modelling the full vessel and its response amplitude operators, measured vessel motions are translated into vertical chute motion. This chute motion is imposed as the upper boundary condition of the cable. When ROV data is available, the ROV position is used as an approximation of the touchdown point location. This approach allows measured operational data to be included in the numerical model while keeping the model relatively simple and computationally efficient.

However, the available project data introduces an important limitation. The selected operational cases mainly represent normal lay conditions with relatively mild dynamic excitation. Several cases also lack

complete ROV data, which limits the possibility of validating touchdown point behaviour directly. As a result, the Python model can be validated for calm or near-static conditions, but not for a measured severe dynamic case in which compressive waves occur. This means that the available project data is not sufficient on its own to fully confirm or reject the occurrence of compressive waves in reality.

Because the project-data-based dynamic assessment did not reproduce compressive waves, the research is extended with a tensioner analysis. Eleven operational cases are selected based on tension peaks, irregular tensioner behaviour, and intervals where the measured tension signal becomes negative. These cases are analysed in OrcaFlex using the corresponding cable properties and measured vessel motions. In parallel, available ROV footage is reviewed to check whether any visible compressive behaviour can be identified near the touchdown region.

The tensioner analysis shows that negative or irregular tensioner readings do not automatically indicate axial compression in the suspended cable span. The tensioner measurement represents a differential force across the onboard tensioner system, rather than the true top tension of the free-hanging cable behind the vessel. It is affected by both the deployed cable and the built-up tension in the cable highway. Therefore, tensioner irregularities are useful for identifying interesting operational events, but they cannot be interpreted directly as evidence of compressive waves.

The OrcaFlex simulations of the selected tensioner cases do not show clear travelling compressive waves. Some local reductions in effective tension and limited local compression are observed, but these do not develop into sustained or propagating compression waves near the touchdown point. The ROV footage also does not provide visual evidence of compressive-wave behaviour in the selected operational cases. This indicates that the analysed normal lay operations do not contain sufficient dynamic excitation to trigger the phenomenon.

As a final step, a parameter variation study is performed to investigate which modelling parameters may trigger compressive waves. The bending stiffness, touchdown point location, and imposed chute motion are varied separately, followed by a combined variation. The bending stiffness variation shows that very low bending stiffness can lead to limited local compression, but it does not independently generate a travelling compressive wave. The touchdown point variation shows a similar result. Moving the touchdown point changes the global catenary shape and local force distribution, and extreme touchdown point locations can create local compression, but no clear propagating wave is formed.

The strongest influence is found in the imposed chute motion. A sinusoidal vertical chute motion is applied, and the amplitude is varied while the period remains constant. Increasing the amplitude also increases the maximum chute velocity. The results show that, once the imposed chute motion becomes sufficiently dynamic, compressive waves can be reproduced in the numerical model. This indicates that chute velocity is the dominant trigger among the investigated parameters. Bending stiffness and touchdown point location influence the local cable response, but they do not appear to initiate compressive waves without sufficient dynamic boundary excitation.

The combined variation confirms this conclusion. A boundary motion case close to the compression threshold is selected, after which the bending stiffness and touchdown point location are modified. Although this leads to some local compression on the seabed, no travelling compressive wave develops. This confirms the conclusion that static configuration changes alone are not sufficient to trigger the phenomenon.

The main conclusion of this thesis is that compressive waves were not observed in the analysed project-data-based cases or in the selected normal lay operations. The available operational data was not dynamic enough to reproduce the phenomenon. At the same time, compressive waves cannot be fully excluded as a physical possibility under more severe dynamic excitation. The theoretical proof and parameter variation study show that compression and compressive-wave behaviour can occur in numerical models when the imposed boundary motion is sufficiently strong.

Overall, the results indicate that compressive-wave formation is predominantly governed by dynamic factors, with imposed chute velocity identified as the principal trigger. Bending stiffness and touchdown point location primarily affect the cable's response after compression has been initiated, rather than serving as primary causes. This finding carries significant practical implications for both simulation practices and operational planning: installation scenarios that involve rapid or unanticipated

chute motions may present elevated risks for compressive-wave initiation, whereas standard configurations with lower dynamic excitation appear less susceptible. To translate these research insights into practical guidance for cable installation and risk management, further validation is necessary using complete operational datasets acquired under more dynamically severe installation conditions. Such datasets should include synchronised vessel motion, chute motion, tensioner measurements, ROV observations, lay speed, and environmental parameters, thereby enabling a more robust assessment of when compressive-wave phenomena genuinely pose operational or integrity risks.

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Nomenclature

Abbreviations

Abbrev.	Definition
2D	Two-dimensional
3D	Three-dimensional
CIGRE	International Council on Large Electric Systems
DEME	Dredging, Environmental and Marine Engineering
DOF	Degree of Freedom
DP	Dynamic Positioning
DP3	Dynamic Positioning Class 3
DNV	Det Norske Veritas
EA	Axial stiffness, defined as Young's modulus multiplied by cross-sectional area
EI	Bending stiffness, defined as Young's modulus multiplied by second moment of area
FE	Finite Element
FEM	Finite Element Method
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
MBR	Minimum Bending Radius
MRU	Motion Reference Unit
MWS	Marine Warranty Survey
OD	Outer Diameter
OIM	Offshore Installation Manager
RAO	Response Amplitude Operator
RMSE	Root Mean Square Error
ROV	Remotely Operated Vehicle
SOG	Speed Over Ground
SPC	Subsea Power Cable
TDP	Touchdown Point
TP	Transition Piece
XLPE	Cross-linked Polyethylene

Symbols

Symbol	Definition	Unit
A	Cross-sectional area	m^2
a	Acceleration or imposed motion amplitude, depending on context	m/s^2 or m
a_c	Catenary constant	m
$b_{\max}$	Maximum vertical acceleration amplitude	m/s^2
B_{up}	Buoyant force per unit length	N/m
C_a	Added mass coefficient	–
C_D	Drag coefficient	–
C_L	Lift coefficient	–
C_m	Inertia coefficient	–
d	Diameter / cable outer diameter	m
d_a	Axial drag diameter	m
d_n	Normal drag diameter	m
D	Cable outer diameter	m
E	Young's modulus	Pa
EA	Axial stiffness	N
EI	Bending stiffness	Nm^2
EI_1	Bending stiffness in the first curvature regime	Nm^2
EI_2	Bending stiffness in the second curvature regime	Nm^2
F	Generic force	N
F_b	Buoyancy force	N
F_d	Drag force	N or N/m
F_f	Friction force	N
F_g	Gravity force	N
F_i	Inertia force	N or N/m
F_n	Normal reaction force	N
g	Gravitational acceleration	m/s^2
H	Horizontal tension component in catenary formulation	N
H_s	Significant wave height	m
I	Second moment of area	m^4
K	Stiffness matrix / tangent stiffness matrix	N/m
K_b	Bending stiffness coefficient	Nm^2
K_e	Axial stiffness coefficient	N
K_{eff}	Effective stiffness matrix in the dynamic solution procedure	N/m
K_s	Shear stiffness	N
k_{bot}	Seabed penalty stiffness	N/m
k_n	Normal contact penalty stiffness	N/m
L	Total cable length	m
l	Node or segment length	m
ℓ_i	Current length of cable segment i	m
ℓ_0	Reference or undeformed segment length	m
m	Mass per unit length	kg/m
m_{eff}	Effective mass, including structural and added mass	kg
m_{seg}	Structural mass of a cable segment	kg
$m_{a,\text{seg}}$	Added mass of a cable segment	kg
M	Bending moment	Nm
N	Axial force or number of nodes, depending on context	N or –
P	Wave or imposed vessel/chute motion period	s
p	Wet proportion in OrcaFlex line model	–
q	Vector of nodal degrees of freedom	m
$\dot{q}$	Nodal velocity vector	m/s
$\ddot{q}$	Nodal acceleration vector	m/s^2

Symbol	Definition	Unit
R	Bend radius or residual vector, depending on context	m or N
R_c	Contact, drag, and friction contribution to the residual	N
R_{ext}	External force vector	N
R_{int}	Internal force vector	N
s	Arc length along the cable	m
T	Total tension	N
T_0	Bottom tension	N
T_d	Dynamic tension component	N
T_i	Axial tension in cable segment i	N
T_{min}	Minimum axial tension along the cable	N
T_s	Static tension component	N
t	Time	s
u	Axial displacement	m
v	Transverse displacement or velocity component, depending on context	m or m/s
v_n	Normal velocity component	m/s
v_r	Relative fluid-structure velocity	m/s
v_z	Axial velocity component	m/s
V	Vertical force component in catenary formulation	N
w	Submerged weight per unit length	N/m
w_{net}	Net submerged weight per unit length	N/m
x, y, z	Global coordinates	m
x_A	Horizontal position of the chute / upper boundary point	m
z_A	Vertical position of the chute / upper boundary point	m
x_B	Horizontal position of the lower boundary or ROV-based TDP estimate	m
z_B	Vertical position of the lower boundary / seabed elevation	m
x_p	Penetration depth into the seabed contact model	m
Δl	Change in length / axial deformation	m
Δs	Reference segment length in the FE discretisation	m
Δt	Time step	s
α	Lift decay or interpolation factor, depending on context	–
β	Newmark-beta integration parameter	–
γ	Newmark-beta integration parameter	–
ϵ	Axial strain	–
κ	Curvature	m^{-1}
κ_{trans}	Transition curvature between bending stiffness regimes	m^{-1}
λ	Transition factor for hydrodynamic coefficient variation	–
μ	Friction coefficient	–
ρ	Fluid density	kg/m^3
ω	Angular frequency of imposed sinusoidal motion	rad/s

Chapter 1

Introduction

(Disclaimer)

During the preparation of this work, the author used Copilot and DeepL to assist with the LaTeX layout and translations (Dutch → English). After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the publication's content.

DEME is a world leader in the highly specialised fields of dredging, marine engineering and environmental remediation. Although DEME's activities originated with the core dredging business, the portfolio diversified substantially over the decades, including solutions for the offshore energy market. For the renewables customers, DEME Offshore provides flexible and tailored solutions, including foundation/-turbine Transport & Installation, cable installation and Operations & Maintenance activities up to full Engineering, Procurement, Construction and Installation (EPCI) contracts.

The subject of this thesis is related to DEME's cable installation activities and completed from the Breda office. Throughout the cable installation team's projects, there are several recurring phenomena that is not fully understood. This is the basis for the start of this thesis. Axial stress modelling is a key component for DEME's offshore arm, and the industry by extension. To better understand the knowledge surrounding this stress, solving this thesis is an important first step. This thesis examines compression waves in simulations in detail. In this literature review, previously conducted research, and the structure of the thesis are presented.

1.1 Subsea Power Cable Modelling

Offshore cable installation is carried out by a cable installation vessel. The cable is led from a drum through a cable highway, then through a tensioner and chute into the water. It will be free hanging in between the chute and the seabed, and over this length it will be exposed to waves, currents and vessel motions. A systematic view is shown in Figure 1.1. Before cable installation, each project must be simulated in a virtual environment. This is done in OrcaFlex. In this environment, various boundary conditions are set. Properties are assigned to the vessel, cable, and the environment in which the cable is located, just as in the project environment. These include environmental factors, waves (significant height and period, direction), current, depth and seabed properties. Different vessels respond to waves in specific ways. For this reason, it is important to set specific boundary conditions for vessel responses in waves (RAOs) once. Finally, cable properties must also be clearly specified. This includes the cable's geometry and its different stiffnesses [16].

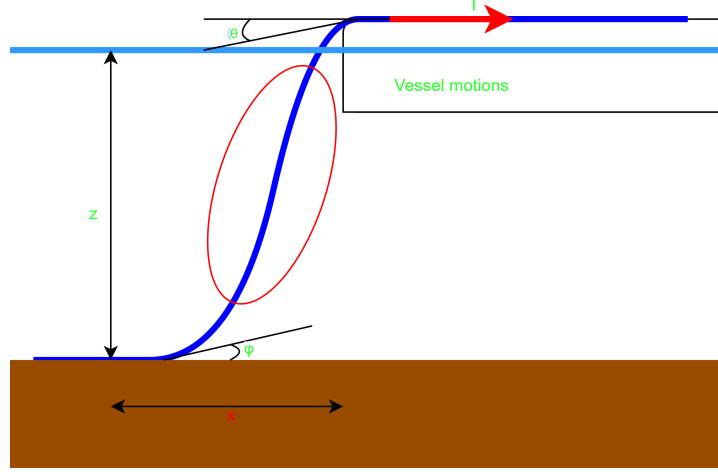


Figure 1.1: Cable laying diagram with known variables (green) and unknown variables (red)

1.2 Research Motivation

Compression modelling is a scarcely discussed topic in academic reports. There are gaps in knowledge and in guidelines for modelling this compression truthfully. Especially since, in many cases, compression is a limiting factor for the industry in both simulations and projects [30]. In simulations, compression is observed, it is not certain whether it occurs in reality. And so are examples of compression failures during projects [6], such as birdcaging or buckling, which are difficult to model in a virtual environment. For this reason, every step toward better understanding compression is an important step for the offshore industry.

1.3 Problem Statement

Tension is often reported extensively for Subsea Power Cables (SPCs). However, it should be clear that compression and tension are distinct load types in SPCs because they act on different layers. The recommendations made by the International Council on Large Electric Systems (CIGRE) rely on cable properties based on tensile tests. Compression-based tests are not prescribed; quantifying limits and cable properties under compressive loading is uncertain [3]. It can be assumed that the values under compression are conservative, but in certain circumstances, this can be a limiting factor.

Maximum compression often appears to be a limiting factor in these normal lay simulations. However, several academic reports show that this compression is not uniformly modelled today ([13], [30], [28]) and needs further research. Different cable manufacturers provide different limits/determine cable properties in different ways. Simulations based on these cable properties create a compression wave in certain situations, as shown in Figure 1.2. It is not clear whether these compression waves are a real phenomenon or a simulation error. For this reason, this thesis has been drafted and examined to see if this can be investigated.

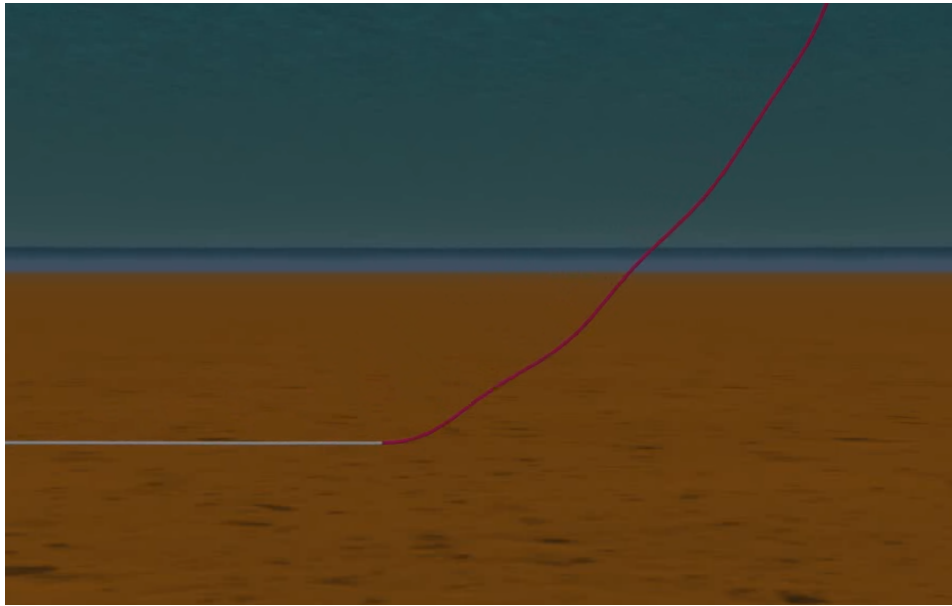


Figure 1.2: A compression wave occurring during critical lay operations

1.4 Research Goal

Determining whether this phenomenon is real is a first step toward accurately modelling cable compression. Based on the results of this research, follow-up studies can be conducted. The thesis focuses on determining whether this compression-wave phenomenon is real or can be excluded from consideration when assessing project workability.

This question would be addressed in different ways. First, compression would be modelled theoretically in a simplified way. Following this, a comparative study would be carried out between OrcaFlex and an FE method. The differences will be examined here to determine why this is the case. Emphasising that both OrcaFlex and the FE Model could contain errors in the simulations. Ultimately, reality would be mimicked by attaching dynamic boundary conditions to the simulations. By running simulations based on these boundary conditions, reality should be approximated.

Chapter 2

Literature Review

2.1 Subsea Power Cable Mechanics

An important part of offshore wind farms is the cables that connect them to each other, the offshore substation and to the mainland. Before these cables are installed, they must undergo several analyses. A normal lay analysis is an important part of this. This analysis is conducted before a project begins. This allows validation that the cable can be laid without damage and specifies the exact weather conditions under which this is possible. To make this simulation representative, a good model is essential. This starts by having a good working method. That is why a static analysis is often carried out first. Once this has been converted into a solution, it can be moved on to a dynamic solution. Furthermore, many factors must be considered in the model. These are discussed in the following sections.

2.2 Mechanical Mechanisms Relevant to Compression

Many different forces affect cables. In an initial model, all relevant static forces for normal lay operations are taken into account. In this way, a realistic starting position for a dynamic model can be obtained. Additional loadings are included in the dynamic model.

2.2.1 Static and Dynamic Loading

The static model is based on a tolerance. All external forces acting on the nodes must remain below a specified tolerance. When this value approaches zero, the system can be assumed to be in equilibrium. A 2D model is assumed. The following formulas are used to translate this into reality.

$$\sum F_x = 0$$

$$\sum F_z = 0$$

Once the static model has reached equilibrium, the configuration must be saved. Subsequently, a motion can be introduced, with two effects. New forces will act on the system and must be integrated into the model. The accelerations will also affect the system's behaviour. These must also be integrated. As a result, the force equilibrium that applied to the static model will change.

The static cable configuration is obtained by enforcing force equilibrium at every node of the discretised cable model. In the present 2D formulation, the static equilibrium can be written in vector form as

$$F_g - F_b + F_k + F_M + F_n + F_f = 0 \quad (2.1)$$

where $\mathbf{F}_{g/b}$ is the submerged weight contribution (gravity and buoyancy combined), $\mathbf{F}_{ax}$ is the axial elastic force, $\mathbf{F}_M$ is the equivalent nodal force resulting from bending stiffness, $\mathbf{F}_n$ is the seabed normal contact force, and $\mathbf{F}_f$ is the seabed friction force. For nodes not in contact with the seabed, $\mathbf{F}^n$ and $\mathbf{F}^{fr}$

vanish. The static solution is reached when the residual force vector $\mathbf{R}^{\text{stat}}$ falls below the prescribed tolerance.

Once the static equilibrium configuration has been established, the cable's dynamic response is obtained by including inertia and time-dependent loading effects. The governing equation of motion for the discretised cable can be written as

$$F_g - F_b + F_k + F_M + F_n + F_f + F_d = F_a \quad (2.2)$$

where $\mathbf{M}_{\text{eff}}$ is the effective mass matrix, including both structural mass and added mass, $\ddot{\mathbf{q}}$ is the nodal acceleration vector, and $\mathbf{F}^{\text{drag}}$ is the hydrodynamic drag force. In the dynamic configuration, the internal cable forces and the seabed interaction are therefore balanced by the cable's inertial response. Time-varying boundary motions, such as the imposed chute motion at the vessel, are incorporated into the model through prescribed boundary conditions and indirectly influence the force terms via the evolving cable geometry, velocity, and acceleration.

Buoyancy and Gravity Forces

Both gravity and buoyancy are important factors when examining the behaviour of a cable. In principle, these should be determined independently. For gravity, the mass per metre is used.

$$F_g = m \cdot g$$

Buoyancy would be based on Archimedes' principle, which is determined on the basis of the amount of water displaced. This is also the reason why these two forces are taken together. Inside the cable, there are cavities that fill with water during installation. This makes it difficult to determine the effective buoyancy.

$$F_b = \rho \cdot V \cdot g$$

The submerged weight is determined by the cable manufacturer and is assumed to be an accurate approximation when the cable is submerged. This is an important condition that must be checked, regardless of whether the cable is submerged.

Axial Elastic Forces

A cable is deformed under tension. The degree of deformation determines the axial elasticity. This is an important factor in determining the cable's shape under both static and dynamic conditions. For this reason, it is important to include this factor in these models. The model assumes linear axial elasticity, with an upper limit beyond which it becomes unreliable. This simplification improves the model's calculation speed.

$$F_k = E \cdot A \cdot \frac{\Delta l}{l}$$

The elastic forces are calculated for every line segment in the model, where Δl is equal to the change in length to the undeformed configuration. E is equal to the Young's modulus and the A the cross-section of the cable [17], [20].

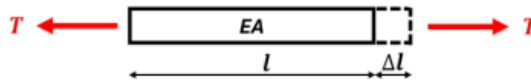


Figure 2.1: Axial loading on a cable [12]

Bending Moment

In addition to axial forces, a subsea cable is subjected to bending due to its curvature. Bending stiffness plays an important role in determining the local shape of the cable, especially near boundaries such as the touchdown point or connection interfaces. Neglecting bending effects may lead to unrealistic sharp angles between adjacent cable segments. The bending moment is related to the cable's curvature and

thus to its bending stiffness. A basic model assumes linear elastic bending behaviour, which is a valid approximation for small curvatures, but for complex cables such as subsea power cables, a nonlinear approach is needed. The bending stiffness is determined by the product of the Young's modulus and the second moment of area. The bending moment is evaluated discretely at each node based on the change in angle between adjacent line segments. In reality, the bending stiffness is determined by the cable manufacturer.

In the model, this moment is converted into forces in the x- and z-directions on the segment. In this way, it can be clearly integrated into both the static and dynamic models by adding it to the force equilibrium used by the models.

$$M = \frac{E \cdot I}{R}$$

Where R is the bend radius of the cable. The resulting bending moment can be converted into bending forces using the cable profile. This ensures that bending effects can be integrated into the tension analysis.

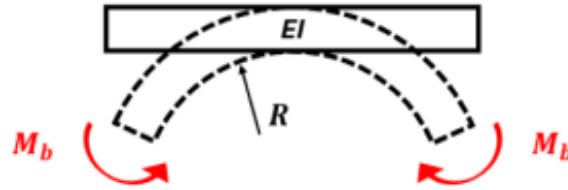
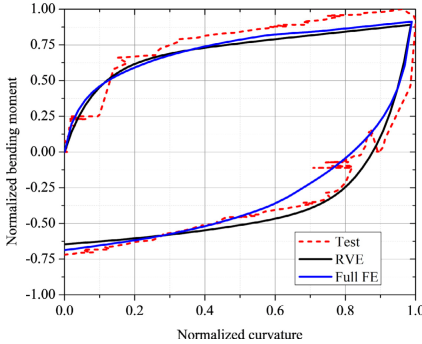
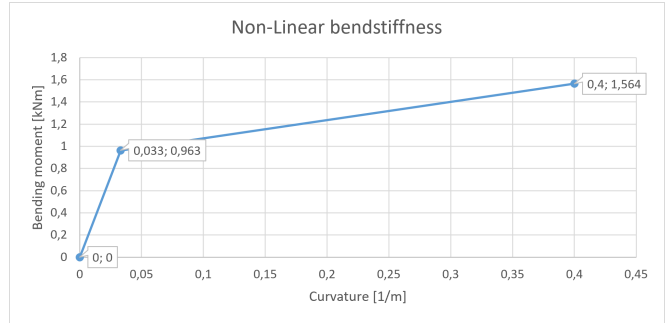


Figure 2.2: Bending stiffness in a cable [12]

However, the bending moment of a cable should not be assumed to be linear. Due to interlayer interactions in the SPC, this bending moment has a hysteresis curve. Because these layers transition from a stick state to a slip state, this curve is created, which is visible in Figure 2.3a. In order to build an accurate model, it is necessary to include this bending moment curve. To do this, cable specifications determined by the cable manufacturer must be used [18], as shown in Figure 2.3a. While in reality the bendingstiffness given by the manufacturers is often simplified, as can be seen in Figure 2.3b.



(a) Normalised hysteresis behaviour [18]



(b) Cable stiffness graph from manufacturer

Figure 2.3: Comparison of hysteresis behaviour and actual cable stiffness given by cable manufacturer

Friction Forces

Friction forces become relevant when the cable is in contact with the seabed. These forces resist relative motion between the cable and the seabed and significantly influence both static and dynamic configurations.

The friction forces are calculated based on the normal forces exerted by the seabed on the subsea power cable. Based on the submerged weight of the SPC, a Coulomb force can be calculated. Where

the maximum friction force is proportional to the normal force through a friction coefficient. The seabed is modelled as a flat plane with a constant friction coefficient.

$$F_f = \mu \cdot F_n$$

Here, μ represents the friction coefficient between the cable and the seabed, and F_n is the normal contact force. The direction of the friction force opposes the direction of relative motion or the tendency to move. This simplified friction model is sufficient for static analyses and captures the resistance from seabed contact without introducing excessive complexity [10].

Type friction	Value (μ)
Static friction	1.0
Dynamic friction	0.85

Table 2.1: Static and Dynamic friction values provided by [10]

Viscous Drag

When the cable is exposed to water motion, viscous drag forces act on its surface. These forces arise due to the relative velocity between the cable and the surrounding fluid and oppose the cables motion. Viscous drag is particularly relevant in dynamic analyses, where currents and wave-induced water particle velocities contribute to the overall force balance. The drag force is modelled per unit length of cable using a quadratic formulation, commonly applied to flow regimes with sufficiently high Reynolds numbers. The force acts in the direction opposite to the relative velocity between the cable and the fluid.

$$F_d = \frac{1}{2} \rho C_d D v_r^2$$

Here, ρ is the fluid density, C_d is the drag coefficient, D is the cable diameter, and v_r is the relative velocity between the cable and the water. The drag coefficient is treated as a constant, representing an average value over the expected range of flow conditions. This simplification allows the drag forces to be included efficiently in the model.

Accelerations

Cable accelerations arise from time-varying forces, such as waves, currents, and changes in boundary conditions. These accelerations introduce inertial forces that must be considered in dynamic simulations. For static analyses, acceleration terms are neglected, as the system is assumed to be in equilibrium. The inertial force at each node is calculated using Newton's second law, based on the nodal mass, and acceleration. The mass consists of both the cable's structural mass and an added mass due to the surrounding water.

$$F_a = m_{\text{eff}} \cdot a$$

where m_{eff} is the effective mass and a is the nodal acceleration. The added mass accounts for the water that is accelerated together with the cable and is treated as a constant fraction of the displaced fluid volume. Including acceleration effects allows the model to capture the cable's dynamic responses and transient behaviour under environmental loading.

Loading Components

SPCs are subjected to many different loadings, as mentioned in section 2.2. These loadings can cause failures in various ways. It is important to properly account for these across the various cable models. However, these do not affect how the cable responds to loading, but do indicate the cable installation limits. All relevant loadings are discussed in this section, which contains the following sections: Maximal Tension, Maximal Axial Compression, Minimum Bending Radius, Maximum Crush Load, Maximum Squeeze Load, Maximum Side Wall Pressure and Maximal Impact.

Maximal Tension

Tension is created by the static weight of the catenary stretching between the cable-laying vessel and the touchdown point, as well as by dynamic forces resulting from the vessel's vertical motion, currents, and waves. The residual ground tension exerted by the cable on the seabed is caused by residual tension, but also by friction between the seabed and the cable. This ground tension T_0 ensures that the cable approaches the seabed, preventing excessive bending. At the same time, however, it is important to ensure that the tension does not become too great. For this reason, cable manufacturers provide a tension/bending envelope indicating the limits within which cable-laying operations must operate. These are shown in Figure 2.4.

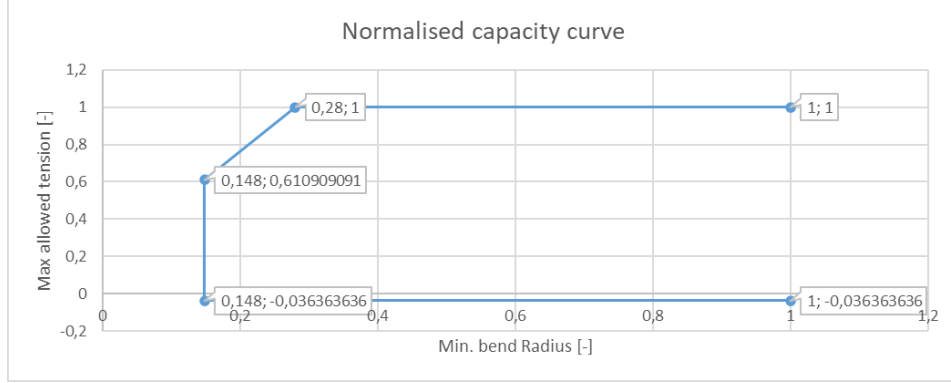


Figure 2.4: Normalised capacity curve for an SPC [9]

To obtain the tension equation, formulae 2.3 and 2.4 are used [34]. When these are summed, the total tension can be estimated.

$$T_s = \sqrt{T_0^2 + w^2 s^2} \quad (2.3)$$

Here, T_s [N] is the static tension, without taking dynamic effects into account. T_0 [N] represents the bottom tension, s [m] is the length of the catenary cable, and w [N/m] is the weight per unit length in water.

$$T_d = m \cdot b_{\max} = m \cdot \left(\frac{h}{2} \cdot \left(\frac{2\pi}{P} \right)^2 \right) \quad (2.4)$$

T_d [N] represents the tension due to dynamic effects. With m [kg] being the mass of the submerged cable and $b_{\max}$ [m/s^2] the maximum acceleration of the cable. [34] calculates the maximum acceleration based on h [m], the vertical amplitude of the cable motion at the vessel chute, and P [s], the period of the vessel motion.

The maximum tension can be calculated by summing the static and dynamic tension components:

$$T = T_s + T_d$$

Maximal Axial Compression Axial compression is a complex load. It is difficult to predict when it will occur, and when it does, it can have fatal consequences for the SPC as can be seen in Figure 2.5 [30], [7], such as birdcaging or buckling. In general, cable manufacturers provide a standard limit of 10 kN [9]. However, it is unclear on what basis this value is determined, and it often constitutes a limiting factor for cable-laying operations. For this reason, industry demands further investigation of this phenomenon and determination of both the occurrence and the effective limits of axial compression, as is done for tension.

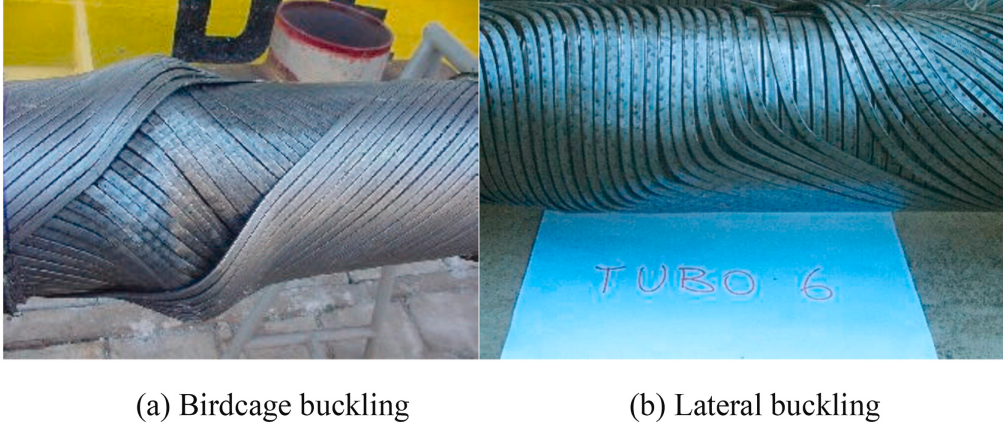


Figure 2.5: Effects of axial compression in SPCs [36]

It is known that factors such as cable weight, vessel movements, and irregularities on the seabed can influence the occurrence of excessive axial compression [30]. In general, bottom tension is maintained during cable-laying operations to minimise the number of compression events. However, compression can still occur in some cases.

Minimum Bending Radius The bending radius is limited by compression and tension. Bending stresses occur throughout various phases of the process. This starts with storing the cable in the drum on board. There are also bends in the cable highway, chute and trencher. Finally, bends may also occur in the cable during laying due to vessel motion and catenary effects. The relief of the seabed is also important. Various limits are set for this. If the bending radius becomes too small, the cable's internal structure can be damaged, compromising its integrity. Various minimum bending radii (MBR) are therefore determined. For example, the minimum bending radius during storage is not the same as the one during installation. Figure 2.4 shows that the higher the tension, the higher the MBR. There is no maximum bending radius, as this can be seen as a straight pull, where the maximum tension/compression indicates the limit [9].

Touch Down Point Dynamics

The touchdown point (TDP), defined as the location where the cable first contacts the seabed, plays a critical role in determining the mechanical and geometric behaviour of a submarine cable during installation. Its local conditions govern the catenary shape, bending loads, tension distribution, and seabed interaction [12].

The TDP is the region of highest combined bending, tension, and compression within the catenary. The bottom tension ensures a smooth approach to the seabed, insufficient bottom tension results in a steep touchdown angle, increasing curvature and raising the risk of axial compression or buckling [12]. Vessel-induced dynamics can enlarge these stresses, as the TDP responds to vertical vessel motion, creating transient peaks in curvature and tension that must remain within allowable limits during installation [12].

Catenary geometry is directly defined by the boundary condition at the touchdown point. The relationship

$$z(x) = \frac{H}{\rho'g} \left[\cosh\left(\frac{\rho'g}{H}x\right) - 1 \right]$$

shows that the TDP determines both the layback length and the touchdown angle. These parameters strongly influence seabed normal force, frictional resistance, and the risk of local cable sliding on the seabed [12]. Since the TDP is also the point of maximum curvature, maintaining the minimum bending radius (MBR) is essential to avoid mechanical damage.

The installation methodology directly influences the mechanical conditions at the touchdown point. Tension control introduces significant differences in tension between cable types, leading to high strap

loads and excessive bending at the TDP. SPCs tension control-MR free produces large compressive forces in the MR cable, making it unworkable. Only individual tension control provides aligned catenary shapes and minimal internal tension imbalance, thereby minimising curvature and twisting at the touchdown point [12].

2.2.2 Subsea Power Cable-Wave/Current Interaction

During installation, a subsea power cable is subjected to hydrodynamic loading from waves and currents. These environmental loads influence the suspended cable span between the chute and the touchdown point. Waves generate oscillatory water particle velocities and accelerations, while currents introduce a more steady flow component. The interaction between these water motions and the cable produces distributed forces along its length, which influence the cable shape, tension distribution, curvature, and dynamic response.

For slender offshore structures such as subsea power cables, the hydrodynamic loading is commonly described using Morison-type formulations. In this approach, the loading consists mainly of a drag component and an inertia component. The drag force is proportional to the relative velocity between the cable and the surrounding water, while the inertia force is proportional to the acceleration of the water particles and to the added mass of the cable. The magnitude of these forces depends on the cable diameter, hydrodynamic coefficients, water density, and the local flow conditions around the cable [16].

Wave-induced loading is strongly dependent on the selected wave theory and the sea-state description. Linear wave theory provides an efficient approximation for small-amplitude waves and is often sufficient when the cable is located sufficiently deep below the free surface. In this case, wave-induced particle motions decay with depth, reducing the direct wave influence on deeper cable sections. However, in shallow water, near the vessel, or during more energetic sea states, non-linear wave effects may become more relevant. These effects can increase local water particle velocities and accelerations, potentially leading to greater dynamic forces on the cable [16].

Currents also contribute to cable loading by creating a steady relative velocity between the water and the cable. This mainly affects the drag force and can alter the equilibrium configuration of the suspended span. In dynamic simulations, the current-induced drag acts together with wave-induced velocities and cable motion. Therefore, the total hydrodynamic response depends on the relative motion between the cable and the surrounding fluid rather than on the environmental flow alone [16].

In the context of this thesis, wave and current interaction is important because hydrodynamic loading can influence the dynamic tension and compression in the cable. Variations in water particle velocity, combined with vessel-induced motion at the chute, can amplify local changes in cable tension and curvature. These effects are especially relevant near the touchdown point, where the cable transitions from a suspended span to seabed contact and where compressive behaviour may occur.

2.2.3 Vessel Motion Induced Loading

In addition to direct hydrodynamic loading on the cable, vessel motions form an important source of dynamic excitation during cable-lay operations. The cable is connected to the vessel through the cable handling system and leaves the vessel at the chute. As a result, motions of the vessel are transferred to the upper boundary of the suspended cable span. These motions can introduce dynamic tension fluctuations, curvature variations, and, under certain conditions, local compression in the cable.

The motion response of a vessel in waves is commonly described by response amplitude operators (RAOs). RAOs describe how a vessel responds to environmental excitation as a function of wave frequency and direction. They are therefore an important input in commercial cable-lay simulations, such as OrcaFlex, where the vessel response is used to determine the motion of the cable departure point. Wave height, wave period, wave direction, current, water depth, and vessel heading all influence the resulting vessel motions [16].

A vessel has six rigid-body degrees of freedom: surge, sway, heave, roll, pitch, and yaw. These motions describe the translational and rotational response of the vessel in waves, as illustrated in Figure 2.6 [8]. Not all of these motions have the same influence on the cable response. For the research question of this

thesis, the vertical motion of the chute is of primary importance, since it directly changes the suspended cable geometry and the dynamic force balance. Heave and pitch are therefore expected to have the strongest influence on the cable tension and compression response [33]. Roll can also contribute when the chute is laterally offset from the vessel reference point, whereas surge, sway, and yaw primarily affect cable response through changes in horizontal position and heading.

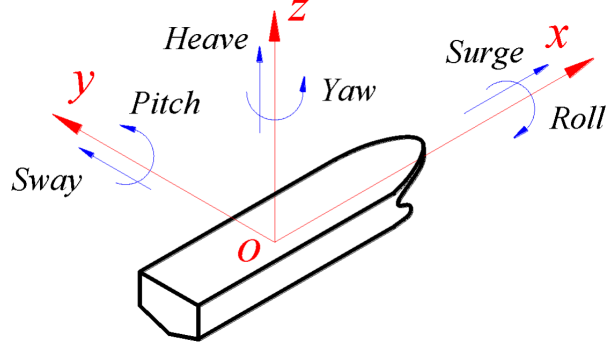


Figure 2.6: Vessel motions [8]

Vessel-induced loading can compromise the cable’s structural integrity when it results in excessive mechanical loads. As discussed in Section 2.2.1, the most relevant cable limits during installation are maximum tension, maximum compression, minimum bending radius (MBR), and side wall pressure. Dynamic vessel motions can affect all of these quantities. For example, upward chute motion may increase cable tension, while downward motion or rapid curvature changes near the touchdown point may contribute to local compression.

In cable-laying operations, the deployed cable also introduces an additional load path between the vessel and the seabed. In principle, the cable can add restoring and damping contributions to the vessel system through its tension, curvature, and dynamic interaction with the environment. However, these effects are generally small compared with the dominant hydrostatic and radiation–diffraction terms that govern the vessel RAOs. Therefore, the vessel motion is usually treated as an imposed input to the cable model rather than being solved as a fully coupled vessel–cable interaction problem [25].

In the Python model developed in this thesis, the full vessel dynamics are not modelled explicitly. Instead, the measured vessel motions are transformed to the vertical motion at the chute location. This derived chute motion is then imposed as a prescribed boundary motion at the upper end of the cable. This approach allows the main vessel-induced excitation to be included in a simplified two-dimensional model, without requiring full RAO-based vessel modelling. It also allows comparing the Python model with OrcaFlex simulations by applying equivalent boundary motions to both models.

2.3 Modelling Approaches

A system that simulates subsea power cables can be set up in various ways. A balance must be struck between speed and accuracy in a model. These SPCs can be modelled quite simply, but this does not benefit accuracy. A highly accurate model will increase computation time. Various modelling options are discussed below, along with the most appropriate model. First, a static simulation is performed to establish an initial equilibrium. Based on this model, the dynamic model is started, and movements and dynamic forces are introduced.

2.3.1 Catenary Theory

A convenient theoretical baseline for cable mechanics is the classical variational formulation of the inextensible catenary. Veseli (2010) presents an elementary but complete derivation of the catenary as the minimiser of gravitational potential energy under a fixed-length constraint. The problem is first

posed in the form:

$$\min_y \mathcal{J}[y] = \rho g \int_0^{x_1} y \sqrt{1 + (y')^2} dx, \quad \text{s.t.} \quad \int_0^{x_1} \sqrt{1 + (y')^2} dx = d,$$

With either fixed-fixed boundary conditions $y(0) = 0$, $y(x_1) = y_1$ or a sliding right end constrained along a line $y = \beta x$, the latter implying an orthogonality condition at the end point [32].

To avoid the complications associated with the variable domain in the sliding-end case, Veselic reformulates the problem in an arc-length parameterisation,

$$x = x(s), \quad y = y(s), \quad (x')^2 + (y')^2 = 1,$$

with $s \in (0, d)$. The functional then reduces to a linear expression in $y(s)$,

$$\mathcal{J}[x, y] = \rho g \int_0^d y(s) ds,$$

subject to the quadratic kinematic constraint above and fixed endpoint conditions. Because the functional is linear and the constraint quadratic, the optimisation problem admits an elementary solution path, including an algebraic proof of the strict global minimality and uniqueness of the resulting catenary shape [32].

Integrating the Euler-Lagrange equations yields closed-form expressions for the optimal curve,

$$x(s) = c_1 \left(\operatorname{arsinh} \left(\frac{s}{c_2} \right) - \operatorname{arsinh} \left(\frac{c_2}{c_1} \right) \right), \quad y(s) = \sqrt{c_2^2 + s^2} - \sqrt{c_2^2},$$

which reduce, after eliminating s , to the classical hyperbolic-cosine representation

$$y(x) = c_1 \frac{\cosh \left(\frac{x}{c_1} + b \right)}{\cosh b},$$

with (c_1, b) determined from the cable length and boundary conditions [32]. The paper provides explicit formulae for both fixed-fixed and sliding-end cases and shows that a unique pair of constants always exists that satisfies the constraint equations.

These analytical results underpin several aspects of our finite-element formulation. First, the constraint $(x')^2 + (y')^2 = 1$ motivates our discretisation strategy in which each element carries a tangent/normal decomposition and an axial strain measure consistent with the continuum arc-length definition. Second, the explicit treatment of boundary conditions (fixed or sliding) parallels the evaluation of end reactions and stiffness matrices in our Newton-based static solver. Finally, in the limit of vanishing bending stiffness $EI \rightarrow 0$, negligible hydrodynamic drag, and no seabed contact, the FE solution must converge to the hyperbolic-cosine catenary. We therefore employ the analytical solution of Veseli as a verification baseline for mesh refinement and solver tolerance studies.

2.3.2 Finite Element Method Modelling

The Finite Element Method (FEM) is a numerical technique for solving boundary value problems in engineering and applied physics. Its fundamental idea is to replace a continuous structure by a discrete model composed of a finite number of interconnected elements. Within each element, the unknown field variables, such as displacement, strain, and stress, are approximated using interpolation (shape) functions. This converts the original differential equations of the continuum into a system of algebraic equations that can be solved numerically [22].

In a typical structural application, the domain is discretised into elements with nodes carrying the degrees of freedom. The displacement field $u(x)$ inside an element is approximated as

$$u(x) \approx \mathbf{N}(x) \mathbf{u}_e,$$

where $\mathbf{N}(x)$ is the matrix of shape functions, and $\mathbf{u}_e$ is the vector of nodal displacements. Strains follow from the spatial derivatives of the displacement field,

$$\boldsymbol{\varepsilon} = \mathbf{B} \mathbf{u}_e,$$

with $\mathbf{B}$ the strain-displacement matrix. Assuming an appropriate constitutive law, stresses are expressed as

$$\boldsymbol{\sigma} = \mathbf{D} \boldsymbol{\varepsilon},$$

where $\mathbf{D}$ is the material stiffness matrix. The principle of virtual work or an equivalent energy formulation then provides the element stiffness matrix,

$$\mathbf{k}_e = \int_{\Omega_e} \mathbf{B}^T \mathbf{D} \mathbf{B} d\Omega.$$

Assembling the contributions of all elements produces the global equilibrium system

$$\mathbf{K} \mathbf{u} = \mathbf{f},$$

where $\mathbf{K}$ is the global stiffness matrix, $\mathbf{u}$ the global displacement vector, and $\mathbf{f}$ the vector of external loads. Appropriate boundary conditions are applied to ensure a unique and physically meaningful solution.

FEM is particularly effective for problems involving geometric complexity, material nonlinearity, large deformations, or multiphysics coupling. Nonlinear problems require iterative solution techniques, commonly the Newton-Raphson method, in which the residual force vector vanishes at equilibrium. At iteration k , the update is obtained from

$$\mathbf{K}_t(\mathbf{u}^k) \Delta \mathbf{u} = -\mathbf{R}(\mathbf{u}^k),$$

with $\mathbf{K}_t$ the tangent stiffness matrix and $\mathbf{R}$ the residual force. The solution is updated iteratively until the convergence criteria are satisfied.

Overall, the strength of FEM lies in its flexibility: it accommodates arbitrary geometries through discretisation, captures detailed stress distributions, and allows the incorporation of complex material laws and contact conditions. For these reasons, FEM is widely used as a reliable tool for analysing the mechanical behaviour of engineering structures under various loading conditions. As mentioned earlier, there is a trade-off between accuracy and speed. With this in mind, different modelling approaches have been developed and discussed in academic papers. In the following subsection, these models will be introduced, along with their advantages and disadvantages.

Mass-Spring Model [19]

The mass-spring model represents a cable as a sequence of discrete mass points $\mathbf{x}_i$ connected by massless springs. The stretching behaviour between two consecutive points, $i-1$ and i , is captured by a linear spring with potential energy

$$E_i^s = \frac{1}{2} k_s (\ell_i - \ell_i^0)^2, \quad (2.5)$$

where $\ell_i = \|\mathbf{x}_i - \mathbf{x}_{i-1}\|$ is the current length and ℓ_i^0 is the rest length. Bending resistance can be introduced via angular springs at each triplet $(i-1, i, i+1)$, giving

$$E_i^b = \frac{1}{2} k_b \beta_i^2, \quad (2.6)$$

where β_i is the angle between adjacent segments. Similarly, torsional resistance may be included by assigning a twisting spring to each segment:

$$E_i^t = \frac{1}{2} k_t \psi_i^2, \quad (2.7)$$

with ψ_i the twist angle of segment i . The total elastic potential energy of the system is

$$E = \sum_i (E_i^s + E_i^b + E_i^t). \quad (2.8)$$

The internal force applied to mass point i follows from the negative gradient of the energy,

$$\mathbf{F}_i = -\frac{\partial E}{\partial \mathbf{x}_i} + \mathbf{F}_i^{\text{ext}}, \quad (2.9)$$

where $\mathbf{F}_i^{\text{ext}}$ includes external loads such as gravity. The motion of each point is governed by Newton's second law,

$$m_i \ddot{\mathbf{x}}_i = \mathbf{F}_i, \quad (2.10)$$

allowing the model to capture stretching, bending, and twisting in a computationally efficient manner. These are all linear variables, making assumptions that oversimplify reality but also creating an efficient model that can solve systems quickly.

Multi-Body Model [19]

The multi-body model extends the mass-spring formulation by replacing point masses with a chain of rigid bodies connected through joints. While the mass-spring model captures stretching, bending, and twisting through abstract springs, the multi-body model embeds these behaviours into physically interpretable rigid segments and joint constraints, providing a more structured representation of cable kinematics.

In this formulation, each cable segment is treated as a rigid link with centre of mass $\mathbf{x}_i$ and orientation R_i . Adjacent links are connected by joints equipped with linear and angular springs. The linear spring between links $i - 1$ and i produces the internal forces

$$\mathbf{f}_i^- = k_L [(\mathbf{x}_{i-1} + R_{i-1} \mathbf{r}_{i-1}) - (\mathbf{x}_i - R_i \mathbf{r}_i)], \quad (2.11)$$

$$\mathbf{f}_i^+ = k_L [(\mathbf{x}_{i+1} - R_{i+1} \mathbf{r}_{i+1}) - (\mathbf{x}_i + R_i \mathbf{r}_i)], \quad (2.12)$$

where k_L is the linear stiffness and $\mathbf{r}_i$ denotes the joint location expressed in the body frame. These forces generalise the axial springs in the mass-spring model by acting through rigid-body transformations instead of point differences.

In addition, bending and twisting resistance arises from angular springs acting on the orientation variables of adjacent links. The torque contributions may be written as

$$\boldsymbol{\tau}_i^L = (R_i \mathbf{r}_i) \times (\mathbf{f}_i^+ - \mathbf{f}_i^-), \quad (2.13)$$

$$\boldsymbol{\tau}_i^A = k_A R_i [\log(q_i^{-1} q_{i-1}) + \log(q_i^{-1} q_{i+1})], \quad (2.14)$$

where k_A is the angular stiffness and q_i is the quaternion associated with R_i . These angular torques serve the same purpose as bending and twisting springs in the mass-spring model but operate on rotational degrees of freedom, enabling a more realistic representation of segment orientations.

In contrast to point-based dynamics, the configuration now evolves according to rigid-body equations of motion that couple translational and rotational accelerations. The model, therefore, automatically preserves segment lengths and represents bending and twisting via explicit joint mechanics rather than additional spring constructs. This makes the multi-body approach more physically interpretable and often more stable, while still maintaining the computational efficiency of a discrete model.

Elastic Rod Model [19]

The elastic rod model describes a cable as a continuous 3D curve endowed with a local material frame, allowing it to represent stretching, shearing, bending, and twisting in a physically rigorous manner. The centerline of the rod is parametrised by arc length s through $\mathbf{r}(s)$, and each cross-section is associated with an orthonormal triad $(\mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3)$, where $\mathbf{d}_3$ coincides with the tangent when shear is neglected. Compared with discrete models such as mass-spring or multi-body formulations, this continuous description captures deformation using strain measures rather than spring approximations.

The extensional and shear strains are defined by

$$m_k = \mathbf{r}' \cdot \mathbf{d}_k, \quad k = 1, 2, 3, \quad (2.15)$$

while bending and twisting are encoded in the Darboux vector $\boldsymbol{\omega}$, satisfying

$$\mathbf{d}'_k = \boldsymbol{\omega} \times \mathbf{d}_k. \quad (2.16)$$

The components of $\boldsymbol{\omega}$ measure curvature and twist of the rod.

The internal force $\mathbf{F} = (F_1, F_2, F_3)^T$ and internal moment $\mathbf{M} = (M_1, M_2, M_3)^T$ follow linear constitutive laws,

$$F_1 = K_s m_1, \quad F_2 = K_s m_2, \quad F_3 = K_e (m_3 - 1), \quad (2.17)$$

$$M_1 = K_{b1} (\omega_1 - \omega_1^0), \quad M_2 = K_{b2} (\omega_2 - \omega_2^0), \quad M_3 = K_t (\omega_3 - \omega_3^0), \quad (2.18)$$

where $K_s = GA$, $K_e = EA$, $K_{b1} = EI_1$, $K_{b2} = EI_2$, and $K_t = GI_3$. The intrinsic curvatures ω_k^0 represent the stress-free configuration.

The total elastic potential energy combines shear, extension, bending, and twisting contributions,

$$U = \frac{1}{2} \int_0^l [K_s (m_1^2 + m_2^2) + K_e (m_3 - 1)^2 + K_{b1} (\omega_1 - \omega_1^0)^2 + K_{b2} (\omega_2 - \omega_2^0)^2 + K_t (\omega_3 - \omega_3^0)^2] ds. \quad (2.19)$$

This continuous formulation significantly expands on the mass-spring and multi-body models by replacing discrete spring forces and joint torques with strain-energy densities derived from continuum mechanics. As a result, the elastic rod model provides a more accurate and physically grounded description of cable deformation, especially for bending and twisting behaviours that are only approximated in discrete models.

Dynamic Spline Model

The dynamic spline model represents the cable's centreline as a smooth spline curve whose control points carry physical degrees of freedom. Instead of discretising the cable into masses or rigid links, the geometry is defined continuously by a parametric curve

$$\mathbf{P}(u) = \sum_{i=1}^n b_i(u) \mathbf{p}_i, \quad (2.20)$$

where $b_i(u)$ are spline basis functions and $\mathbf{p}_i = (x_i, y_i, z_i, \theta_i)^T$ are the generalised coordinates of the control points, including the position and the roll angle of the cross-section. This formulation expands on the elastic rod model by embedding rod mechanics directly into a spline-based geometric representation, thereby reducing the number of degrees of freedom required to achieve a desired accuracy.

Using Lagrangian mechanics, the motion of the spline is obtained from the equation

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{\mathbf{p}}_i} \right) = \mathbf{F}_i - \frac{\partial U}{\partial \mathbf{p}_i}, \quad (2.21)$$

where T is the kinetic energy, U is the potential energy, and $\mathbf{F}_i$ collects all generalised external forces acting on control point i . The energies incorporate stretching, bending, and twisting deformation

through continuous expressions derived from Cosserat rod theory, but applied to the spline geometry rather than to a piecewise discretisation.

Because the spline defines a smooth centerline, deformation energies depend on the derivatives of $\mathbf{P}(u)$ with respect to u , allowing for a geometrically exact treatment of curvature and torsion. This contrasts with mass-spring and multi-body models, where bending and twisting are approximated through discrete springs or hinge torques. The dynamic spline model, therefore, achieves higher geometric fidelity while requiring significantly fewer degrees of freedom to achieve comparable accuracy. This makes it well-suited for real-time simulation of long, slender structures such as cables, catheters, and guidewires.

2.4 Orcaflex Modelling Principles

OrcaFlex is a time-domain modelling tool for global analysis of marine operations, used to simulate the static and dynamic behaviour of flexible structures such as submarine power cable's, risers, and pipelines under wave, wind, current, and seabed interaction. In cablelay applications, vessel motions are typically imposed via RAO's, and environmental conventions follow standard offshore practice. [24]

While widely adopted in industry, OrcaFlex introduces modelling assumptions that can affect fidelity. For example, seabed interaction is often modelled using spring elements, and static simulations typically exclude friction by default, which complicates static-dynamic consistency. OrcaFlex indicates that compression is a problem in dynamic modelling [23].

2.4.1 Line modelling

OrcaFlex models a cable as a finite element line composed of a series of straight, massless segments connected by discrete nodes. Each node represents the meeting point of two half-segments. Except for the end nodes, which connect to only one half-segment and carry all nonaxial physical properties of the line. The fundamental purpose of this discretisation is to capture axial, torsional, and bending behaviours while efficiently applying hydrodynamic, weight, and buoyancy loads along the line [24].

Nodes

Nodes are the primary mass-carrying points in the OrcaFlex line model. Each node represents the two neighbouring half-segments and carries the lumped properties of the line, such as mass, weight, buoyancy, hydrodynamic drag, and added mass. The axial and torsional properties of the line are not lumped at the nodes, these are modelled through spring-damper systems in the connecting segments, as can be seen in Figure 2.7.

Forces and moments are applied at the nodes, including hydrodynamic forces, buoyancy, and added mass, all of which depend on the instantaneous water-surface level for wet-proportion calculations. Weight may be applied with an offset if required. This nodal representation ensures that all external loads are applied consistently at discrete points while the structural behaviour is governed through the connecting segments [24].

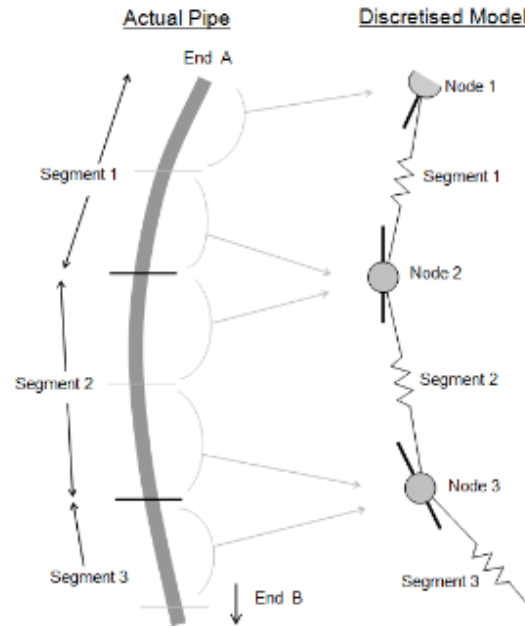


Figure 2.7: Line theory for Finite Element Model OrcaFlex [24]

Segments

Each line segment represents the cable's axial and torsional stiffness as a straight, massless rod. A segment can be visualised as consisting of two coaxial telescoping rods joined through axial and torsional spring-damper elements. These elements provide the effective tension and twist resistance in the line, these are also depicted in Figure 2.7.

Bending behaviour is modelled using rotational spring-dampers at each node. These rotational springs span the interface between the segment's axial direction $\mathbf{s}_z$ and the node's axial direction $\mathbf{n}_z$. This arrangement allows each segment to develop bending moments in two perpendicular planes, enabling the user to prescribe orthogonal bending stiffnesses even if the line lacks axial symmetry.

If torsion is included, a torsional spring-damper at the segment midpoint applies equal and opposite torsional moments to the adjacent nodes. If torsion is disabled, the two half-segments may rotate freely relative to each other, effectively removing torsional stiffness from the line [24].

Spring-Damper Representation

A detailed view of the OrcaFlex line model reveals three principal spring-damper systems that govern its structural response:

- Axial stiffness and damping are represented by an axial spring-damper at the centre of each segment. This element produces equal and opposite effective axial forces at the two segment-end nodes and governs line tension.
- Bending stiffness and damping are represented by rotational spring-dampers at both ends of each segment. These apply nodal bending moments based on the relative rotation between the node direction $\mathbf{n}_z$ and the segment direction $\mathbf{s}_z$.
- Torsional stiffness and damping, if activated, are modelled by a torsional spring-damper at the segment midpoint. This element applies equal and opposite torsional moments to the two associated nodes.

Through these spring-damper systems, OrcaFlex determines the local structural response before assembling global equilibrium equations. The final forces and moments at each node are computed through five internal stages covering tension, bending, shear, torsion, and the resulting total load.

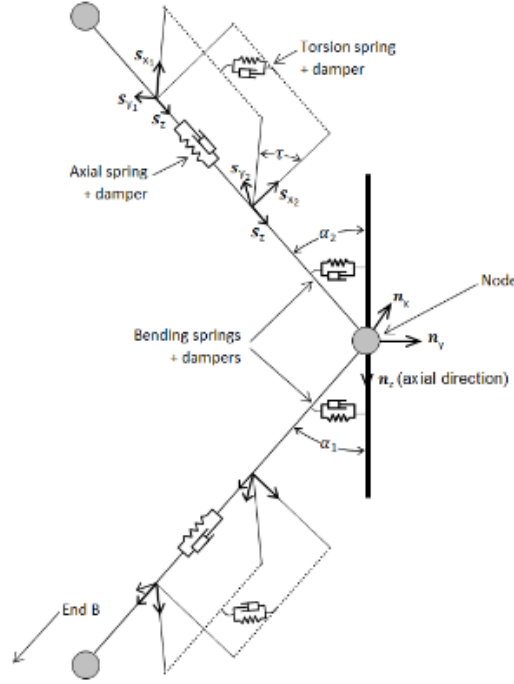


Figure 2.8: Detailed Line Model representation for OrcaFlex [24]

2.4.2 Hydrodynamic Coefficients

The hydrodynamic behaviour of a cable in OrcaFlex is primarily governed by drag, lift, and added mass forces. These forces are applied at the line nodes using Morison-type formulations and depend on the relative velocity between the fluid and the line, the local cable orientation, and environmental conditions. Only hydrodynamic effects are considered unless wind loading is explicitly enabled for the line type, this detailed overview can be seen in Figure 2.8 [25].

Drag

Drag forces in OrcaFlex follow Morison's equation and are applied separately in the two directions normal to the line axis and the direction parallel to the line axis. The relative fluid velocity $\mathbf{v}_r$ is decomposed into normal and axial components,

$$v_n = |\mathbf{v}_r \cdot \mathbf{n}|, \quad v_z = |\mathbf{v}_r \cdot \mathbf{t}|, \quad (2.22)$$

where $\mathbf{n}$ is the normal direction and $\mathbf{t}$ the local tangent of the line.

The standard drag formulation, suitable for most flow conditions, uses direction-dependent drag coefficients C_{Dx} , C_{Dy} and C_{Dz} applies

$$f_{Dx} = \frac{1}{2} p \rho d_n l C_{Dx} v_x |v_n|, \quad (2.23)$$

$$f_{Dy} = \frac{1}{2} p \rho d_n l C_{Dy} v_y |v_n|, \quad (2.24)$$

$$f_{Dz} = \frac{1}{2} p \rho \pi d_a l C_{Dz} v_z |v_z|. \quad (2.25)$$

Here, d_n is the normal drag diameter, d_a the axial drag diameter, l the node length represented, p the wet proportion, and ρ the fluid density.

Drag coefficients may be defined as functions of Reynolds number or height above the seabed. The generalised form for seabed-dependent drag is

$$C_D = \lambda C_{D2} + (1 - \lambda) C_{D1}, \quad (2.26)$$

where C_{D1} and C_{D2} are seabed and freeflow drag coefficients, respectively, and λ is a transition factor depending on the normalised height z_b/d_n [26].

Lift

Hydrodynamic lift arises from transverse flow components and depends strongly on the cable orientation relative to the seabed. The magnitude of the lift force is

$$f_L = p |\mathbf{u}_n \times \mathbf{u}_z| \frac{1}{2} \rho d_n l C_L |v_t|^2 \mathbf{u}_L, \quad (2.27)$$

where v_t is the transverse velocity component, $\mathbf{u}_L$ the lift direction, $\mathbf{u}_n$ the seabed normal, and $\mathbf{u}_z$ the local line axis.

The factor $|\mathbf{u}_n \times \mathbf{u}_z| = \cos \theta$ scales lift according to inclination θ between the line and the seabed. This ensures that the lift force vanishes when the line is vertical and is maximal when it is nearly parallel to the seabed.

The lift coefficient C_L may vary with Reynolds number or with height above the seabed:

$$C_L = \alpha C_{L1}, \quad (2.28)$$

where C_{L1} is the seabed lift coefficient, and α is a decay factor that transitions lift smoothly to zero away from the seabed [26].

Added Mass

Added-mass forces account for the fluid's inertia, which must be accelerated along with the cable. OrcaFlex uses separate coefficients for normal and axial directions: C_{ax}, C_{ay}, C_{az} for added mass, and corresponding added inertia coefficients C_{mx}, C_{my}, C_{mz} .

For constant coefficients, the added mass force follows the Morison inertia term:

$$f_A = C_m \Delta \mathbf{a}_f - C_a \Delta \mathbf{a}_l, \quad (2.29)$$

where Δ is the displaced-fluid mass, $\mathbf{a}_f$ the fluid acceleration, and $\mathbf{a}_l$ the line acceleration relative to the fluid.

Component-wise,

$$f_{Ax} = C_{mx} \Delta a_{fx} - C_{ax} \Delta a_{lx}, \quad (2.30)$$

$$f_{Ay} = C_{my} \Delta a_{fy} - C_{ay} \Delta a_{ly}, \quad (2.31)$$

$$f_{Az} = C_{mz} \Delta a_{fz} - C_{az} \Delta a_{lz}. \quad (2.32)$$

Normaldirection added mass coefficients may also be defined as variable functions of:

- normalised submergence h/s (important near the free surface), or
- normalised seabed height z_b/OD (important near touchdown).

Near the seabed, the variable-coefficient formulation becomes

$$f_{Ax} = C_{mx} \Delta a_{fx} - C_{ax} \left(\frac{z_b}{OD} \right) \Delta a_{lx}, \quad (2.33)$$

with an analogous expression for f_{Ay} . The axial added mass coefficient C_{az} is required to be constant [26].

2.5 Verification of Input Parameters

To validate the numerical and analytical cable-lay models, a set of essential field-derived input parameters must be identified. These parameters ensure that the reconstructed dynamic behaviour and mechanical loads correspond to the real installation conditions. The following subsections describe the most important input values needed to address the research question and enable a reliable comparison between model predictions and field measurements.

2.5.1 Vessel Position, Orientation, and Motions (6 DoF)

Accurate vessel motion data are required to represent the boundary conditions at the cable's upper end. The wave-frequency and low-frequency components of surge, sway, heave, roll, pitch, and yaw directly influence the dynamic tension and departure angle at the chute exit. These motions are typically recorded using the vessel's motion reference unit (MRU), and form the basis for reconstructing the upper boundary kinematics during the lay operation. Also the vessel speed over ground is measured.

2.5.2 Cable Top Tension at the Tensioner

The tension measured at the onboard tensioner is a primary input for validating axial loads in the numerical model. Variations in top tension propagate along the suspended cable span and directly affect touchdown point (TDP) behaviour. High-resolution tension measurements are therefore needed as:

- a boundary condition at the top node,
- a reference for validating dynamic tension levels,
- an indicator of vessel-motion-induced fluctuations.
- subsea power cable lay speed

2.5.3 Layback Distance and Touchdown Geometry

Layback is the horizontal distance between the vessel reference point and the touchdown point. It is typically reconstructed using:

- ROV observations at the TDP,
- vessel positional data (wrt ROV),
- measured water depth.

Correct determination of layback is crucial for validating the numerical model's static catenary shape and seabed touchdown location.

2.5.4 Hydrodynamic Environment: Waves and Currents

The hydrodynamic forcing conditions during the lay operation must be known to reconstruct the environmental loads acting on the cable:

- The significant wave height H_s and peak period T_p define the sea-state energy.
- Directional wave spectra determine heading-dependent vessel motions.
- Current profiles with depth influence drag loading along the suspended cable.

These environmental inputs ensure that the simulated dynamic behaviour matches the actual conditions encountered during installation.

2.5.5 ROV-Based Touchdown Point (TDP) Measurements

ROV footage and sensor data from the TDP provide essential ground truth for validating seabed interactions. These measurements include:

- observed touchdown position,
- cable curvature and lateral movement,
- cyclic motion caused by vessel dynamics and current action.
- depth of the seabed

The comparison between modelled and observed TDP motion is a critical evaluation metric for assessing the realism of the numerical model.

2.6 Industry Standards for Submarine Cable Installation

A number of international standards govern the design, handling, and installation of submarine power cables. These documents define the mechanical behaviour of cables, recommended testing procedures, and the safe execution of marine operations during installation. The most relevant standards for normal lay operations are CIGRE Technical Brochure 623, CIGRE Technical Brochure 669, and DNV-ST-N001.

2.6.1 CIGRE TB 623: Mechanical Handling and Testing of Submarine Cables

The CIGRE 623 document comprises several parts. This document provides a basis for the use of SPCs. It covers topics such as life-cycle use, loading, transport, installation, protection, operations, and repairs. It discusses laying operations and test criteria that cable manufacturers must comply with [3].

On the one hand, CIGRE 623 will issue guidelines for cable operations. The emphasis here is on Normal Lay operations, but shore pulls, joint operations, pull-ins, etc., are also discussed. As mentioned earlier, only guidelines and best practices are discussed here. These can be used to build a model that corresponds to reality. These best practices are based on industry expertise and aim to minimise the risk of cable damage [3].

On the other hand, CIGRE 623 focuses primarily on the test criteria that cables must meet. These tests must represent the conditions in which a cable will be used. This is important because the industry must rely on these test results to perform cable-laying simulations. These, in turn, form the basis for the operational conditions under which a cable-laying vessel may operate. In particular, when certain test criteria are exceeded under specific weather conditions, the ship cannot be operational at that time, as the cable may be damaged [3].

2.6.2 CIGRE TB 669: Thermo-Mechanical Behaviour of XLPE Cable Systems

CIGRE TB 669 focuses on the thermo-mechanical forces in large-conductor-cross-section XLPE cable systems [2]. The document outlines how cable temperature changes induce axial forces, bending stresses, and expansion-contraction cycles during both installation and operation. These aspects are relevant even in standard lay operations when cables transition from seabed-laid conditions to platform-supported or shore-landing environments. It provides guidance on the calculation methods used in different engineering tasks. The relevant formulae are discussed in section 2.2.1.

CIGRE TB 669 distinguishes between rigid, flexible, and transition installation configurations. Rigid configurations rely on fixed cleating or burial, flexible configurations rely on snaking, sagging, or waved geometries to absorb thermal elongation, and transition configurations combine both approaches to control axial thrust at joints and terminations [2].

The report also provides equations for axial thrust, thermal expansion, buckling risk, and bending stiffness (EI) in various installation layouts. These insights directly influence allowable bending radius, cleat spacing, and mechanical design margins in routine cable-lay operations. These, however, are industry guidelines. There is some overlap between what CIGRE expects and what the industry does. Ultimately, a classification agency must approve a project before it can be launched. But again, all these different parties overlap throughout projects.

2.6.3 DNV-ST-N001: Marine Operations and Marine Warranty Requirements

DNV-ST-N001 is the primary international standard governing marine operations related to offshore installation, including the cable-lay process [11]. It defines the operational envelope, safety requirements, and engineering documentation needed for approval under a Marine Warranty Survey (MWS).

The standard covers:

- planning and engineering of marine operations,
- vessel and equipment requirements, including DP capability and positioning,

- environmental limits for weather-restricted and unrestricted operations,
- load-out, transport, towage, and offshore installation procedures,
- route surveys, protection methods, and post-lay intervention,
- monitoring, inspections, and acceptance criteria for subsea products.

During normal lay operations, DNV-ST-N001 serves as the overarching framework for implementing the mechanical recommendations of CIGRE standards. While CIGRE defines the mechanical behaviour and handling limits of the cable, DNV-ST-N001 ensures that offshore operations are planned and performed in accordance with recognised safety levels and industry good practice.

2.6.4 Synthesis of Standards in Normal Cable-Lay Operations

Together, CIGRE TB 623, CIGRE TB 669, and DNV-ST-N001 represent the dominant reference framework for the engineering and execution of standard submarine cable-lay operations. TB 623 identifies mechanical risks, handling constraints, and required testing, TB 669 describes the thermo-mechanical forces and behaviour of large XLPE cables during installation and operation, and DNV-ST-N001 governs the marine operational safety, environmental criteria, vessel requirements, and MWS approval process.

Normal lay operations therefore rely on the interplay between:

- Cable mechanical limits (CIGRE 623),
- Thermo-mechanical behaviour of XLPE systems (CIGRE 669), and
- Marine operational safety and installation assurance (DNV-ST-N001).

The reviewed standards provide important limits for cable handling and marine operations, but they do not fully resolve how transient compressive waves in dynamic cable-lay simulations should be interpreted. This leaves uncertainty in whether simulated compression should be treated as a physical design constraint or as a possible modelling artefact.

2.7 Research Gap

After conducting this literature review, a clear view emerged for executing the thesis and answering the research question. Also, a general outline of how the research will be conducted is provided.

2.7.1 Research Gap

Compression modelling is a scarcely discussed topic in academic reports. There are gaps in knowledge and in guidelines for modelling this compression truthfully. Especially since, in many cases, compression is a limiting factor for the industry in both simulations and projects. In simulations, compression is observed, but it is not certain whether it occurs in reality. And so are examples of compression failures during projects [6], birdcaging or buckling, where it is difficult to model this failure in a virtual environment. For this reason, every step toward better understanding compression is important for the offshore industry.

OrcaFlex has already raised the issue. However, an adjustment to cable properties was proposed, but this is not a viable solution [23]. Furthermore, it is also unclear when a compressive failure criterion is reached. In some cases, birdcaging occurs, but this is also rarely discussed in the existing literature. A first step towards understanding the problem is to investigate whether it actually occurs, hence the urgency of research on this topic [30].

2.7.2 Research Hypothesis

The hypothesis for the research question is as follows:

Compressive waves are not observed during subsea power cable lay operations, but they are observed in OrcaFlex due to the simplified input values provided by the cable manufacturers. Furthermore, OrcaFlex is an overly simplified version of what actually happens in reality.

2.7.3 Research Questions

The main research question is as follows:

Are the compressive waves in Subsea Power Cables observed in OrcaFlex simulations a phenomenon that represents cable behaviour during normal lay operations?

To answer the main research question, several subquestions should be answered:

1. Do the OrcaFlex static results match the Analytical, Python model and MakaiHeave model results?
2. Do the OrcaFlex dynamic results of a base case match the Python model with project data input and MakaiHeave model results?
3. Do the OrcaFlex dynamic results of the compressive wave case match the Python model with project data input and MakaiHeave model results?
4. Can the compressive waves be observed throughout the different simulations?

Chapter 3

Theoretical Basis for Compression in Cables

3.1 Assumptions/simplifications

A cable is modelled as a sequence of N nodes connected by elastic elements that provide both axial stiffness EA and bending stiffness EI , as mentioned in subsection 2.2.1. This discretisation is known as the classical Kirchhoff rod model, as $N \rightarrow \infty$ and the element length decreases [27]. The Kirchhoff rod formulation explicitly includes axial strain, bending curvature, and internal forces, thereby allowing both tensile and compressive axial forces. However, this alone does not show the relevance of compressive forces in a cable-laying simulation. We therefore demonstrate that a time-dependent transverse motion induces compressive forces near the touchdown point in a Kirchhoff rod model. This is a simplification of the cable-laying process, but it remains representative of motions that also occur during the compressive wave phenomena observed in OrcaFlex simulations. It should be noted that this does not prove whether the compressive-wave phenomenon necessarily appears in reality.

3.2 Theoretical Proof

Consider a slender elastic cable modelled as a Kirchhoff rod with axial stiffness EA and bending stiffness EI [27]. The setup of this theoretical proof can be seen in Figure 3.1. The left end and the rest of the cable are simply supported, while the left end is subjected to a prescribed transverse displacement

$$v(0, t) = v_0(t), \quad (3.1)$$

while the right end is fully fixed, and thus no displacement or rotation is possible,

$$v(L, t) = 0, \quad v_x(L, t) = 0. \quad (3.2)$$

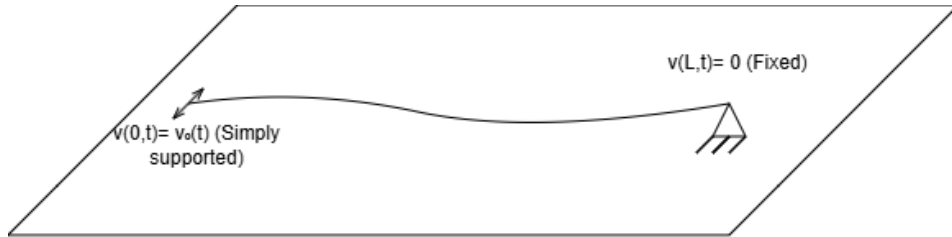


Figure 3.1: Set-up of proof for compression in a Kirchhoff rod

1. Axial-only dynamic argument

Let $u(x, t)$ be the axial displacement and $v(x, t)$ the transverse displacement of the centreline. For small slopes $|v_x| \ll 1$, the instantaneous arc length is

$$s(t) = \int_0^L \sqrt{1 + v_x(x, t)^2} dx \approx L + \frac{1}{2} \int_0^L v_x(x, t)^2 dx. \quad (3.3)$$

Whenever $v_x \neq 0$ on a set of non-zero measure, $s(t) > L$. With the right end fixed (3.2), the end-to-end distance must remain L , so the geometric elongation must be balanced by axial strain $\varepsilon(x, t) = u_x(x, t)$ via the compatibility

$$u_x(x, t) + \frac{1}{2} v_x(x, t)^2 = 0. \quad (3.4)$$

Hence

$$u_x(x, t) = -\frac{1}{2} v_x(x, t)^2 < 0 \quad \Rightarrow \quad N(x, t) = EA u_x(x, t) < 0. \quad (3.5)$$

Conclusion (EA only): Even without bending stiffness, the time-dependent transverse motion $v_0(t)$ enforces compressive axial force through geometric incompatibility when the right end is fixed.

2. Governing equations with bending

We now add bending stiffness. The curvature and bending moment are

$$\kappa(x, t) = v_{xx}(x, t), \quad M(x, t) = EI v_{xx}(x, t). \quad (3.6)$$

The transverse (dynamic) equilibrium for an Euler-Bernoulli/Kirchhoff rod with axial force coupling reads

$$\rho A v_{tt}(x, t) + N(x, t) v_{xx}(x, t) + \frac{\partial^2}{\partial x^2} (EI v_{xx}(x, t)) = 0, \quad (3.7)$$

subject to the boundary conditions (3.1)-(3.2). The axial equilibrium (obtained from conservation of axial linear momentum) gives the identity

$$N_x(x, t) = -M(x, t) v_{xx}(x, t) = -EI (v_{xx}(x, t))^2 \leq 0, \quad (3.8)$$

which is the same monotonicity relation used in static rod theory, but now holds pointwise in time. Integrating (3.8) from x to L yields

$$N(x, t) = N(L, t) - EI \int_x^L (v_{xx}(\xi, t))^2 d\xi < N(L, t) \quad (\text{whenever } v_{xx} \neq 0). \quad (3.9)$$

If at any instant the fixed support is not pulling ($N(L, t) \geq 0$), then (3.9) guarantees the existence of a region where $N(x, t) < 0$, that is, compressive axial force is present in the span.

3. Conclusion

Because the imposed transverse motion at $x = 0$ creates slope/curvature and hence geometric arc-length increase (3.3), the fixed support prevents end-to-end extension, enforcing compressive axial strain (3.4)–(3.5), and dynamic axial equilibrium implies $N_x = -EI(v_{xx})^2 \leq 0$ (3.8), it follows that

A slender dynamic Kirchhoff rod with bending stiffness and a fixed support at one end necessarily develops compressive internal forces when the opposite, simply supported end is subjected to a time-dependent transverse motion.

The theoretical proof shows that axial compression can arise in a simplified cable representation under dynamic excitation. However, this does not yet prove that the compression waves observed in numerical cable-lay simulations actually occur. The proof should therefore be interpreted as a physical feasibility argument, while numerical comparison and field-data validation are still required to assess the realism of the predicted compression waves.

Chapter 4

Methodology

4.1 Verification and Validation Strategy

The methodology of this research follows a stepwise validation and verification approach. The main objective of this approach is to gradually increase the modelling complexity and to verify the Python finite element model before it is used to investigate dynamic cable behaviour and the possible occurrence of compressive waves. Each step builds on the previous one, so the model is applied to more complex simulations only after sufficient agreement has been established in simpler verification cases. But in Section 4.2, the input data is discussed.

4.2 Input Data

The input data used in this research consists of two main parts. The first part contains the cable properties, while the second part consists of operational vessel and ROV data. Together, these data sources define the physical cable characteristics and the boundary conditions used in the static and dynamic simulations.

4.2.1 Cable Data

The cable data is provided by the cable manufacturer and includes the cable's mechanical and geometric properties. These properties are used as input for both the static and dynamic cable models. The cable design specification contains information such as the conductor cross-section, conductor material, outer cable diameter, cable weight, minimum bending radius, pulling tension limits, axial stiffness, bending stiffness and the torsional stiffness. An example of the data used for different models is shown in Table 4.1. The bending stiffness does not transition from stick to slip. Whether or not this data is available depends on the cable manufacturer.

Table 4.1: Cable data from the manufacturer specification used in the simulation models

Parameter	Excel value	Python input	Unit
Cable outer diameter	130	$D = 0.130$	m
Axial stiffness	44	$EA = 44 \cdot 10^6$	N
Linear bending stiffness (stick)	2.7	$EI_1 = 2.7 \cdot 10^3$	Nm ²
Linear bending stiffness (slip)	2.7	$EI_2 = 2.7 \cdot 10^3$	Nm ²
Transition curvature	0.01	$\kappa_{trans} = 0.01$	m ⁻¹
Cable weight in air	26.5	$W = 26.5 \cdot 9.81$	N/m
Cable weight in water, flooded	15.5	$B_{up} = (26.5 - 15.5) \cdot 9.81$	N/m

The cable is defined by a set of cable elements and corresponding design parameters. These parameters are extracted from the manufacturer's specification and converted into the required input format for

the numerical models. For example, the cable's outer diameter, submerged weight, axial stiffness, and bending stiffness are required to describe the cable's mechanical response in the Python finite element model. The minimum bending radius and maximum allowable pulling tension are used to assess whether the simulated cable response remains within the installation limits.

Since manufacturer data is generally provided in a design-oriented format, several parameters require interpretation before they can be used directly in the numerical model. In particular, stiffness values, allowable tensions, and compression limits need to be converted into consistent units and simplified into model parameters. The resulting cable input therefore represents an idealised version of the actual cable, based on the available manufacturer data.

4.2.2 Vessel and ROV Data

In addition to the cable properties, operational vessel and ROV data are used to define the boundary conditions of the model. The vessel data contains the motions of the cable-lay vessel, while the ROV data provides information about the touchdown region of the cable.

The analyses in this thesis are based on data obtained from the Living Stone, one of DEME's cable-laying vessels. The Living Stone is a DP3 cable-lay vessel equipped with two 5,000-tonne cable turntables below deck and is primarily used for the installation of inter-array cables, while also being capable of handling export cables. Its onboard cable installation equipment and dynamic positioning capabilities make it a suitable vessel for the type of installation scenarios considered in this study. A picture of the vessel is included in this section for reference, depicted in Figure 4.1 [12].



Figure 4.1: Living Stone

The vessel motion data used in this thesis is obtained from two sources. Firstly, time series data is extracted from Grafana, which provides access to the monitored vessel motion signals during installation. Secondly, additional operational data received from onboard is used to complement and interpret these measurements. Together, these datasets provide the basis for reconstructing the vessel response during the selected cable-laying events.

The ROV position is used to define the touchdown point of the cable. In the simplified numerical model, the ROV's horizontal position is taken to be the touchdown point's position, since the ROV remains above the touchdown point during normal lay operations. This allows the touchdown point to be prescribed in the Python finite element model for cases where ROV-based touchdown information is available.

The vessel motion data is used to derive the vertical motion at the chute location. The measured vessel motions include heave, roll, and pitch. Since the chute is not located exactly at the vessel reference point, the vertical motion at the chute is calculated by transforming the vessel motions to the chute position. In this way, the chute's motion can be represented as a prescribed vertical boundary condition in the Python model.

The vertical chute motion is calculated from the vessel heave, pitch, and roll according to the position of the chute relative to the vessel reference point. This allows the effect of vessel motion to be included in a relatively simple two-dimensional cable model. Instead of modelling the complete vessel and its six degrees of freedom, only the resulting vertical motion at the cable departure point is imposed on the cable model.

4.2.3 Use of Input Data in the Numerical Model

The manufacturer's cable data defines the cable's physical properties, while the vessel and ROV data define the time-dependent boundary conditions. In the static simulations, the cable properties are used to calculate the equilibrium cable shape under gravity, buoyancy, bending stiffness, axial stiffness, and seabed interaction. In the dynamic simulations, the same cable properties are used, but the boundary conditions are updated over time based on the vessel and ROV data.

The upper boundary of the cable is controlled by the chute location. The vertical movement of this point is prescribed using the derived vessel motion at the chute. The lower boundary, or touchdown region, is prescribed using the ROV-based touchdown point information when this data is available. This approach makes it possible to include measured operational behaviour while keeping the Python model relatively simple and computationally efficient.

By combining manufacturer-cable data with measured vessel and ROV data, the model can simulate cable behaviour under conditions representative of the actual cable-lay operation. However, this also introduces simplifications. The cable properties are based on idealised manufacturer values, the vessel motion is reduced to a prescribed vertical chute motion, and the ROV position is used as an approximation of the touchdown point. These assumptions are considered when interpreting the simulation results.

4.3 Analytical Catenary Validation

The first step is to develop an analytical model based on classical catenary theory. This model provides a theoretical reference solution for the static configuration of a suspended cable subjected to its submerged weight. Since the analytical catenary formulation assumes a highly flexible cable, the comparison with the Python finite element model is performed for a simplified cable configuration.

For this validation case, the cable is modelled with a low bending stiffness and a high axial stiffness. These assumptions ensure that the finite element model behaves close to the ideal catenary solution. The purpose of this comparison is to verify whether the Python model correctly represents the cable's basic static equilibrium, including its geometry, force balance, and tension distribution.

If sufficient correspondence is found between the analytical catenary model and the Python finite element model, the finite element model is considered suitable for further static validation. This first verification step, therefore, acts as a fundamental verification of the numerical implementation.

The second step is to validate the static Python finite element model for a more realistic cable-lay configuration. In this stage, a static base case is simulated for eight different cable types. No touchdown point is prescribed in these simulations, so the model must determine the equilibrium cable shape and touchdown location based on cable properties, boundary conditions, and environmental loading.

The results of the Python finite element model are compared with reference static model results. For each cable type, the cable shape is evaluated, and the deviation between the models is quantified using root-mean-square error (RMSE). The RMSE provides a single quantitative measure of the average difference between the predicted cable geometries and is used to assess the level of agreement between the models.

The RMSE is calculated as:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (z_{FE,i} - z_{ref,i})^2} \quad (4.1)$$

where $z_{FE,i}$ is the vertical position predicted by the Python finite element model, $z_{ref,i}$ is the corresponding reference vertical position, and n is the number of comparison points.

By applying this verification to eight different cables, the robustness of the Python model is assessed for a range of cable properties. This step is important because it evaluates whether the model can reproduce realistic static cable-lay configurations before measured touchdown point data and dynamic vessel motions are introduced.

4.4 Static Verification Using Available Touchdown Point Data

After the general static verification, the next step focuses on two cable cases for which touchdown point data is available. These cases allow for a more detailed comparison between the numerical models and the observed cable-lay configuration.

For these two cables, static simulations are performed in both OrcaFlex and the Python finite element model. In OrcaFlex, simulations are performed without prescribing a touchdown point, allowing the software to determine the static cable configuration independently. In the Python finite element model, the touchdown point is prescribed based on available touchdown-point data.

The aim of this comparison is to investigate how well both models can reproduce the static cable configuration when field-based touchdown information is available. This step also provides insight into the influence of prescribing the touchdown point in the Python model, compared with allowing it to develop naturally in OrcaFlex.

The static comparison includes the cable shape, touchdown location, and relevant force quantities. Differences between the models are analysed to determine whether the Python model remains consistent with the reference modelling approach when more realistic boundary information is introduced.

4.5 Dynamic Verification in Calm Sea Conditions

Once the static behaviour of the Python model has been validated, the methodology proceeds with dynamic simulations. The first dynamic verification case considers a very calm sea state. This calm condition is selected to introduce dynamic vessel motions in a controlled manner, while limiting the influence of strong wave-induced effects.

The calm sea case is simulated in both the Python finite element model and OrcaFlex. The same vessel motions and boundary conditions are applied consistently in both models. The resulting cable response is then compared to assess whether the Python model can reproduce the dynamic behaviour predicted by OrcaFlex under mild environmental conditions.

The comparison focuses on the dynamic cable shape, tension response, touchdown-point behaviour, and possible differences in the time-dependent responses of both models. Since the sea state is calm, only limited dynamic amplification is expected. Therefore, this step primarily serves to validate the dynamic implementation of the Python model rather than to investigate extreme cable behaviour.

The objective of this stage is to confirm that the Python model produces stable, physically reasonable dynamic results before it is applied to more severe environmental conditions.

4.6 Dynamic Assessment in More Severe Sea Conditions

The final step of the methodology considers a more severe sea state. In this case, the focus shifts from general model verification to the investigation of compressive wave phenomena. First, the dynamic

cable response is analysed in OrcaFlex to identify whether compressive waves occur under the selected environmental and operational conditions.

After the compressive wave behaviour has been identified in OrcaFlex, the same vessel motions and boundary conditions are applied in the Python finite element model. The purpose of this comparison is to determine whether the Python model reproduces similar compressive behaviour.

The analysis focuses on the occurrence, location, duration, and propagation of compression along the cable. Particular attention is given to regions where the axial tension becomes negative or where a travelling compression zone can be observed. By comparing the results of both models, it can be assessed whether the compressive waves predicted in OrcaFlex are also present in an independently developed Python finite element model.

This final step is essential for evaluating whether the observed compressive wave phenomenon is likely to be a physical response of the cable system or whether it may be related to modelling assumptions, numerical implementation, or software-specific behaviour.

4.7 Overview of the Verification Strategy

The complete methodology can therefore be summarised as follows:

1. Development of an analytical catenary model based on classical catenary theory.
2. Verification of the Python finite element model against the analytical catenary solution for a simplified cable with low bending stiffness and high axial stiffness.
3. Static verification of the Python model for eight different cables without a prescribed touchdown point, using the RMSE as a quantitative comparison metric.
4. Static comparison for two cable cases with available touchdown point data, comparing OrcaFlex results without a prescribed touchdown point to Python finite element results with a prescribed touchdown point.
5. Dynamic verification of the Python model against OrcaFlex in calm sea conditions.
6. Dynamic assessment in a more severe sea state, focusing on the occurrence of compressive waves in OrcaFlex and evaluating whether the same behaviour appears in the Python model.

Through this stepwise approach, the Python finite element model is first verified against theory, then validated against static reference cases, and finally applied to dynamic simulations. This provides a structured basis for assessing the reliability of the model and for investigating the origin and relevance of compressive wave phenomena during cable-lay operations.

Chapter 5

Numerical Model

5.1 Normal Lay Set Up

As described in Section 1.1, a normal lay operation will be simulated and compared with the results from different simulation software. Since these commercial models are often very refined and used for a more general purpose. For the purpose of this thesis, several assumptions were implemented in the Python model designed to answer the research question at hand. For this work, the MoorPy model [15] served as a foundation for developing a static mooring system representation. MoorPy provides a quasi-static framework for efficiently computing equilibrium configurations of moored structures. Starting from this baseline model, the system was adapted and iteratively refined to meet the specific requirements of this project, including modifications to geometry, boundary conditions, and loading scenarios. This static formulation served as a stepping stone toward a more advanced representation, ultimately enabling the extension to a dynamic model for further analysis.

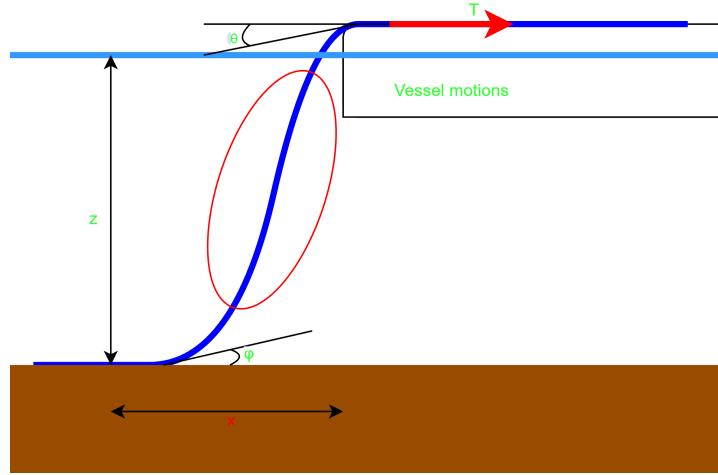


Figure 5.1: A traditional normal lay set-up

- Chute/seabed-to-cable friction is not accounted for. Initially, these were included in the Python simulations. However, they caused complications in Python simulations. A balance had to be found between accuracy (tolerance) and computational power, which became a limiting factor. For this reason, it was investigated whether friction significantly influences the recurrence of the compressive wave phenomenon. This was not the case, and so friction was disregarded. Below are compressive waves shown in Figure 5.2 with and without friction included in the model, as described. The geometry is the same. Also, the tension curves are displayed in Figure 5.3. A difference can be seen in how the minimum and maximum tension curves behave. This can be

explained by the fact that the tension can act on the cable both by pulling and pushing, thereby influencing the cable's maximum tension. The key point here is that, at the minimum stress curve, the stress becomes negative or compression is present at the touchdown point.

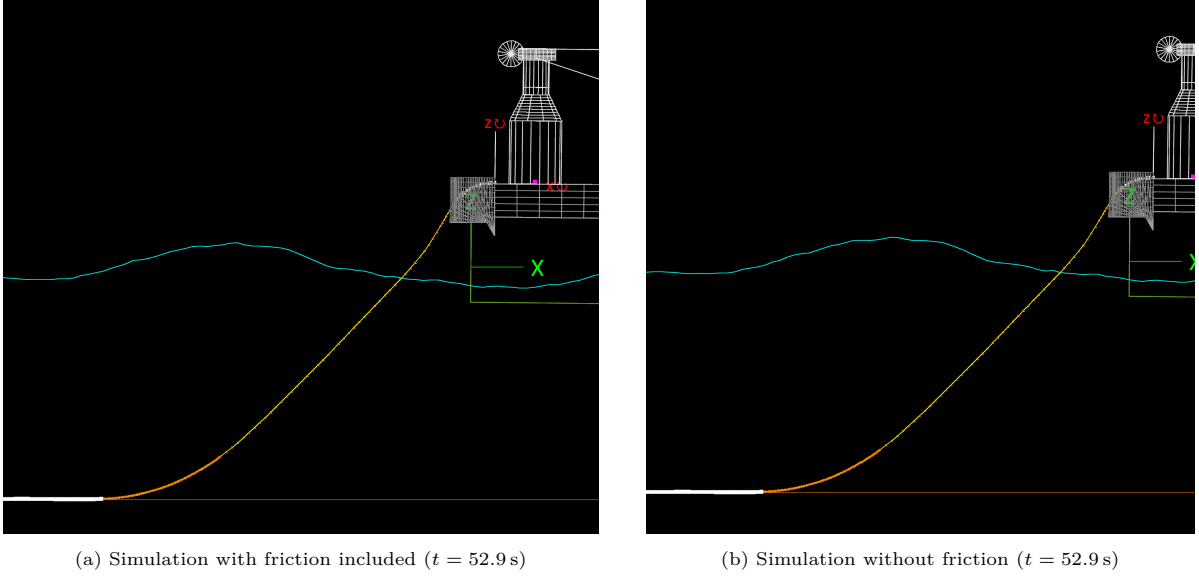


Figure 5.2: Comparison of the simulated system state at $t = 52.9$ s with and without friction.

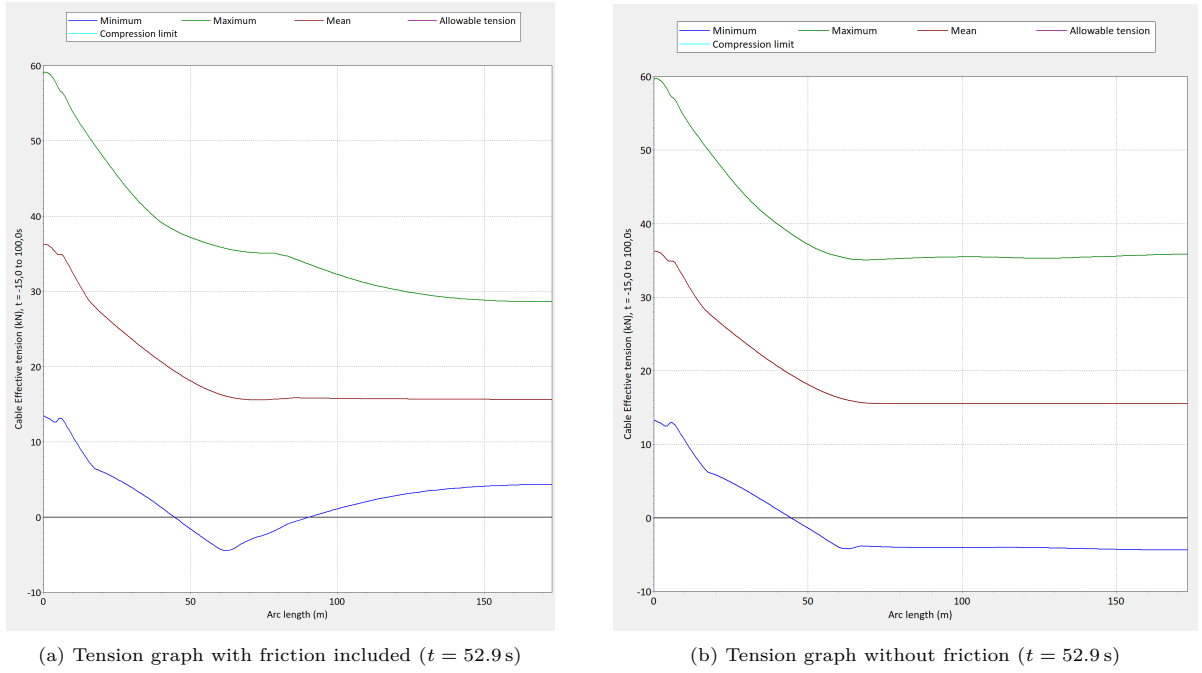


Figure 5.3: Comparison of tension within the cable at $t = 52.9$ s with and without friction.

- The non-linear bending stiffness defined by the cable manufacturers is simplified. However, it is not possible to estimate this more accurately without making unwarranted assumptions. For this reason, this bending stiffness was retained for the analysis. This bending stiffness is also used in the other models, ensuring consistent modelling.
- The RAOs as they are incorporated into OrcaFlex are not included. Instead, the cable movements at the chute are used as input. This makes the Python model simpler and reduces issues related

to the use of confidential information. As third-party software is used, preference was given to not sharing the RAOs of Deme vessels. This also indirectly accounts for any cable influence on the ship, as the chute movements are derived from projects that were actually carried out. It is also assumed that excitations occur in the xz-plane, as mentioned earlier.

5.2 OrcaFlex Model Setup

This section describes how the general OrcaFlex modelling principles were applied in the OrcaFlex model developed for this thesis. The purpose of this model is to represent the subsea power cable during lay operations and to allow comparison with the analytical and Python-based models. The OrcaFlex model and the Python model must represent each other as closely as possible. DEME engineers utilise a pre-built model that allows a wide range of different input variables to be entered with relative ease. The following items can be entered easily.

- Sea depth
- Cable variables
- Environment variables (wave height, wave period, current)
- Vessel responses
- Anchorpoints

For the present thesis, however, the OrcaFlex model was not used in its most general form. Instead, it was configured to reproduce, as closely as possible, the assumptions adopted in the Python models developed in Sections 5.3 and 5.4.

5.2.1 Model Objective

The purpose of the OrcaFlex model is to provide a benchmark to cheque the FE Model for both the static and dynamic base cases, as discussed in Section 4. Next to that it is used to find compression cases based on the vessel data. The OrcaFlex model was therefore set up such that the same cable geometry, cable properties, environmental conditions, and boundary excitations could be represented as consistently as possible in both modelling approaches.

5.2.2 OrcaFlex Simplifications

As discussed in 5.1, certain choices have been made to simplify the model. These are explained below.

For instance, the OrcaFlex model generally operates in a 3D environment. However, it was decided to describe the model in 2D. This is primarily to improve computational efficiency. It has become apparent that, although the OrcaFlex model has no issues with a 3D model, the Python script is unable to compute it due to computational capacity constraints. The difference in model layout can be seen in Figure 5.4.

Furthermore, the vessel itself was excluded from the analysis. There were several reasons for this. Using vessel data, it is possible to precisely simulate the vessel's movements at the chute. This means, amongst other things, that the vessel's RAOs did not need to be considered. This, in turn, makes the model simpler and more accurate, as the movements are taken directly from MRUs on board the vessel. Furthermore, only the chute was modelled as a circle/cylinder, based on the chute radius of the Living Stone. The motions were specified in an Excel file by a z-location and a timestamp, which could also be easily incorporated into the Python model.

Friction was not included in this model, as mentioned in Section 5.1. It has little effect on the compression phenomenon, which also benefits the Python model in achieving stable configurations.

Torsional stiffness has not been included in the model, as this is, in principle, not possible in a 2D model. Here, the cable is treated as an infinitely rigid tube in axial rotation.

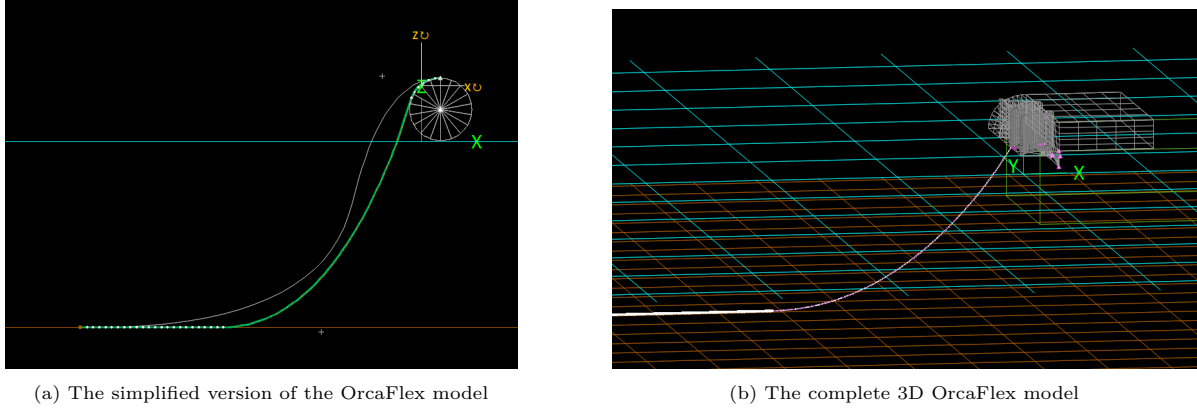


Figure 5.4: Comparison between the 2D OrcaFlex model and the complete 3D model, where the vessel is included

5.2.3 Boundary Conditions and Vessel Motion

As stated before, the chute's motion is prescribed identically for both models. By assigning a location in combination with a timestamp. The cable is fixed at the top of the chute with an anchor point. This anchor point moves in tandem with the chute. An anchor point has also been placed on the seabed. In the static configuration, this is located 25 metres beyond the TDP. Furthermore, a spring constant of 1000 kN/m is assumed for both the seabed and the chute as a boundary condition for these model boundaries.

5.3 Static Python Model

This section describes the static, time-independent Python model developed to predict the equilibrium configuration and internal force distribution of a suspended subsea cable with possible seabed contact. The static model serves two purposes. First, it provides a reference equilibrium configuration that is used as the initial condition for the dynamic model. Second, it enables verification of the finite element (FE) formulation against an analytical catenary solution before time-dependent effects are introduced.

Two complementary formulations are used:

- an analytical catenary model, which provides a fast reference solution for the suspended cable shape, touchdown location, and global force distribution;
- a finite element (FE) model, which includes axial extensibility, bending stiffness, seabed contact, and nonlinear equilibrium solving.

The analytical model is introduced to verify the FE implementation under simplified conditions. Since catenary behaviour with partial seabed contact has been extensively described in the literature, closed-form expressions can be used to determine the cable shape and force distribution for an idealised cable. These results provide a useful benchmark for assessing the FE formulation. In addition, analytical geometry is used as an initial guess for the FE solver, thereby improving the robustness and efficiency of the nonlinear equilibrium iterations.

The analytical model is discussed in Subsection 5.3.1, the FE model in Subsection 5.3.2, and both are compared in Subsection 5.3.4.

5.3.1 Analytical Model Description

The analytical formulation is based on the static equilibrium of an ideal slender cable under a uniformly distributed net vertical load. An overview of the analytical solution procedure is shown in Figure 5.5. In the classical catenary idealisation [31], the cable is assumed to be perfectly flexible in bending, inextensible, and subjected to a constant vertical load per unit arc length. Under these assumptions, the suspended part of the cable follows the well-known catenary shape, while the internal force components can be obtained from standard catenary relations commonly used in riser analysis.

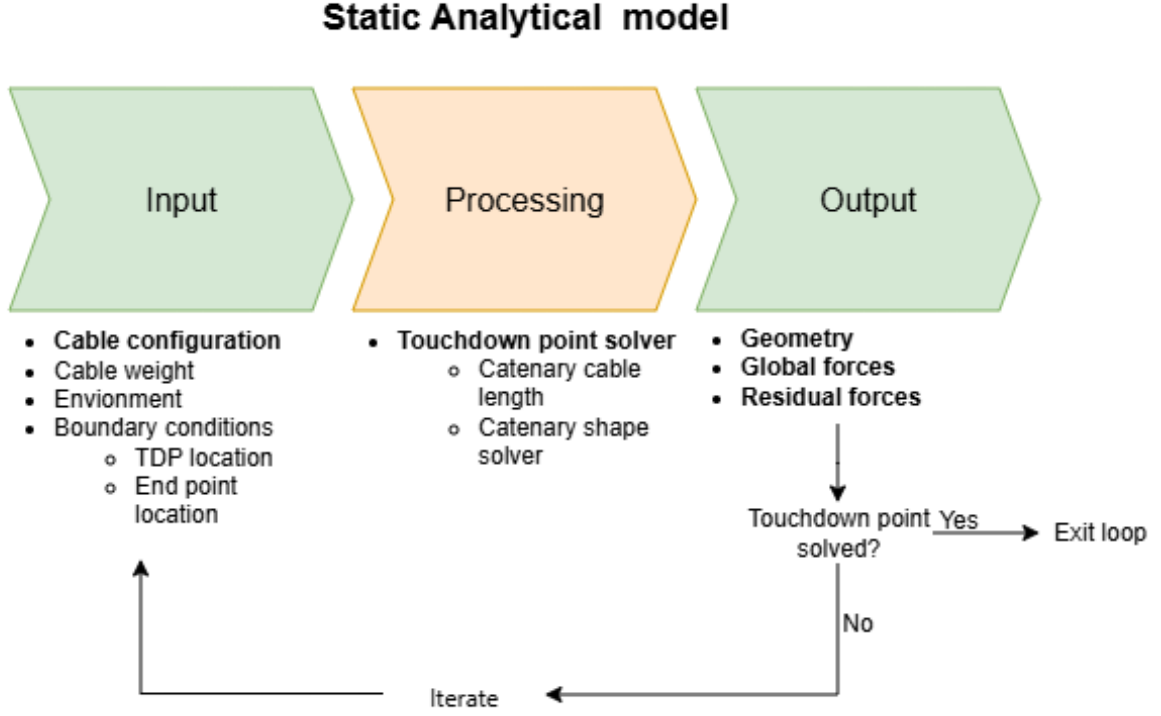


Figure 5.5: Static analytical solver overview

Idealised cable formulation

In the present model, the distributed load is taken as the net submerged weight

$$w_{\text{net}} = w_{\downarrow} - b_{\uparrow}, \quad (5.1)$$

where $w_{\downarrow}$ is the weight per unit length and $b_{\uparrow}$ is the buoyancy per unit length. The analytical model requires $w_{\text{net}} > 0$ in order to admit a hanging cable configuration. [5]

A key property of the catenary in static equilibrium is that the horizontal component of tension remains constant along the suspended span in the absence of horizontal distributed loading. This constant horizontal tension H defines the catenary constant

$$a = \frac{H}{w_{\text{net}}}. \quad (5.2)$$

The vertical force component increases with suspended arc length as it balances the accumulated distributed load, and the resulting total tension is given by

$$T = \sqrt{H^2 + V^2}. \quad (5.3)$$

These relations form the basis for the analytical prediction of the cable shape and force distribution. [5]

Seabed interaction and touchdown point

To include seabed contact in the analytical description, the cable is divided into two parts: a suspended catenary span and a seabed span. The transition between both regions is the touchdown point (TDP). The TDP is determined by enforcing compatibility between the available total cable length and the arc length required by the suspended catenary together with the seabed contact length. This leads to a nonlinear scalar equation for the touchdown coordinate, which is solved by root-finding. In this way, the suspended part and the grounded part of the cable are coupled through a single length-compatibility condition. [5]

Once the touchdown point has been determined, the analytical model provides the full cable geometry together with the global horizontal and vertical force distributions. In this simplified representation, the seabed segment is treated as lying on the seabed, while the suspended segment follows the catenary relation.

Role in the modelling workflow

Bescable's static equilibrium configuration shape and end tensions, the analytical model is also used to generate an initial configuration for the FE solver. This is beneficial because nonlinear FE contact problems are sensitive to the starting geometry, and a catenary-based initial guess improves convergence and reduces the number of Newton iterations. [4]

5.3.2 Finite Element Model Description

This subsection presents the finite element (FE) formulation used to determine the cable's static equilibrium configuration. The cable is represented as a discretised structural system, in which the equilibrium shape is determined by nodal force balance under internal structural actions and external loading. The formulation accounts for geometric nonlinearity, axial deformation, bending stiffness, and seabed interaction. An overview of the FE solution procedure is shown in Figure 5.6.

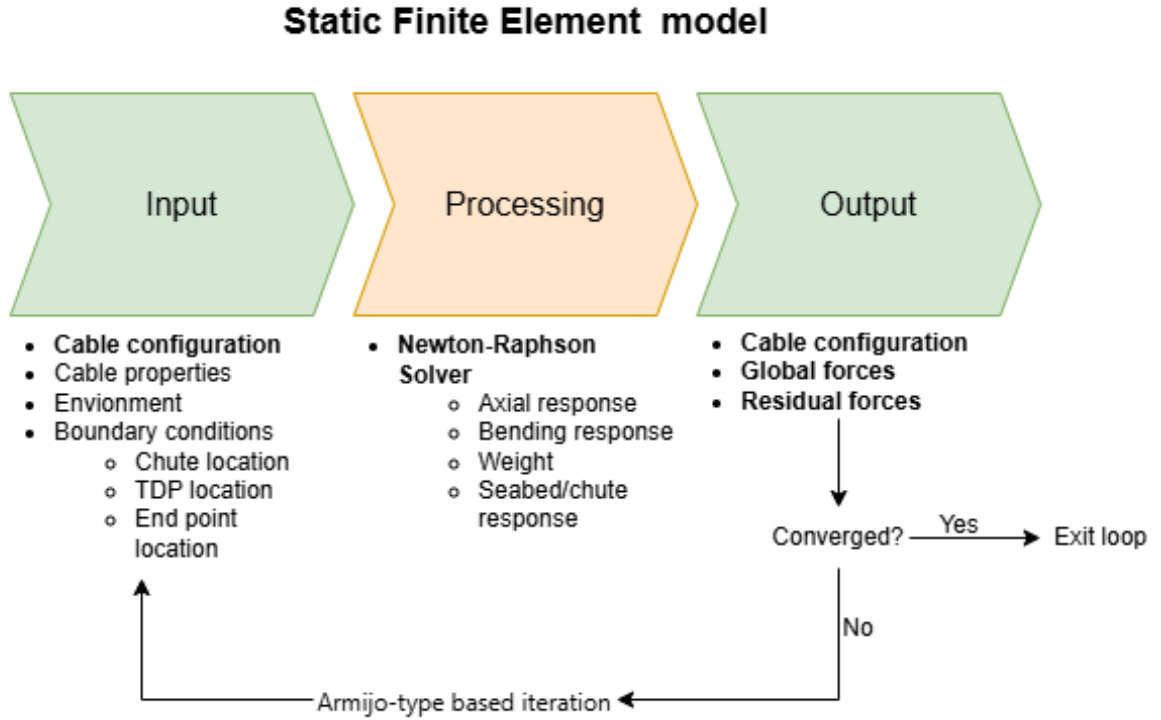


Figure 5.6: Static FE solver overview

Discretisation and degrees of freedom

The FE model discretises the cable centerline into N nodes with positions

$$\mathbf{r}_i = (x_i, z_i), \quad i = 1, \dots, N,$$

and uses nodal translations as degrees of freedom, giving two degrees of freedom per free node. The end nodes can be fixed at prescribed coordinates representing the cable connection points. Equilibrium is obtained by enforcing force balance at all free nodes, which is standard in nonlinear FE formulations for slender structural systems. [4]

Element mechanics

Each segment between nodes $(i, i + 1)$ has a current length ℓ_i and a reference length

$$\Delta s = \frac{L}{N - 1}.$$

The axial strain is approximated by

$$\epsilon_i \approx \frac{\ell_i - \Delta s}{\Delta s},$$

which leads to a linear axial constitutive relation

$$T_i \approx EA \epsilon_i,$$

with EA the axial stiffness. Because the segment lengths depend on the unknown nodal coordinates, the internal axial forces are geometrically nonlinear. [4]

Bending stiffness is introduced through a discrete curvature estimate based on the change in angle between neighbouring segments. This follows the standard Euler–Bernoulli moment-curvature relation

$$M = EI \kappa,$$

where EI is the bending stiffness and κ is the curvature. In the present model, a piecewise bending stiffness may be used, with different stiffness values for different curvature regimes. This allows the model to represent changes in bending response while retaining a conventional beam-like formulation. [4]

Loads, seabed interaction, and touchdown point

The static cable configuration results from the balance between internal structural forces and externally applied loads. The dominant external load is the distributed submerged weight, which governs the cable's catenary-like shape. In addition, external loads can be applied at the cable ends, and prescribed end-node coordinates are used to impose the problem's physical boundary conditions. All of the relevant loads in the static configurations have been discussed in section 2.2. All of these loads have been included in the FE model.

Within the FE model, the touchdown point is not obtained from a separate analytical condition but follows naturally from the contact state. Nodes are considered to be in contact when their vertical coordinate reaches the seabed elevation within a prescribed numerical tolerance. The touchdown point can then be approximated either by the first contacting node or by interpolation between the last non-contacting node and the first contacting node. In this way, touchdown is treated as a direct outcome of the FE contact formulation rather than as an additional unknown to be solved separately. [1, 35]

Nonlinear solution procedure

The FE formulation leads to a nonlinear algebraic system expressing nodal equilibrium:

$$\mathbf{R}(\mathbf{q}) = \mathbf{0}, \tag{5.4}$$

where $\mathbf{q}$ collects the unknown nodal coordinates of the free nodes and $\mathbf{R}$ denotes the residual vector, defined as the difference between internal and external nodal forces. The nonlinearity arises from the dependence of segment lengths, angles, and contact conditions on the unknown configuration. [4, 35]

The equilibrium equations are solved using a Newton-Raphson procedure. At each iteration, the residual is linearised about the current estimate $\mathbf{q}^k$:

$$\mathbf{K}(\mathbf{q}^k) \Delta \mathbf{q}^k = -\mathbf{R}(\mathbf{q}^k), \tag{5.5}$$

after which the nodal coordinates are updated according to

$$\mathbf{q}^{k+1} = \mathbf{q}^k + \Delta \mathbf{q}^k.$$

To avoid the need for a fully analytical tangent stiffness, the Jacobian matrix $\mathbf{K}$ is evaluated numerically using finite differences of the residual. In addition, damping or line search techniques can be applied to improve convergence when strong contact nonlinearities are present. [4]

Role in the modelling workflow

The FE model provides the final static equilibrium configuration, which serves as the initial state for the dynamic cable model. In contrast to the analytical catenary solution, it can account for finite axial and bending stiffness, as well as localised seabed interaction, making it suitable for realistic subsea cable configurations.

5.3.3 Mesh convergence based on bottom tension

A mesh convergence study was performed by comparing the bottom tension obtained with the current mesh to the result obtained with the previous mesh. The relative change between two consecutive mesh refinements was calculated as

$$\Delta_{\text{rel},i} = \frac{|T_i - T_{i-1}|}{|T_{i-1}|} \cdot 100\%, \quad (5.6)$$

where T_i is the bottom tension obtained with the current mesh and T_{i-1} is the bottom tension obtained with the previous mesh. This approach allows the influence of mesh refinement on the solution to be evaluated directly. When the relative change becomes sufficiently small, further mesh refinement has only a limited influence on the result, and the solution can be considered mesh-independent for engineering purposes.

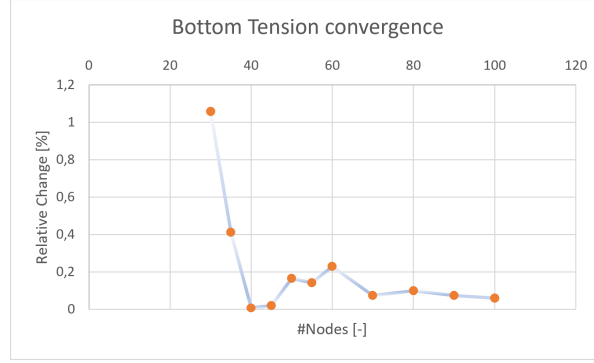


Figure 5.7: Relative change of the bottom tension between consecutive mesh refinements.

Figure 5.7 shows that the relative change is largest for the coarser meshes. At the beginning of the refinement process, the difference between consecutive meshes remains significant, indicating that the solution remains sensitive to mesh density. After approximately 40 to 50 nodes, the relative change decreases strongly and remains at a low level. From this point onward, the curve begins to flatten, with only minor variations. This indicates that the bottom tension is approaching a converged value, since additional mesh refinement no longer causes a substantial change in the calculated tension.

The bottom tension was selected as the convergence quantity instead of the top tension. The top tension is located at the vessel's chute, where local contact, support, and geometric effects introduce strong variations in the solution. These local variations can lead to mesh-sensitive peaks, especially in configurations with a small number of nodes, which are difficult to interpret and may not reflect the system's global convergence behaviour. The bottom tension provides a more stable and representative measure of convergence, as it is less affected by local disturbances.

A convergence limit of approximately 1% was used as a practical engineering criterion. Once the relative change between consecutive meshes remains below this threshold, the solution is considered sufficiently stable for the purpose of the present study. In the plotted results, the relative change remains well below this criterion after the initial refinement steps, indicating that the solution has entered a converging region.

It should also be noted that the convergence study is limited by the available computational resources. Increasing the number of nodes generally increases the computational time and memory requirements.

Therefore, it is not always practical or possible to continue refining the mesh indefinitely. In this study, the maximum mesh density investigated was limited by available computing power. Since the relative change already becomes small in the investigated range, further refinement would be expected to provide only limited improvement at an additional computational cost.

5.3.4 Static Model Verification

The static model is verified in two steps. First, the FE model is compared with the analytical catenary solution for a simplified cable configuration. In this comparison, the bending stiffness is neglected, and the axial stiffness is chosen sufficiently high such that the FE formulation approaches the assumptions of the analytical model. This provides a direct check of the implementation of the basic cable geometry, force equilibrium, and tension distribution.

Figure 5.8 shows that the FE model converges towards the analytical catenary solution under these simplified assumptions. Small remaining differences are expected due to the discrete representation of the cable in the FE model and the numerical solution procedure.

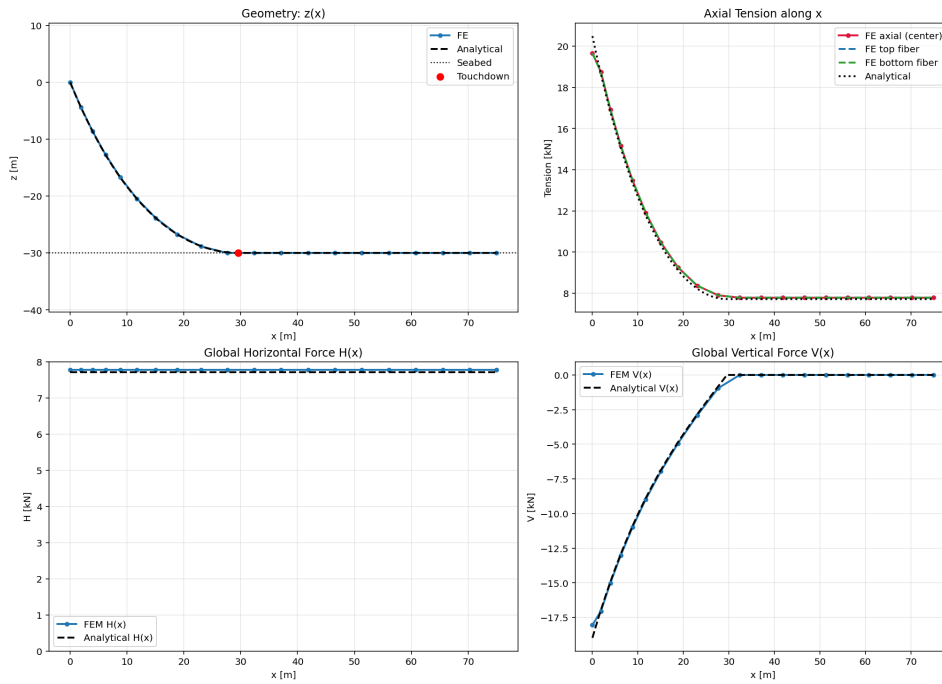


Figure 5.8: Comparison between the analytical and FE model with zero bending stiffness and very high axial stiffness

In the second verification step, the FE model is compared with a static OrcaFlex simulation for a realistic subsea power cable configuration. This comparison includes chute contact, realistic cable properties, and seabed interaction. The purpose is to assess whether the Python model reproduces the static cable geometry and the effective tension predicted by OrcaFlex.

The input parameters used for this verification case are listed in Table 5.2. The visual comparison of geometry and effective tension is shown in Figure 5.9, while the quantitative agreement is summarised in Table 5.1. The resulting error levels indicate that the Python model reproduces the static OrcaFlex response with good accuracy for the investigated case.

Table 5.1: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.185
Maximum deviation	0.282

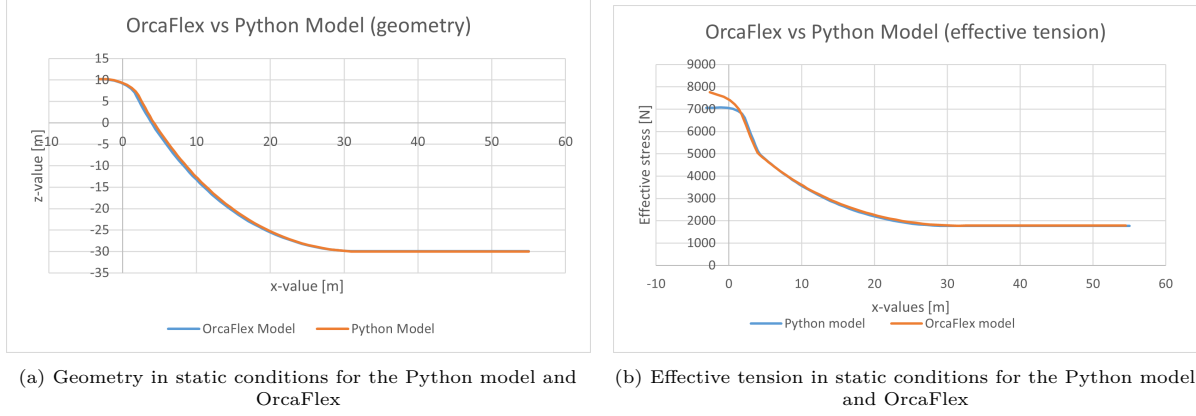


Figure 5.9: Comparison between the Python model and OrcaFlex for a realistic static cable configuration

Table 5.2: Main input parameters used for the static cable solve

Category	Parameter	Value
Geometry	Horizontal chute anchor point	-3.1
Geometry	Vertical chute anchor point	10.2
Geometry	Horizontal anchor point X_F	55.0 m
Geometry	Vertical anchor point (seabed) Z_F	-30.0 m
Geometry	Cable length L	70.0 m
Cable	Outer diameter D	0.1395 m
Cable	Cross-sectional area A	$1.53 \times 10^{-2} \text{ m}^2$
Cable	Young's modulus E	$265 \times 10^6 \text{ Pa}$
Cable	Axial stiffness EA	$4.05 \times 10^6 \text{ N}$
Cable	Bending stiffness (stick) EI_1	$29.2 \times 10^3 \text{ N m}^2$
Cable	Bending stiffness (slip) EI_2	$2.91 \times 10^3 \text{ N m}^2$
Cable	Transition curvature κ_{trans}	0.033 m^{-1}
Cable	Submerged weight W	425.75 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m^3
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	$1.0 \times 10^6 \text{ N/m}$
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

In addition to this reference case, several other cable configurations were evaluated, covering six cable types with variations in both geometric and physical properties. These additional verification results, along with the corresponding cable data, are presented in Appendix A.

Limitations of the Python Model

The agreement between the Python model and OrcaFlex is not uniform across all investigated cable types. For some configurations, the correspondence in geometry and effective tension is very good, whereas for others, larger deviations are observed. These differences are mainly associated with cable configurations in which the static response is highly sensitive to localised effects such as chute contact, touchdown behaviour, and sharp curvature variations.

In particular, cables with higher bending stiffness are more difficult to reproduce accurately, because their response depends less on global catenary behaviour and more on local mechanical effects. As a result, the present model is most reliable for static configurations in which the overall response is dominated by submerged weight and axial tension, with relatively smooth curvature development along the span. For cables exhibiting stronger local bending effects, pronounced contact interaction, or greater

axial extensibility, the predictive accuracy decreases, and the model should therefore be applied with caution.

The verification results should therefore be interpreted as indicating the model's practical applicability rather than as demonstrating universal validity across all subsea cable configurations.

5.4 Dynamic Python Model

This Section describes the dynamic (time-dependent) Python model developed to simulate the cable's transient response during lay operations. In contrast to the static model, which considers only equilibrium, the dynamic model includes inertia, time-dependent boundary motion, and velocity-dependent external loading. The purpose of this model is to investigate how transient effects, such as vessel-induced motion at the chute and cable-seabed interaction, affect the compressive wave phenomena near the touchdown region. And if so, why did it occur or not? However, it is also important to define the model's boundaries, since it is hard to build a simulation model that captures every possible situation.

The dynamic model is formulated as an extension of the finite element model presented in Section 5.3. The same discretisation strategy, internal force formulation, and contact treatment are retained, while mass and time integration are added. In this way, the static FE solution serves as the starting point of the dynamic simulation and provides a physically consistent initial geometry. This was also mentioned in the literature review: the dynamic model corresponds to the static model, but certain factors need to be added to make it more realistic. A simplified overview of the model can be seen in Figure 5.10.

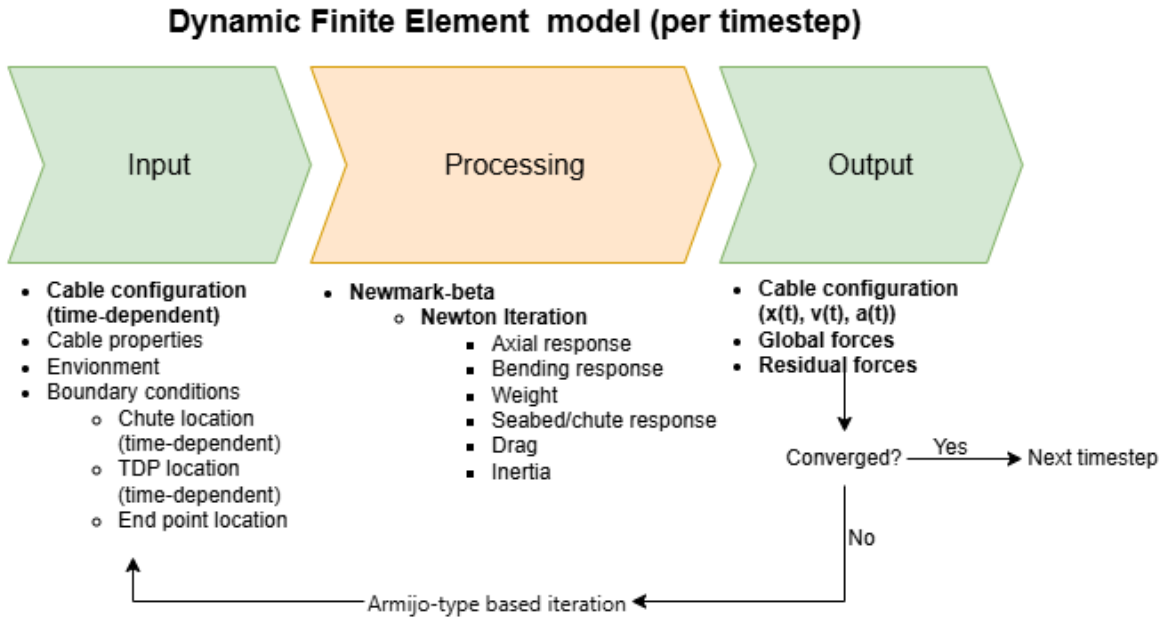


Figure 5.10: Dynamic FE solver overview

5.4.1 Start Configuration

The dynamic simulation is initialised from a configuration that is already in static equilibrium. This is important because it prevents the model from generating artificial start-up oscillations caused purely by inconsistent initial conditions. In the present workflow, the initial cable shape is imported from a previously stored static result. The static solution, therefore, represents the state of the system at $t = 0$, after which the prescribed dynamic excitations are applied.

Let the vector of free nodal degrees of freedom be denoted by $\mathbf{q}$. At the start of the dynamic simulation, the following initial conditions are adopted:

$$\mathbf{q}(0) = \mathbf{q}_{\text{static}}, \quad \dot{\mathbf{q}}(0) = \mathbf{0}, \quad (5.7)$$

where $\mathbf{q}_{\text{static}}$ is the converged static solution. The initial acceleration is then obtained implicitly from the dynamic equilibrium equation. Starting from a statically admissible configuration is common practice in nonlinear structural dynamics, since it improves numerical robustness and ensures that the subsequent response is caused by the applied excitations rather than by initialisation errors.

5.4.2 Included Loads

Several forces are included in the model. To go from a static model to one that can handle motions and accelerations, some forces need to be added. The static forces: cable weight, seabed normal force, boundary conditions, bending and linear stiffness have already been discussed. Frictional drag and added mass forces have been added next to the cable velocities and accelerations through the fluid.

Inertia forces

The most important extension from the static to the dynamic formulation is the inclusion of inertia effects. The cable mass is represented through a lumped mass matrix, assembled from the effective mass per unit length and the discretised segment length. For a segment of length Δs , the structural (submerged) mass is approximated as

$$m_{\text{seg}} = \frac{W}{g} \Delta s, \quad (5.8)$$

where W is the submerged weight per unit length of the cable and g the gravitational acceleration. This formulation accounts for buoyancy by using the effective submerged weight rather than the dry weight.

In addition to the structural mass, hydrodynamic added mass effects are included to account for the inertia of the surrounding fluid, which is accelerated along with the cable. The added mass per segment is modelled according to Morison-type formulations as

$$m_{\text{a,seg}} = C_a \rho \frac{\pi D^2}{4} \Delta s, \quad (5.9)$$

where C_a is the added mass coefficient, ρ the fluid density, and D the cable outer diameter. The total inertial mass attributed to each segment is thus obtained as the sum of the structural and added mass contributions.

A lumped-mass approximation is adopted, in which the segment mass is distributed directly to the translational degrees of freedom of the adjacent nodes, yielding a diagonal mass matrix. This approach is widely used in dynamic finite element analyses of slender structures such as cables and mooring lines due to its computational efficiency and its ability to accurately capture transient response characteristics [29].

Hydrodynamic drag

In addition to gravity and inertia, the model includes hydrodynamic drag as a distributed velocity-dependent load. The drag force is evaluated from the relative velocity between the cable and the surrounding water, consistent with a Morison-type approach. In simplified form, the drag load per unit length may be written as

$$\mathbf{f}_d = \frac{1}{2} \rho C_d D |\mathbf{v}_r| \mathbf{v}_r, \quad (5.10)$$

where ρ is the fluid density, C_d the drag coefficient, D the cable diameter, and $\mathbf{v}_r$ the relative velocity vector. Such a drag representation is standard in offshore hydrodynamics and is widely used when the structural diameter is small compared with the wavelength [29].

In the present implementation, drag is evaluated dynamically from the current nodal velocities and is added to the residual force vector separately from the static structural forces. This allows damping and transient flow effects to be captured without modifying the underlying static residual formulation.

Seabed contact

Seabed interaction is included through the same penalty-based contact formulation as in the static model. When a node penetrates the seabed, an upward normal reaction is activated:

$$F_n = k_n x_p, \quad (5.11)$$

where k_n is the seabed penalty stiffness and x_p is the penetration depth. Penalty methods are a standard and computationally convenient way to handle contact in nonlinear FE simulations.

Seabed friction

Although the general formulation allows tangential contact resistance to be included through a Coulomb-type friction law, friction is neglected in the main dynamic analyses presented in this thesis. As discussed in Section 5.1, this simplification was introduced because friction significantly increases numerical complexity while having a limited influence on the recurrence of the compressive wave phenomenon in the investigated cases.

Boundary excitation and end loads

The upper boundary motion is prescribed through the chute kinematics, with the end-node coordinates defined as time-dependent input functions:

$$x_A = x_A(t), \quad z_A = z_A(t). \quad (5.12)$$

This means that vessel-induced motion is introduced directly at the cable entry point, rather than through vessel RAOs. In addition, a time-dependent external force can be applied at the lower end of the cable if required by the simulation case. This treatment is fully consistent with standard FE practice, where prescribed nodal

5.4.3 Equation of Motion

After spatial discretisation, the dynamic cable problem can be written in the standard semi-discrete form

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{R}_{\text{int}}(\mathbf{q}) + \mathbf{R}_c(\mathbf{q}, \dot{\mathbf{q}}, t) = \mathbf{R}_{\text{ext}}(t), \quad (5.13)$$

where $\mathbf{M}$ is the lumped mass matrix, $\mathbf{R}_{\text{int}}$ contains the internal structural forces due to axial deformation and bending, $\mathbf{R}_c$ contains contact, friction, and drag-related contributions, and $\mathbf{R}_{\text{ext}}$ represents externally applied nodal forces and prescribed boundary excitation.

The problem is nonlinear for several reasons. First, the internal forces depend nonlinearly on the current nodal coordinates because the cable undergoes large displacements and rotations. Second, contact with the seabed introduces changing constraint conditions. Third, the hydrodynamic drag depends on the instantaneous nodal velocities and therefore contributes additional nonlinear terms. As a result, the governing equations must be solved incrementally in time using an iterative nonlinear method [29].

5.4.4 Newmark-Beta Method Solver

Time integration is performed using the implicit Newmark-beta method. This method is widely used in structural dynamics because it is robust, easy to implement, and unconditionally stable for linear systems when appropriate parameter values are chosen [21].

For a time step Δt , the Newmark update equations are

$$\mathbf{q}_{n+1} = \mathbf{q}_n + \Delta t \dot{\mathbf{q}}_n + \Delta t^2 \left[\left(\frac{1}{2} - \beta \right) \ddot{\mathbf{q}}_n + \beta \ddot{\mathbf{q}}_{n+1} \right], \quad (5.14)$$

$$\dot{\mathbf{q}}_{n+1} = \dot{\mathbf{q}}_n + \Delta t [(1 - \gamma) \ddot{\mathbf{q}}_n + \gamma \ddot{\mathbf{q}}_{n+1}]. \quad (5.15)$$

In the present implementation, the parameters are taken as

$$\beta = 0.25, \quad \gamma = 0.5, \quad (5.16)$$

which corresponds to the average acceleration scheme. This choice is classical in nonlinear structural dynamics and provides a good balance between stability and accuracy [14].

Because the internal and external forces depend on the unknown configuration at time step $n + 1$, the Newmark update yields a nonlinear system that must be solved iteratively at each time step.

5.4.5 Nonlinear Solution Procedure

At each time step, the Newmark discretisation leads to a nonlinear residual equation of the form

$$\mathbf{G}(\mathbf{q}_{n+1}) = \mathbf{0}, \quad (5.17)$$

where $\mathbf{G}$ contains the inertia contribution as well as the structural, contact, and drag forces evaluated at the trial state. This nonlinear system is solved with a Newton-type iterative procedure.

Linearising around the current iterate $\mathbf{q}^k$ gives

$$\mathbf{K}_{\text{eff}}(\mathbf{q}^k) \Delta \mathbf{q}^k = -\mathbf{G}(\mathbf{q}^k), \quad (5.18)$$

followed by the update

$$\mathbf{q}^{k+1} = \mathbf{q}^k + \Delta \mathbf{q}^k. \quad (5.19)$$

The effective tangent matrix $\mathbf{K}_{\text{eff}}$ includes the contribution of the mass matrix arising from the Newmark discretisation as well as the tangent of the nonlinear force terms. Newton-type methods are the standard approach for nonlinear FE equilibrium and dynamic problems because of their rapid local convergence when the tangent is sufficiently accurate [4].

In the present Python implementation, the tangent matrix is approximated numerically by finite differences of the residual rather than derived analytically. This reduces implementation complexity and is acceptable in a research-oriented model, although it increases the computational cost. To improve robustness in the presence of strong nonlinearities, such as seabed contact or step damping, line-search control can be applied when necessary. Such globalisation techniques are standard in nonlinear mechanics solvers [4, 35].

5.4.6 Dynamic Input Data

The dynamic model is driven by time-dependent boundary conditions derived from the processed vessel and ROV data. The upper boundary of the cable is prescribed by the motion of the chute, while the touchdown region is represented through the ROV-derived horizontal position of point B.

The vertical motion of the upper boundary, $z_A(t)$, is obtained from the vessel motion data. The measured heave, roll, and pitch are transformed to the chute location, since the chute is offset from the vessel reference point. In this way, the vessel motion is reduced to a prescribed vertical displacement at the cable departure point. The horizontal position of the upper boundary, $x_A(t)$, is kept constant in the present two-dimensional formulation.

The lower moving boundary is defined by the ROV-based touchdown point estimate. The horizontal ROV position is interpreted as the prescribed horizontal position of point B, $x_B(t)$. The vertical position of point B, $z_B(t)$, is set to the seabed elevation and held constant throughout the simulation. This means that the model captures the measured horizontal movement of the touchdown region while assuming a locally flat seabed.

The simulation timestep is obtained from the processed time-gap data. A constant timestep is used based on the median positive value of the measured time increments. This provides a stable and consistent temporal discretisation for the Newmark-beta integration scheme.

5.4.7 Boundary Motion and Chute Representation

A central aspect of the dynamic model is the representation of the upper boundary motion. Rather than modelling the complete vessel dynamics, the motion at the chute is prescribed directly from measured

or pre-processed time histories. This greatly simplifies the model while still capturing the physical excitation that is transferred from the vessel to the cable.

In the implementation, the chute can be represented geometrically and linked to the motion of the upper cable end. The horizontal and vertical motions of the upper node are imposed through the functions $x_A(t)$ and $z_A(t)$, and these functions may be based on realistic project data. This approach is consistent with the modelling philosophy adopted throughout the thesis: the cable response is studied under realistic boundary excitation, without introducing the extra complexity and confidentiality issues associated with full-vessel RAO modelling.

5.4.8 Dynamic Touchdown Behaviour and Output Quantities

During the simulation, the touchdown point is no longer fixed but moves as a function of time. Its position depends on the instantaneous cable shape, the local contact state, and the transient balance between inertia, internal forces, and seabed reaction. In practice, the touchdown region is identified from the nodes' contact states, as for the static FE model, but now evaluated at each time step. This allows tracking touchdown migration and studying whether compressive regions or rapid tension changes develop locally.

The solver stores time histories of nodal positions, velocities, accelerations, end reactions, nodal force components, tension, contact forces, and boundary motion. These outputs are essential for comparing the Python model to OrcaFlex and the FE Model, and for evaluating the temporal and spatial development of compressive waves. In particular, the evolution of axial tension near the touchdown point is one of the most important indicators for identifying the onset and propagation of compressive behaviour in the cable.

5.4.9 Role in the Overall Workflow

The dynamic Python model is the primary tool for investigating transient cable behaviour under realistic lay conditions. The static model provides the initial equilibrium geometry, while the dynamic model predicts how the cable evolves once the chute motion and other time-dependent excitations are applied. In this sense, both models are closely connected: the static model defines the physically meaningful initial configuration, and the dynamic model describes how the system evolves from that configuration over time.

This dynamic framework enables the study not only of the global cable shape and tension response, but also of local transient mechanisms near the touchdown zone that cannot be captured by a purely static formulation. For that reason, it forms the basis for the later comparison with commercial software and for the analysis of the recurrence of compressive wave events.

5.5 Dynamic Model verification

The dynamic model is validated by comparing the time-dependent response of the Python model with OrcaFlex simulations for several representative cases. Whereas the static verification focused on the cable's equilibrium configuration, the dynamic verification assesses whether the model can also reproduce the cable's transient evolution in geometry and effective tension. The comparison assesses the accuracy of the predicted cable motion, the tension development along the cable, and the influence of dynamic effects, such as inertia, bending, and contact with surrounding boundaries.

It should be noted that the dynamic verification is currently limited to relatively simple (easy-state) cases. More complex dynamic scenarios, such as highly nonlinear configurations or cases with strong contact interactions, are not yet included. As a result, the verification mainly demonstrates the model's capability under controlled conditions, and further work is required to confirm its accuracy in more challenging dynamic regimes.

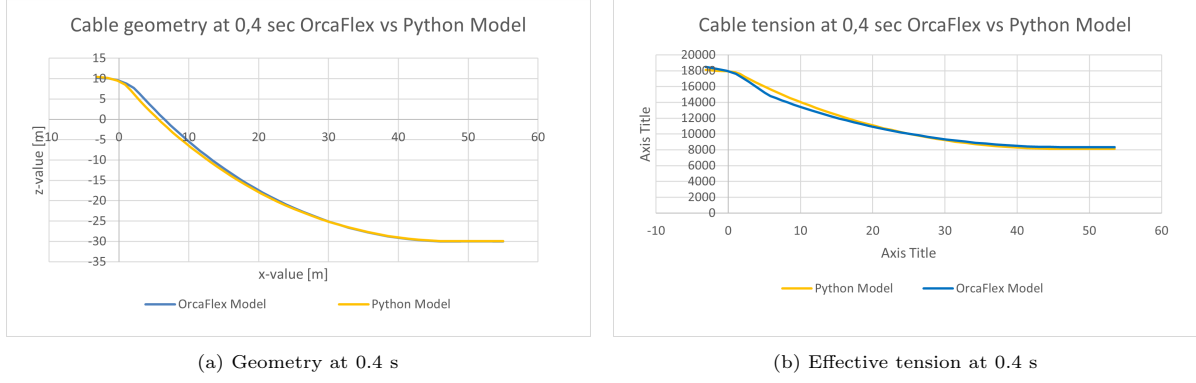


Figure 5.11: Comparison of the cable geometry and effective tension for the easy-state dynamic validation case.

5.6 Scope limitation of the dynamic validation

The methodology presented in Chapter 8 included a final comparison under more severe sea-state conditions, specifically to investigate whether the compressive-wave behaviour observed in OrcaFlex could also be reproduced in the Python finite element model under equivalent boundary excitation. In practice, this step required measured operational data to define realistic time-dependent boundary conditions, including vessel-induced chute motion and touchdown-related information. Since the Python model was intentionally formulated using measured boundary motion rather than full vessel RAO modelling, the realism of the severe-case simulation depended directly on the availability of suitable field data.

For the project data available within the scope of this thesis, no severe sea-state case was found for which the required measurements were available with sufficient completeness and reliability. As a result, dynamic validation could be performed only for a steady-state case. The results of this thesis, therefore, demonstrate that the Python model can reproduce the observed response for almost static conditions, but they do not constitute a field-validated assessment of compressive-wave behaviour under severe sea states. In Table 5.3, an overview of the different relevant cases can be seen. All of these cases have been selected to be at a speed close to 0.0 m/s. And the vessel is in normal lay operation. In this configuration, the ROV is supposed to be positioned to monitor the touchdown point. However, in several cases, no valid ROV data was captured, and it could not be used.

Table 5.3: Summary of motion cases

Case	Total elapsed time [s]	Δz_A [m]	Δx_B [m]
11 April 2026	4002.00	3.965643	9.180037
28 April 2026	4.96	0.358154	0.438313
Case 1 8 May 2026	36.00	0.283114	0.877302
Case 1 9 May 2026	16470.00	0.496202	0.496202
5th of December 2025	3450.02	-0.958578	N/A
Case 2 8 May 2026	492.00	0.343114	N/A
Case 2 9 May 2026	13375.98	1.736701	N/A
3 May 2026	2193.02	0.273848	N/A
4 May 2026	60641.01	1.039338	N/A

Reasoning for Cable Laying operational limits

No data is recorded during severe sea states due to a combination of operational, safety, and environmental constraints. First, the decision to continue or abort operations is taken by the Offshore Installation Manager (OIM) or the vessel captain whenever the second end pull-in cannot be performed safely. During such operations, the vessel's heading is fixed, limiting the ability to respond to changing wind directions. In the presence of strong beam winds or excessive environmental loads, the vessel may no longer be able to maintain its position safely, even when considering redundancy in thrusters or

engines required by the dynamic positioning (DP) system. In these conditions, operations are halted and the vessel is moved to a safer heading, typically into the wind, until conditions improve (so-called survival mode).

Additionally, operational limitations of support vessels play a role. The walk-to-work vessel may be unable to safely transfer personnel to the transition piece (TP) due to excessive vessel motions, for example, when the motion-compensated gangway (e.g., Ampelmann system) exceeds its operational limits. This prevents the execution of the pull-in activities.

Weather conditions such as thunderstorms further restrict operations, as working on the tower or even moving on deck becomes unsafe. Furthermore, swell conditions are a critical but often underestimated factor. Even when the significant wave height (H_s) remains within operational limits, long-period swell (typically with periods of 7–8 seconds or longer) approaching from unfavourable directions (e.g., beam seas) can induce excessive vessel motions such as roll and heave. This significantly affects station-keeping capability and operational safety during the second end pull-in, especially in configurations with quadrant overboarding.

If the combined effects of environmental loads result in vessel motions or DP performance outside acceptable limits, operations are not initiated or are stopped, and alternative strategies may be considered, such as selecting a different cable or waiting for more favourable conditions. In some cases, if environmental predictions prove inaccurate or swell conditions evolve differently than expected, the vessel may need to enter survival mode before even starting critical operations.

Finally, it should be noted that long-period swell with low wave height may still have a significant impact on vessel behaviour, although this effect is often overlooked in analyses. Altogether, these constraints explain why no operational data is captured during severe sea states.

5.7 Limitations of the Dynamic FE Model

An important practical limitation of the dynamic model is its reduced numerical robustness as the bending stiffness increases. In the current implementation, quasi-static and dynamically flexible cases can converge satisfactorily, whereas simulations with higher flexural rigidity can lose convergence over time. This behaviour is consistent with the structure of the implemented formulation.

The primary reason is that the bending contribution becomes strongly sensitive to small geometric changes when the flexural rigidity is large. In the finite-element force assembly, curvature is computed from the change in angle between adjacent segments, and the local bending moment is evaluated as $M = EI \kappa$. As a result, increasing EI does not merely scale the bending response; it also increases the sensitivity of the residual force vector to perturbations in the nodal coordinates. The nonlinear equilibrium equations thereby become significantly stiffer and harder to solve iteratively.

A second factor is the discrete curvature representation itself. Curvature is evaluated from the turning angle between neighbouring straight segments rather than from a smooth beam interpolation. This is a practical approximation, but it can produce a relatively sharp response to small nodal movements, especially in regions with local contact, chute interaction, or touchdown. For low bending stiffness, these discretisation effects may remain limited, but for large EI , they are directly amplified into large bending moments and, correspondingly, large nodal force corrections.

The problem is further aggravated by the constitutive treatment of bending stiffness. The implementation uses a piecewise curvature-dependent flexural rigidity, with one stiffness below a prescribed curvature threshold and another above it. This introduces a non-smooth constitutive transition in the residual. Newton-type methods are known to perform best when the residual is smooth and differentiable; when the curvature state crosses a threshold, the local tangent may change abruptly. This effect becomes increasingly severe as the absolute stiffness level rises, and it can contribute to the observed loss of convergence in high-stiffness simulations.

Another important aspect is that the tangent matrices in both the static and dynamic solvers are not assembled analytically, but approximated by finite differences of the residual. This means that the Jacobian quality depends on the chosen perturbation size and on the local smoothness of the

response. For strongly bending-dominated configurations, the residual varies more sharply with position, making the finite-difference approximation more sensitive to numerical noise and local non-smoothness. Consequently, the Newton update may become inaccurate exactly in the regime where an accurate tangent is most needed.

In the dynamic formulation, the issue becomes even more pronounced because the implicit Newmark step solves a nonlinear system based on the effective matrix

$$K_{\text{eff}} = \frac{1}{\beta \Delta t^2} M - K_q,$$

. where K_q is the tangent of the structural residual. When the bending stiffness is increased, the structural tangent grows in magnitude, while the inertial regularisation term remains controlled by the chosen time step Δt . If the time step is not reduced accordingly, the effective system can become difficult to solve, and the Newton iterations may stall or diverge even though the same formulation remains stable for more flexible cases. In that sense, the loss of convergence is not only a material-stiffness issue, but also a stiffness–time-step compatibility issue.

Finally, the dynamic cable model combines bending stiffness with additional nonlinearities such as seabed contact, regularised friction, and remeshing of the suspended span when the touchdown location changes. These mechanisms already challenge solver robustness in highly nonlinear phases of motion. When the cable is very flexible, the resulting force redistribution remains relatively smooth. When the cable is stiffer in bending, however, the same local geometric transitions generate much larger restoring moments and a more abrupt residual response. This provides a plausible explanation for why convergence difficulties tend to arise only after some time, namely, when the evolving configuration enters a sufficiently curved or contact-dominated regime.

Overall, the observed loss of convergence at large bending stiffness should therefore be interpreted as a structural limitation of the current numerical formulation rather than as an isolated implementation defect. The combination of a curvature-based discrete bending model, a piecewise stiffness law, finite-difference Jacobians, and an implicitly integrated nonlinear dynamic solve makes the formulation increasingly sensitive to EI as EI is increased. This limitation should be explicitly acknowledged when discussing the model’s valid operating range.

Chapter 6

Tension Analysis

6.1 Tensioners

6.1.1 Tensioner Description

A tensioner on board a cable-laying vessel is a mechanical system that grips and controls cable movement during installation. The system typically consists of two opposing tracks: one above and one below the subsea power cable. These tracks form a clamping mechanism that firmly holds the cable in place.

The tracks serve two primary functions:

- Application of normal force (squeeze force)
The tracks apply a controlled vertical force on the cable, pressing it between them. This force is necessary to generate sufficient friction to prevent uncontrolled movement of the cable.
- Controlled movement of the cable
Both tracks are driven by hydraulic motors and rotate at a predefined speed. This rotational movement defines the payout rate of the cable. Importantly, this rate is fixed and does not automatically adapt to sudden vessel motions.

Because of this fixed payout rate, the tensioner does not actively accelerate in response to external disturbances (e.g., vessel surge due to waves). Instead, if the vessel makes a sudden movement, the cable may slip between the tracks. This will occur only when the tension on the cable exceeds the friction force between the subsea power cable and the tensioner tracks.

Cable manufacturers specify a maximum allowable squeeze (clamping) force, which must not be exceeded, as excessive compression can damage the cable structure.

Squeeze Load

Squeezing force is an important mechanical load acting on the cable during installation. This force arises from the gripping mechanism of the tensioner tracks, which applies a controlled normal load to prevent slippage while maintaining the required installation tension. As a result, squeezing forces can locally deform the cable's outer layers, increase contact pressures, and contribute significantly to the build-up of residual tension after the cable leaves the lay-vessel equipment. Excessive squeezing may damage the cable's internal structure. A schematic representation or magnitude estimate of this squeezing force is shown in Figure 6.1.

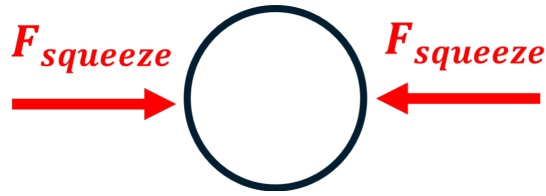


Figure 6.1: Squeeze Load [12]

6.1.2 Function of the Tensioner

The primary function of the tensioner is to control both the tension and the payout rate of the cable during installation. By regulating these two parameters, the installation process can be carefully managed.

A key outcome of this control is the ability to influence the touchdown point. Although not directly controlling it, adjustments in tension and payout shift the touchdown point within a certain margin, which is crucial for accurate cable placement.

6.1.3 Tension Measurement and Interpretation

During cable laying operations, the tension measured at the tensioner is typically expressed in kN. However, this measurement does not represent the true top tension of the cable suspended in the water column behind the vessel.

Instead, the measured value is influenced by two contributions:

- The tension in the cable already deployed behind the vessel
- The built-up tension within the cable highway (the routing system onboard the vessel in front of the tensioner)

As a result, the tensioner reading should be interpreted as a differential tension measurement rather than an absolute value. It reflects the balance of forces across the tensioner rather than the exact cable tension at a single point in the system. A visualisation of this can be seen in Figure 6.2.

Therefore, these values should not be used directly as top-tension values in engineering calculations. However, they are useful for monitoring installation performance, detecting anomalies, and analysing trends over a given time period during cable laying operations.

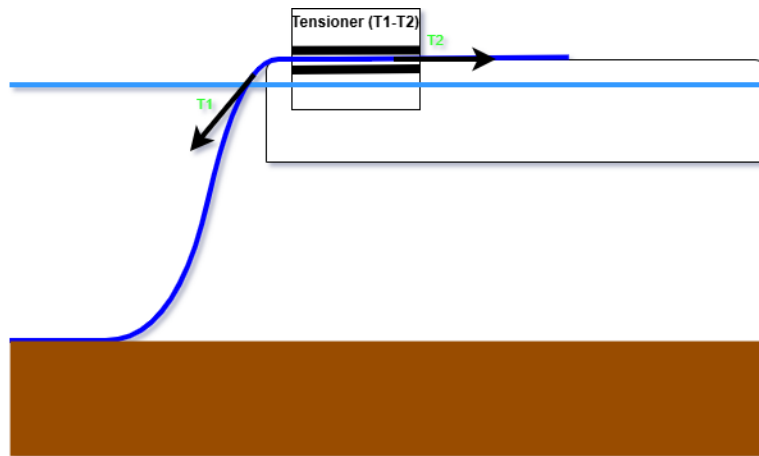


Figure 6.2: Tensioner set-up on board of the Living Stone

6.2 Set-up of the Analysis

To identify relevant cases for further analysis, a structured selection procedure was applied.

Firstly, all time periods during which the vessel was performing normal cable laying operations were identified. These periods form the baseline dataset, ensuring that only consistent operational conditions were considered.

For each candidate case, it was verified whether tensioner data was available in the online Grafana monitoring tool. Only those periods for which reliable and complete datasets were available were retained for further analysis.

Subsequently, the time series data were examined for distinct peaks and irregularities in the measured tension. Special focus was placed on events where the tension signal exhibited negative values, indicating relative compression rather than tensile loading.

For these events, additional data was extracted, specifically focusing on the chute motion responses during the same time intervals. This allowed for a more detailed analysis of the interaction between vessel motion and cable behaviour.

Applying this methodology resulted in the identification of the following cases:

Case	Date	Start Time	End Time	Timezone
1	14/07/2025	02:05	02:10	UTC-4
2	21/07/2025	00:48	00:55	UTC-4
3	10/08/2025	06:00	06:10	UTC-4
4	04/12/2025	23:10	23:12	UTC-5
5	04/12/2025	23:47	23:49	UTC-5
6	05/12/2025	00:22	00:30	UTC-5
7	07/12/2025	02:54	02:57	UTC-5
8	28/04/2026	11:45	12:30	UTC-4
9	07/05/2026	12:05	12:07	UTC-4
10	07/05/2026	22:15	23:17	UTC-4
11	08/05/2026	00:20	00:22	UTC-4

Table 6.1: Selected Cable Laying Cases

All selected cases, which can be seen in Table 6.1, are analysed using the OrcaFlex model developed within this thesis. For each case, the recorded vessel motions are extracted from the available Grafana measurement data and translated into the corresponding chute motions. Most cases analysed are export cables with high bending stiffness. For this reason, it was decided to disregard the Python model, as it is unable to handle high-bending-stiffness cables, as discussed in section 5.3.4. Instead, the OrcaFlex simulations are set up with the correct cable properties for each case, so that the cable's structural and hydrodynamic responses are represented as realistically as possible.

After implementing the case-specific input data, simulations are carried out for all selected events. The numerical results are then assessed with a specific focus on the occurrence of compressive behaviour in the cable. In parallel, available ROV video footage is reviewed over the same time intervals to investigate whether any visually observable compressive events correspond to the behaviour predicted by the simulations.

The outcomes of this combined numerical and visual assessment are presented and discussed in the following sections. Based on these results, the cases are compared to draw conclusions about the occurrence of compressive phenomena during cable installation. All these cases will be analysed in OrcaFlex.

6.2.1 OrcaFlex Analysis

All selected cases from the tension analysis were subsequently assessed in the dynamic analysis. The objective of this step was to determine whether the intervals showing relevant tension behaviour in

the operational data would also result in observable compressive-wave behaviour in the corresponding dynamic simulations.

For the investigated cases, no clear compressive waves were observed in the dynamic results. Although local variations in effective tension and cable curvature were present, these did not develop into travelling regions of axial compression near the touchdown point. The minimum effective tension remained within a range that did not indicate sustained or propagating compression waves. This outcome is consistent with observations from the tension analysis, in which the selected operational events did not provide clear evidence of compressive-wave behaviour.

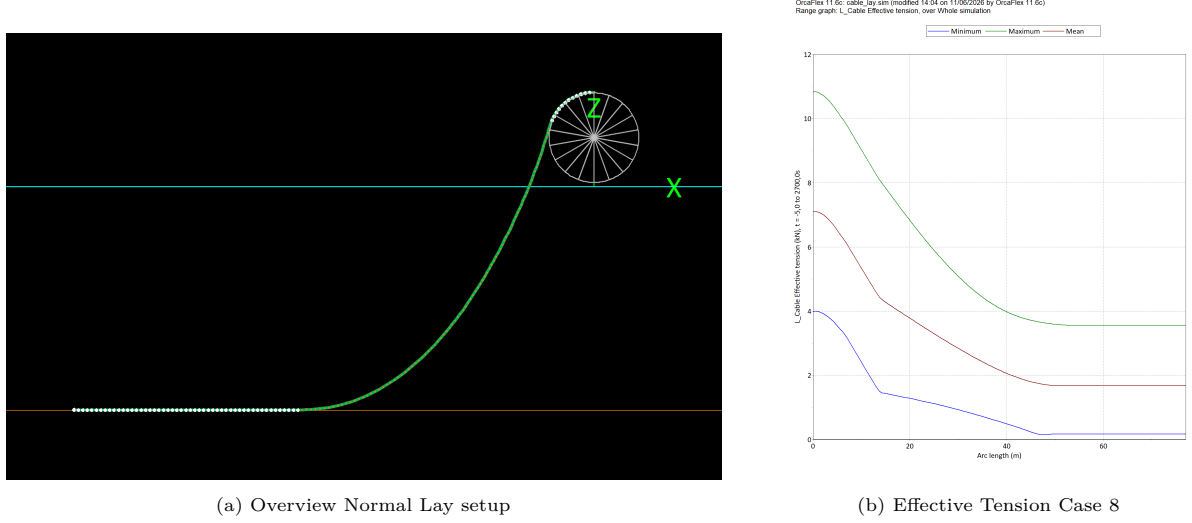


Figure 6.3: Combined figure showing setup and cable lay

The absence of compressive waves can be explained by the same practical limitations discussed earlier. The available operational cases represent normal lay conditions and do not include sufficiently severe dynamic excitation to trigger the phenomenon observed in critical OrcaFlex simulations. Furthermore, the vessel motions, touchdown point movement, and measured tension response remained within the operational range expected during controlled cable laying. As a result, the dynamic loading was not large enough to create the combination of axial compression and local curvature required for a compressive wave to develop.

This does not mean that compressive waves cannot occur in the model or in OrcaFlex simulations. Rather, it indicates that they were not reproduced for the selected field-based cases. Therefore, an additional numerical investigation is required to determine which modelling parameters can trigger the phenomenon. As a final step, the occurrence of compressive waves will be investigated by varying influential parameters: the cable's bending stiffness, the touchdown point location, the chute's excitation, and its speed. These parameters will first be varied separately to identify their individual influence on the cable response. Afterwards, they will be varied in combination to assess whether their interaction can reproduce the compressive-wave behaviour observed in OrcaFlex.

6.2.2 ROV Footage analysis

All available ROV footage corresponding to the selected normal lay cases has been systematically reviewed. Particular attention was given to identifying any visual indications of compressive wave behavior along the cable. However, no clear or consistent signs of compressive waves were observed in the footage. While minor variations in the cable's appearance and motion are visible, these do not indicate the presence of compressive wave formation and are more likely attributable to normal operational or environmental conditions.

In addition to the standard ROV video footage, supplementary data included targeted video recordings at the touchdown point and sonar sensor data for mapping the entire cable configuration. These

complementary perspectives provide both a localised view of the cable-seabed interaction and a global overview of the cable geometry. Together, they offer a more complete understanding of the cable behaviour during installation. Representative examples of these datasets are shown in Figure 6.4, where both the visual inspection at the touchdown point and the sonar-based cable mapping are illustrated.

(a) Video footage

(b) Sonar footage

Figure 6.4: fig:ROV footage

6.3 Parameter Variation

After the project-data-based dynamic cases were analysed, no clear compressive waves were observed under the investigated operational conditions. This indicates that the available project data did not contain sufficiently strong dynamic excitation to reproduce the compressive-wave behaviour observed in critical OrcaFlex simulations. Therefore, a parameter variation study was performed as a final step. The purpose of this study was to investigate which parameters are most influential in triggering compression, and whether compressive waves can be reproduced by varying these parameters in a controlled way.

The parameter study was divided into four parts. First, the cable's bending stiffness was varied. Second, the touchdown point location was varied. Third, the imposed chute motion was varied by applying a sinusoidal vertical motion. Finally, a combined case was investigated, in which bending stiffness and touchdown point location were adjusted for a boundary motion case in which no compressive wave had yet occurred.

An overview of the investigated variations is provided in Table 6.2. The corresponding simulation results are included in Appendix B.

Table 6.2: Overview of the parameter variations used to investigate compressive-wave occurrence

Variation group	Parameter varied	Appendix reference
Bending stiffness variation	Cable bending stiffness EI	Appendix B.2
Touchdown point variation	TDP / layback location	Appendix B.4
Motion variation	Chute motion period and velocity	Appendix B.5
Combination of factors	EI , TDP location, and chute motion	Appendix B.7

6.3.1 Bending Stiffness Variation

The first parameter investigated was the cable's bending stiffness. The bending stiffness determines the cable's resistance to local curvature. Since compressive waves are associated with a combination of axial compression and local bending, it was expected that the bending stiffness could influence the way compression is relieved through curvature.

The tested bending-stiffness values are shown in Appendix B.2. The variation ranged from very low bending stiffness values to the reference bending stiffness used in the cable model. The results show that changing the bending stiffness alone does not strongly influence the occurrence of compressive waves. For most bending-stiffness values, no travelling compression wave was observed.

However, for very low bending stiffnesses, limited local compression can occur. This can be explained by the fact that a very flexible cable can deform more easily, allowing local regions of negative effective tension to form. Nevertheless, these regions of compression did not develop into a clear propagating compressive wave. The bending stiffness, therefore, influences the local cable response, but does not appear to be the primary trigger for compressive-wave formation.

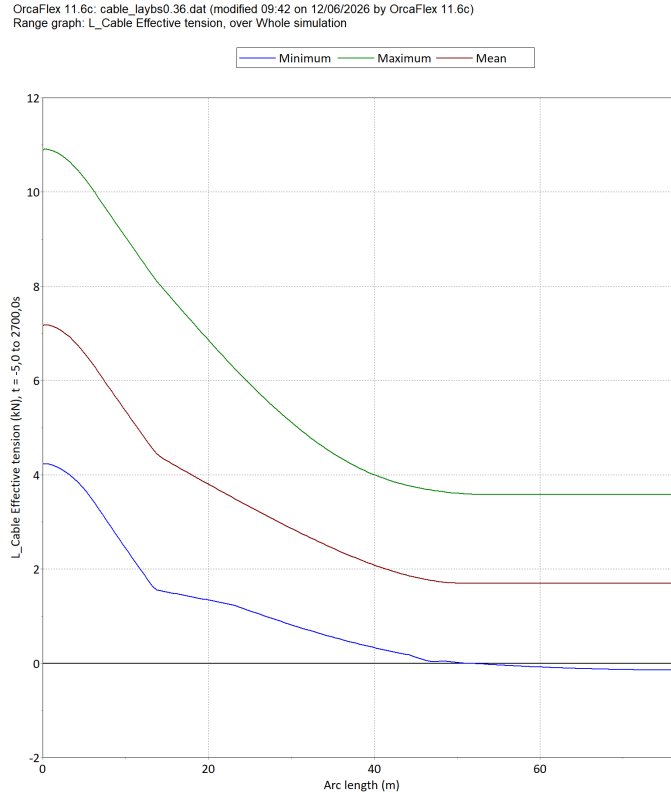


Figure 6.5: Low bending stiffness showing the max, mean and lowest effective tensions.

Figure 6.5 shows one of the most interesting bending-stiffness cases, for example, the case where local compression first becomes visible. This figure should preferably show the effective tension distribution along the cable, since the main observation concerns the occurrence of local negative tension rather than a large change in the cable's global geometry.

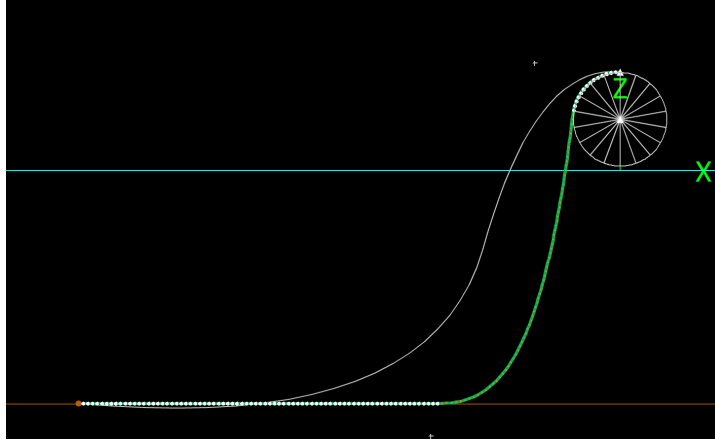
6.3.2 Touchdown Point Variation

The second parameter investigated was the touchdown point location. The touchdown point determines the global catenary geometry, the suspended span length, and the touchdown angle. These quantities influence the distribution of tension and the local curvature near the seabed. Therefore, the touchdown point was expected to have an influence on compressive behaviour.

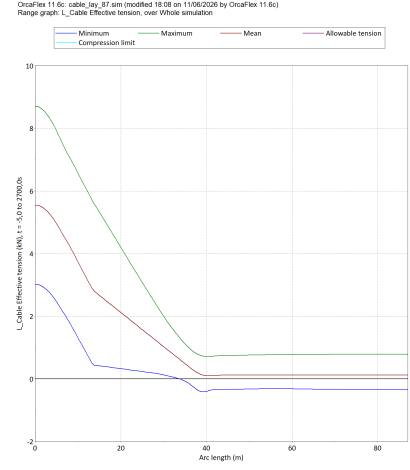
The touchdown point was varied over a wide range, from approximately 30 m layback to locations just below the vessel. The corresponding results are shown in Appendix B.4. This variation significantly alters the cable's static configuration. A shorter layback creates a steeper cable configuration, while a larger layback creates a more stretched suspended span.

The results show that changing the touchdown point location alone does not create a clear compressive wave. Some local compression can occur at extreme touchdown points, especially when the cable configuration is either very steep or very stretched. However, this compression remains local and does not develop into the characteristic travelling wave pattern.

This indicates that the touchdown point location affects the initial geometry and local force distribution, but is not, by itself, sufficient to trigger compressive-wave behaviour. Similar to the bending stiffness variation, the TDP location should therefore be interpreted as a secondary influence rather than as the main cause of compressive waves.



(a) Overview Normal Lay setup (Touchdown Point 20m)



(b) Effective Tension for different Touchdown Points

Figure 6.6: Combined figure showing setup and cable lay with TDP at 20m

When comparing Figure 6.3 and Figure 6.6, it can be seen that compression starts to occur. However, travelling compressive waves are not yet present. This remains the case for the other TDP cases, as shown in Appendix B.4.

6.3.3 Motion Variation

Since neither bending stiffness nor touchdown point location was sufficient to reproduce compressive waves independently, the imposed chute motion was varied next. This was done because the project data used in the earlier dynamic analyses appeared not to be dynamic enough to trigger the phenomenon. The measured chute motions remained within the range expected during normal lay operations, and no clear compressive waves were observed.

To investigate the influence of stronger dynamic excitation, a simplified sinusoidal vertical chute motion was imposed. In this variation study, the amplitude of the motion was varied between cases, while the period remained constant. The prescribed chute location was defined as

$$z_A(t) = a \sin(\omega t), \quad (6.1)$$

where $z_A(t)$ is the vertical chute position, t is time, a is the motion amplitude, and ω is the angular frequency. In this formulation, the period of motion is fixed, and the different cases are obtained by varying the amplitude a . A larger amplitude results in a larger chute displacement and a higher chute velocity.

The chute velocity is obtained by differentiating Equation 6.1 with respect to time:

$$\dot{z}_A(t) = \frac{d}{dt} [a \sin(\omega t)] = a\omega \cos(\omega t). \quad (6.2)$$

The maximum chute velocity is therefore

$$|\dot{z}_A|_{\max} = a\omega. \quad (6.3)$$

If the motion is described by a period P , the angular frequency is given by

$$\omega = \frac{2\pi}{P}. \quad (6.4)$$

Since the period is constant for all investigated cases, the maximum chute velocity varies linearly with the imposed amplitude:

$$|\dot{z}_A|_{\max} = a \frac{2\pi}{P}. \quad (6.5)$$

The different motion cases are shown in Appendix B.5. Table 6.3 gives the maximum chute velocity for the investigated amplitude variations. Since the period is constant, the increase in maximum chute velocity is solely caused by the increase in imposed motion amplitude.

Table 6.3: Maximum chute velocity for the imposed sinusoidal motion amplitude variations

Case	Amplitude a [m]	Period P [s]	Maximum speed [m/s]
Motion case 1	0.85	P	$0.85 \frac{2\pi}{P} = 5,338$
Motion case 2	0.95	P	$0.95 \frac{2\pi}{P} = 5,966$
Motion case 3	1.05	P	$1.05 \frac{2\pi}{P} = 6,594$
Motion case 4	1.10	P	$1.10 \frac{2\pi}{P} = 6,908$
Motion case 5	1.25	P	$1.25 \frac{2\pi}{P} = 7,850$

The results of the motion variation show that the speed of the chute is an important factor in the development of compressive waves. When the imposed motion amplitude is relatively small, the cable response remains close to quasi-static and no clear propagating compression wave is observed. As the motion amplitude increases, the maximum chute velocity increases, leading to stronger dynamic excitation of the suspended cable span. This increases the likelihood of local axial compression near the touchdown region.

This suggests that compressive waves are more strongly related to dynamic excitation than to static configuration changes alone. The bending stiffness and touchdown point location influence how the cable responds, but the imposed boundary velocity appears to be a more important trigger for the formation of compressive-wave behaviour. In the present study, this increase in boundary velocity is due to an increase in motion amplitude rather than a change in period.

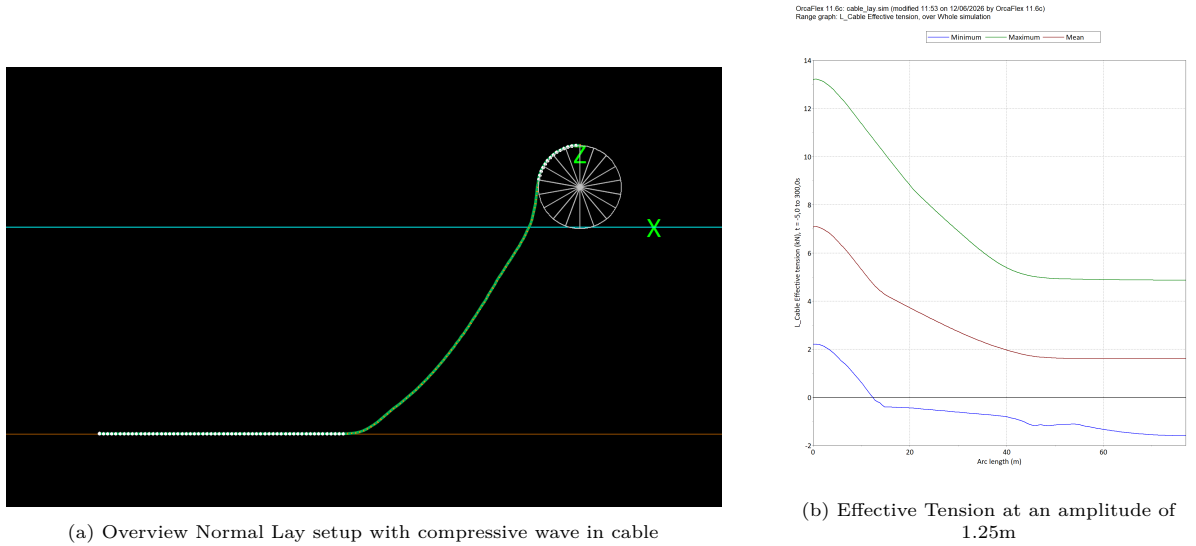


Figure 6.7: Combined figure showing setup and cable lay with a compressive wave

Figure 6.7 shows the first motion case where compression becomes visible. This is one of the most important figures in this section, because it supports the conclusion that chute velocity is a dominant factor. In the lower amplitude cases, no clear compressive waves are observed. At higher amplitudes, compressive waves continue to occur.

6.3.4 Cable weight variation

The Archimedes component (buoyancy) per unit length of the cable is equal to the mass of water displaced by the cable:

$$m_A = \rho_w \frac{\pi D^2}{4} \quad (6.6)$$

where

- m_A = Archimedes component (kg/m),
- ρ_w = water density (1025 kg/m³ for seawater),
- D = cable outer diameter (m).

For an outer diameter of

$$D = 0.1395 \text{ m}, \quad (6.7)$$

the displaced water mass per meter becomes

$$m_A = 1025 \times \frac{\pi(0.1395)^2}{4} = 15.67 \text{ kg/m}. \quad (6.8)$$

This value represents the buoyancy force expressed as an equivalent mass per unit length. Consequently, any cable with a submerged weight lower than 15.67 kg/m will experience a net upward force and will tend to float. Such a configuration is not relevant for the present analysis, as the objective is to investigate negatively buoyant cables that remain submerged.

Therefore, the cable weight is varied between

$$16 \leq w_c \leq 32 \text{ kg/m}, \quad (6.9)$$

using increments of

$$\Delta w_c = 2 \text{ kg/m}. \quad (6.10)$$

The resulting set of cable weights considered in the analysis is

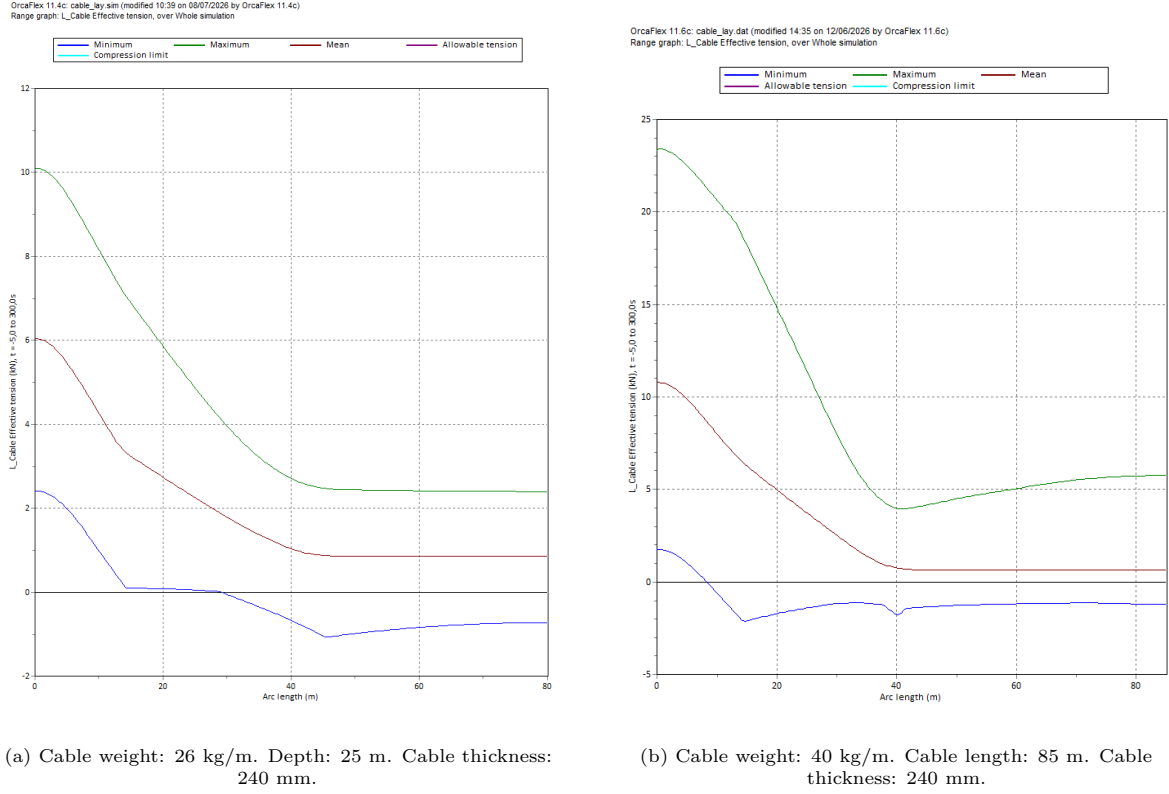
$$w_c = \{16, 18, 20, 22, 24, 26, 28, 30, 32\} \text{ kg/m}. \quad (6.11)$$

The cable weight per unit length was varied to investigate its influence on effective tension and the occurrence of compressive waves. The analysed cable weights ranged from 16 kg/m to 32 kg/m. The lower limit of 16 kg/m corresponds to a cable that is almost floating, since this value is close to the buoyancy limit.

The results show that cable weight significantly influences the formation of compressive waves. For very light cables, compressive waves are generated near the top of the suspended cable, close to the vessel, and propagate downwards towards the seabed. When the cable weight is increased, this compressive behaviour becomes less pronounced. From a cable weight of approximately 26 kg/m onwards, the downward-propagating compressive wave disappears completely, as can be seen in Figure 6.8a.

This indicates that the cable weight has a strong impact on the compressive wave phenomenon. A heavier cable can maintain a higher effective tension along its suspended length, thereby reducing the risk of compression.

However, the analysis also shows that compressive waves do not only depend on cable weight. When the layback is close to the vessel, the cable weight is high, and vessel motions are severe, compressive waves can begin to form at the bottom near the touchdown point. This case can be seen in Figure 6.8b. This demonstrates that cable weight is an important parameter, but it should not be considered independently.



Overall, it can be concluded that increasing the cable weight reduces the occurrence of compressive waves, especially for the waves that originate near the vessel and propagate towards the seabed. Nevertheless, the influence of chute speed should not be understated, as it remains an important factor in the cable's dynamic response and can contribute to the formation of compressive waves under unfavourable installation conditions. The rest of the cases can be seen in Appendix B.3.

6.3.5 Waterdepth Variation

The water depth was varied to investigate its influence on the effective tension response and the occurrence of compressive waves. In this analysis, the water depth was varied from 10 m to 40 m, while the layback was kept constant at 25 m. By keeping the layback fixed, the influence of the water depth on the suspended cable geometry and tension distribution could be studied more directly.

Changing the water depth significantly influences the cable configuration. At shallow depths, the suspended portion of the cable is relatively short, and the cable geometry remains compact. As water depth increases, the suspended cable length also increases, altering the global catenary shape and the distribution of effective tension along the cable. A deeper seabed results in a longer suspended span, which makes the cable more sensitive to dynamic excitation from the vessel and chute motion.

The results show that water depth significantly influences the formation of compressive waves. For smaller water depths, no clear travelling compressive wave is observed. The cable response remains

more stable, and the effective tension does not show strong propagating compression zones. However, as the water depth increases, compressive behaviour becomes easier to trigger. This indicates that deeper installation conditions are more sensitive to compressive-wave formation.

An important observation from the depth variation is that, for deeper seabeds, compressive waves can start near the seabed itself. In these cases, the compression originates close to the touchdown region and propagates upward into the suspended cable span. This differs from the behaviour observed for very light cables, where compressive waves were mainly generated near the vessel and propagated downwards. The depth variation, therefore, shows that the origin of the compressive wave depends on the combined effect of water depth, cable geometry, and dynamic excitation. The results also confirm that chute speed remains a dominant factor in the compressive-wave phenomenon. Increasing the water depth makes the cable more sensitive to compression, but the dynamic excitation imposed at the chute is still required to trigger a clear travelling wave. A deeper seabed, therefore, lowers the threshold for compressive-wave formation, while the chute velocity determines whether the dynamic loading is strong enough to initiate and sustain the wave.

Overall, it can be concluded that increasing the water depth increases the likelihood of compressive-wave occurrence. For deeper seabeds, the longer suspended cable span and changed touchdown geometry make it easier for compression to develop near the seabed. Nevertheless, the influence of chute speed should not be underestimated, as the imposed boundary motion remains one of the main drivers of the cable's dynamic response.

6.3.6 Combination of Factors

As a final check, a boundary motion case was selected in which no compressive waves had yet occurred, but where the motion level was close to the range where compression started to appear. This case was used to investigate whether changing the bending stiffness and touchdown point location could trigger compressive-wave behaviour when the dynamic excitation was already close to the apparent boundary case.

For this combined variation, both the bending stiffness and the touchdown point location were adjusted. The objective was to determine whether these parameters could push the cable response from a non-compressive state into a compressive-wave state. The corresponding results are shown in Appendix B.7.

The results show that the combination of a changed bending stiffness and modified touchdown point location did not produce a clear compressive wave for the selected boundary motion case. Although some local compression occurred on the seabed, this compression remained limited and did not develop into a propagating wave near the touchdown region. This indicates that the dynamic motion level was still not sufficient to create the characteristic compressive-wave response, even when the static configuration and bending stiffness were modified.

Therefore, the combined parameter study supports the conclusion that bending stiffness and touchdown point location are secondary parameters in the occurrence of compressive waves. They influence the local cable geometry and the distribution of compression once the cable is dynamically excited, but they do not appear to be the primary trigger. The imposed chute motion, and especially the associated chute velocity, appears to be the dominant factor in the formation of compressive waves in the investigated simulations. Figure 6.9 shows clear compressive behaviour in the cable for the minimum effective tension case, but no compressive waves occur throughout the simulation.

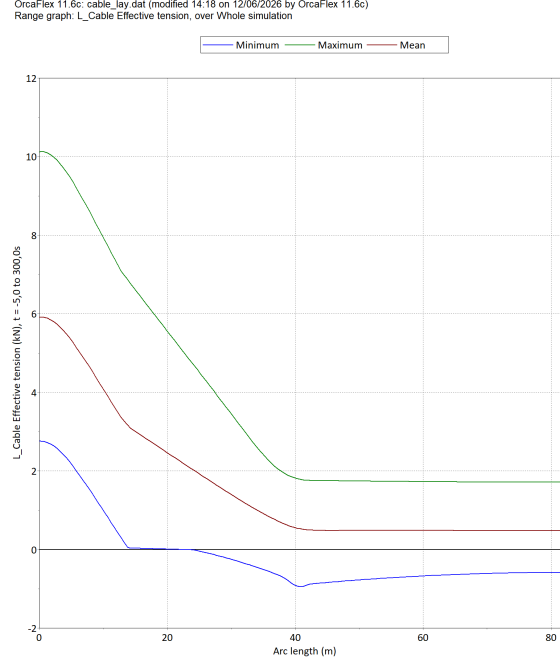


Figure 6.9: Combination with a bending stiffness of $1.5kNm^2$ and a touchdownpoint at 20m behind the chute.

6.4 Results

The tension analysis, dynamic simulations, and parameter variation study together provide a consistent picture of the conditions under which compressive behaviour may occur during cable installation.

From the operational data, eleven cases were selected in which the measured tensioner signal showed peaks, irregular behaviour, or negative values. These cases were analysed further using the OrcaFlex model developed in this thesis, with case-specific cable properties and imposed chute motions derived from the measured vessel response. The purpose was to determine whether the unusual tension behaviour observed in the field data could be linked to compressive phenomena in the suspended cable.

The simulations of the selected operational cases did not show clear travelling compressive waves. Although local reductions in effective tension were observed, and in some cases short regions of limited compression occurred, these effects remained local and did not develop into the characteristic propagating compressive-wave pattern near the touchdown point. This indicates that, despite showing irregular tensioner behaviour, the selected field cases did not contain sufficiently strong dynamic excitation to trigger compressive-wave formation in the numerical model.

This result is consistent with the interpretation of the tensioner measurements. Since the tensioner reading reflects a differential force across the tensioner rather than the true top tension in the suspended cable, negative or irregular values do not automatically imply that axial compression develops in the free cable span. Instead, they mainly indicate an imbalance between the tension behind the vessel and the built-up force in the cable highway. The simulations suggest that the observed operational tension anomalies are therefore not, by themselves, sufficient evidence of compressive-wave occurrence.

The separate parameter variation study provided additional insight into the governing mechanisms. Varying the bending stiffness of the cable showed that this parameter influences the local cable response, especially the ease with which local curvature and small compressive regions can develop. For very low bending stiffness values, limited local compression became visible. However, in none of these cases did the response develop into a clear travelling compressive wave. This shows that bending stiffness affects the manifestation of compression, but is not the primary trigger for the phenomenon.

A similar conclusion was found for the touchdown point variation. Changing the touchdown point

location significantly altered the cable's global geometry, layback, and local force distribution near the seabed. Extreme touchdown point positions led to some local compression, particularly for steep or highly stretched configurations, however, no distinct propagating compressive wave was observed. The touchdown point location, therefore, primarily serves as a secondary parameter that modifies the cable response rather than initiating compression on its own.

The most important result of the parameter study was obtained from the imposed motion variation. In these cases, a sinusoidal vertical chute motion was prescribed with increasing amplitude while keeping the period constant. Since the period remained unchanged, increasing the amplitude directly increased the maximum chute velocity. The simulations showed that for low amplitudes, the cable response remained largely quasi-static, with no clear compressive waves. As the amplitude and corresponding chute velocity increased, local compression near the touchdown region became more pronounced. At sufficiently high imposed motion amplitude, a clear compressive wave was observed in the OrcaFlex results. This demonstrates that the boundary motion speed, and more specifically the chute velocity, is the dominant factor in triggering compressive-wave behaviour in the investigated model.

The combined variation study confirmed this conclusion. A motion case just below the compression threshold was selected, after which both the bending stiffness and touchdown point location were modified in an attempt to force the system into a compressive-wave state. Although these combined changes increased the level of local compression, no propagating compressive wave developed. This confirms that favourable static conditions alone are not enough to produce the phenomenon when the dynamic excitation remains too low.

Overall, the results show that compressive waves were not reproduced in the selected project-data-based cases, indicating that this behaviour was not observed during the analysed normal lay operations. The numerical analyses indicate that the operational vessel motions remained within a range for which the cable response stayed predominantly tensile, even when the tensioner signal showed negative excursions. The additional parameter study demonstrates that compressive waves can occur in the model, but only when the imposed dynamic excitation becomes sufficiently strong. Among the investigated parameters, the imposed chute motion, particularly the resulting chute velocity, is the most influential. Bending stiffness and touchdown point location primarily determine how the cable responds once compression begins, but they do not appear to be the main cause of compressive-wave initiation.

These findings lead to the general conclusion that compressive-wave formation during cable installation is primarily a dynamic rather than a static phenomenon. Under normal lay conditions, the combination of cable geometry, bending stiffness, and operational vessel motions is not severe enough to generate sustained axial compression near the touchdown point. Only when the boundary motion becomes sufficiently rapid does the cable response transition toward compressive-wave behaviour.

Chapter 7

Conclusion

7.1 Results

The results of this thesis should be interpreted as a stepwise investigation into the occurrence of compressive waves during subsea power cable installation. First, the theoretical analysis showed that axial compression can arise in a simplified cable representation when a time-dependent transverse boundary motion is imposed. This demonstrates that compression is mechanically possible, but it does not, by itself, prove that the compressive waves observed in OrcaFlex occur during normal lay operations.

The static verification showed that the Python finite element model can reproduce the global cable configuration with sufficient accuracy for the purpose of this thesis. The model agreed with the analytical catenary solution under simplified assumptions and showed good agreement with OrcaFlex for realistic static cable configurations. The reference static comparison resulted in an RMSE of 0.185 m and a maximum deviation of 0.282 m. This indicates that the global force balance and cable geometry are captured adequately, although the model becomes less reliable for cases dominated by local bending and contact effects.

The dynamic validation using project data was limited by the available operational conditions. The selected project-data-based cases mainly represented calm or near-static normal lay operations. Consequently, no clear compressive waves were reproduced using the measured vessel and touchdown-related input data. This means that the available project data was not sufficiently dynamic to validate compressive-wave behaviour under severe excitation.

The parameter variation study provided the clearest insight into the conditions required to trigger compressive waves. Varying the bending stiffness showed that very low bending stiffness can lead to limited local compression, but it does not, in itself, generate a travelling compressive wave. Similarly, varying the touchdown point location altered the global catenary shape and local force distribution, but only led to local compression in more extreme configurations. No clear propagating compressive wave was produced by changing the touchdown point alone.

The imposed chute motion was found to be the most influential parameter. When the amplitude of the imposed sinusoidal chute motion was increased while keeping the period constant, the resulting chute velocity also increased. At low chute velocities, the cable response remained mainly quasi-static. At higher chute velocities, compressive waves were reproduced in the OrcaFlex simulations. This indicates that the formation of compressive waves is primarily governed by dynamic boundary excitation rather than by static cable configuration alone. The additional cable weight variation showed that submerged weight influences tension level and the cable's sensitivity to compression. Lighter cables were more prone to compressive behaviour, whereas increasing cable weight generally reduced compression by maintaining higher effective tension along the suspended span. However, cable weight alone did not provide a complete explanation for the phenomenon, since unfavourable combinations of cable geometry and dynamic excitation could still lead to compression.

The water depth variation showed that deeper water conditions increase the suspended span length and

modify the touchdown geometry. As the water depth increased, the cable became more sensitive to dynamic excitation, and compression was more easily initiated near the touchdown region. Nevertheless, water depth should also be considered a secondary parameter: it affects the cable configuration and sensitivity, but a sufficiently dynamic chute motion remains necessary to generate a clear travelling compressive wave.

The combined parameter study confirmed this interpretation. Even when bending stiffness, touchdown point location, cable weight, and water depth were varied, no travelling compressive wave developed when the imposed boundary motion remained below the required dynamic threshold. These results indicate that bending stiffness, touchdown location, cable weight, and water depth primarily influence the local cable response and its sensitivity to compression, whereas chute velocity is the dominant trigger.

Overall, the results show that compressive waves were not observed in the analysed project-data-based cases. They can be reproduced numerically, but only when the imposed boundary motion becomes sufficiently dynamic. Therefore, the analysed normal lay operations do not provide evidence of compressive waves, whereas the parameter study shows that the phenomenon cannot be fully excluded under more severe dynamic excitation.

7.2 Discussion

The tensioner analysis provides an important interpretation of the operational data, but it should not be treated as direct proof of compression in the suspended cable span. Several selected normal lay cases showed tension peaks, irregular tensioner behaviour, or negative measured tension values. However, the tensioner measurement represents a differential force across the onboard tensioner system rather than the true top tension of the free-hanging cable. It is influenced by both the cable already deployed behind the vessel and the built-up tension in the cable highway. For this reason, negative tensioner values cannot be interpreted directly as axial compression near the touchdown point.

The OrcaFlex simulations of the selected tensioner cases did not show clear travelling compressive waves. Some local reductions in effective tension were observed, and limited local compression occurred in certain cases, but these effects remained local and did not propagate. The available ROV and sonar observations also did not provide visual evidence of compressive-wave behaviour. The tensioner cases are therefore useful for identifying operational events of interest, but they do not confirm the presence of compressive waves during the analysed normal lay operations.

This supports the broader conclusion that the analysed field data did not contain sufficiently severe dynamic excitation to trigger the phenomenon. In normal lay conditions, vessel motions are intentionally kept within operational limits, and severe sea states are generally avoided for safety and workability reasons. It is therefore reasonable that the available measurements mostly represent mild dynamic conditions. As a result, the absence of compressive waves in the analysed data should not be interpreted as proof that the phenomenon can never occur. It only shows that it was not observed for the available normal lay cases.

The parameter variation study helps explain why the operational cases did not reproduce compressive waves. Variations in bending stiffness, touchdown point location, cable weight, and water depth all affected the local cable response, but none acted as a primary trigger when considered alone, without sufficiently strong boundary motion. Cable weight and water depth were found to influence the system's sensitivity: lighter cables and deeper water conditions increased the likelihood of compression, while heavier cables and shallower water conditions reduced the tendency toward compression. However, even in these cases, the dynamic excitation level remained decisive.

The most important practical implication is therefore that compressive-wave formation is mainly a dynamic phenomenon. Rapid chute motion, expressed through high chute velocity, appears to be the dominant trigger in the investigated simulations. Static parameters such as bending stiffness, touchdown point location, cable weight, and water depth determine how the cable responds once compression begins, but they do not, in themselves, initiate a travelling compressive wave. This distinction is important for installation assessments: attention should not only be given to static cable properties and geometry,

but also to transient vessel-induced chute motions.

A limitation of this conclusion is that the available operational data did not include a complete severe dynamic case with synchronised vessel motion, chute motion, tensioner data, ROV observation, lay speed, and environmental conditions. Further validation is therefore required using operational datasets from more dynamically severe installation conditions. Such data would make it possible to determine whether the compressive waves observed in numerical simulations can also occur in reality under unfavourable but physically realistic installation conditions.

7.3 Recommendations

The first recommendation is to collect more complete operational datasets during future cable-lay operations. The main limitation of this thesis is the lack of measured data for sufficiently dynamic conditions. For stronger validation, future datasets should include synchronised vessel motion data, chute motion, tensioner data, ROV-based touchdown-point observations, lay speed, and environmental data. These signals should be recorded with consistent timestamps so that they can be used directly as input for numerical simulations.

A second recommendation is to improve the interpretation of tensioner data. The tensioner signal is useful for detecting operational irregularities, but it should not be interpreted as the true cable tension in the suspended span. Future work should investigate the relation between tensioner measurements, cable highway effects, and actual top tension behind the vessel. This would make it easier to distinguish between onboard tensioner effects and true subsea cable response.

Third, future research should focus on identifying a dynamic threshold for compressive-wave formation. The parameter variation study indicates that chute velocity is an important trigger. Therefore, a systematic study should be performed in which chute amplitude, period, velocity, and acceleration are varied independently. This would enable determination of whether a critical boundary velocity or acceleration exists for the onset of compressive-wave behaviour.

A fourth recommendation is to further investigate the role of touchdown point behaviour. Although the touchdown point location did not, by itself, trigger compressive waves, it did influence local compression and seabed interaction. Future models should therefore include more detailed seabed contact behaviour, including friction, variation in seabed stiffness, and possible out-of-plane touchdown motion. This is especially relevant because real cable touchdown behaviour is three-dimensional and may differ from the simplified two-dimensional representation used in this thesis.

The Python model could also be improved. The current model is useful for understanding the governing mechanisms, but it becomes less robust in high-bending-stiffness cases. At this moment, it is based on three points provided by the cable manufacturer, as shown in Figure 2.3b. Future development should include a smoother bending stiffness formulation, an analytical tangent stiffness matrix, and improved contact treatment. These improvements would increase numerical stability and enable the simulation of a wider range of cable properties.

Finally, future verification should include a direct comparison between OrcaFlex, an improved independent numerical model, and measured offshore observations for a case with strong dynamic excitation. Only such a dataset would make it possible to determine whether compressive waves predicted in OrcaFlex are representative of real cable behaviour or mainly a result of modelling assumptions.

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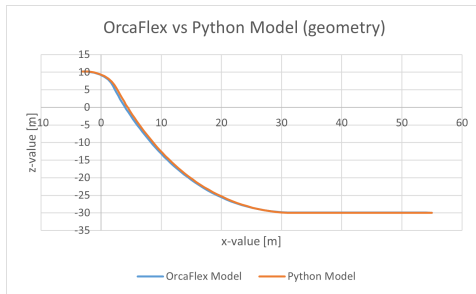
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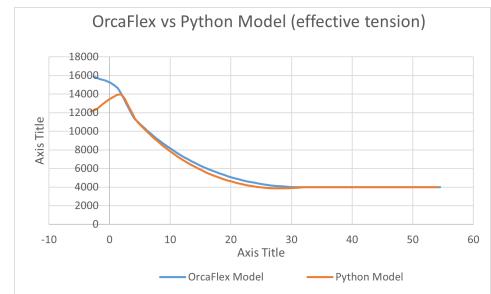
Appendix A

Appendix A Static Configuration

A.1 Subsea Power Cable 3x300mm²



(a) Geometry in static conditions for both Python model en OrcaFlex



(b) Tension in static condition for both Python model en OrcaFlex

Figure A.1: Static Configuration 3x300² Subsea Power Cable

Table A.1: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.185
Maximum deviation	0.282

Table A.2: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.125 m
Cable	Axial stiffness EA	1.42×10^8 N
Cable	Bending stiffness (stick) EI_1	5.5×10^3 N m ²
Cable	Bending stiffness (slip) EI_2	5.5×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.033 m ⁻¹
Cable	Submerged weight W	226.6 N/m
Cable	Buoyant force B_{up}	120.7 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

A.2 Subsea Power Cable 3x185mm²

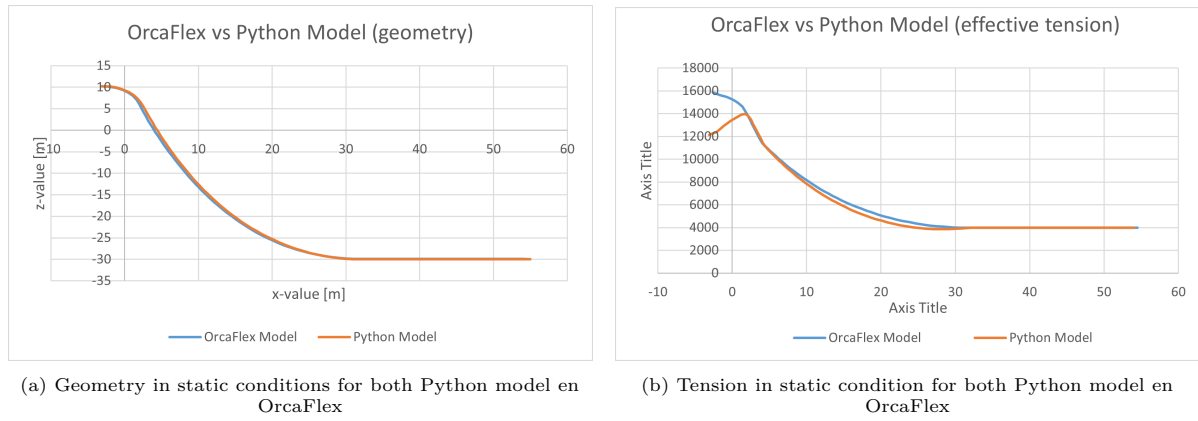
Figure A.2: Static Configuration 3x185² Subsea Power Cable

Table A.3: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.187
Maximum deviation	0.298

Table A.4: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.151 m
Cable	Axial stiffness EA	4.83×10^8 N
Cable	Bending stiffness (stick) EI_1	8.56×10^3 N m ²
Cable	Bending stiffness (slip) EI_2	8.56×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.033 m ⁻¹
Cable	Submerged weight W	428.6 N/m
Cable	Buoyant force B_{up}	162.3 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

A.3 Subsea Power Cable 3x150m²

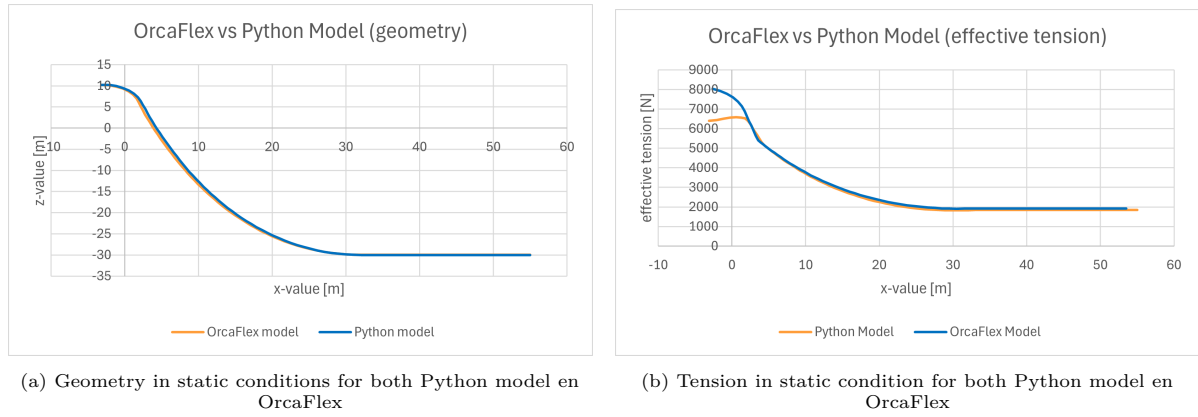
Figure A.3: Static Configuration 3x150² Subsea Power Cable

Table A.5: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.201
Maximum deviation	0.320

Table A.6: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.111 m
Cable	Axial stiffness EA	1.75×10^7 N
Cable	Bending stiffness (stick) EI_1	2.0×10^3 N m ²
Cable	Bending stiffness (slip) EI_2	2.0×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.033 m ⁻¹
Cable	Submerged weight W	196.2 N/m
Cable	Buoyant force B_{up}	78.48 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

A.4 Subsea Power Cable 3x630m²

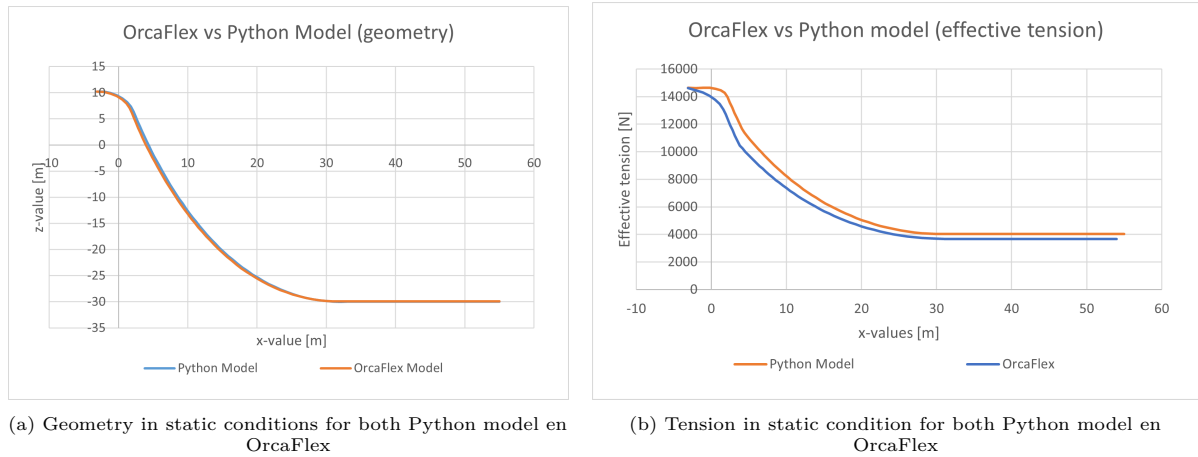
Figure A.4: Overall caption for both figures Static Configuration 3x630² Subsea Power Cable

Table A.7: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.182
Maximum deviation	0.280

Table A.8: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.149 m
Cable	Axial stiffness EA	4.60×10^8 N
Cable	Bending stiffness (stick) EI_1	2.65×10^3 N m ²
Cable	Bending stiffness (slip) EI_2	2.65×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.033 m ⁻¹
Cable	Submerged weight W	401.7 N/m
Cable	Buoyant force B_{up}	147.2 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

A.5 Subsea Power Cable 3x800m²

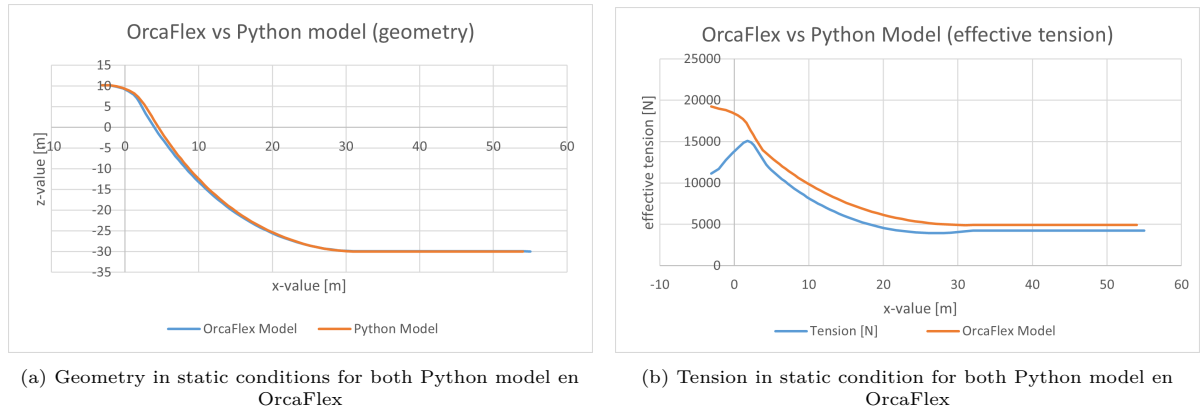
Figure A.5: Static Configuration 3x800² Subsea Power Cable

Table A.9: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.195
Maximum deviation	0.350

Table A.10: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.166 m
Cable	Axial stiffness EA	5.28×10^8 N
Cable	Bending stiffness (stick) EI_1	1.50×10^4 N m ²
Cable	Bending stiffness (slip) EI_2	3.16×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.040 m ⁻¹
Cable	Submerged weight W	499.8 N/m
Cable	Buoyant force B_{up}	196.7 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

A.6 Subsea Power Cable 3x500m²

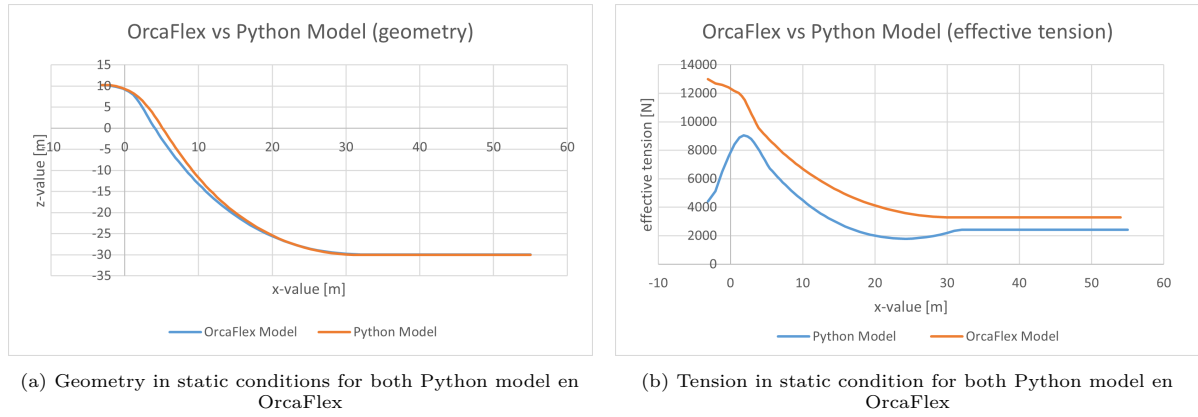
Figure A.6: Static Configuration 3x500² Subsea Power Cable

Table A.11: Comparison of cable shape between OrcaFlex and Python model

Metric	Value [m]
RMSE	0.304
Maximum deviation	0.565

Table A.12: Main input parameters used for the dynamic cable simulation (config.py)

Category	Parameter	Value
Geometry	Horizontal anchorpoint X_F	55.0 m
Geometry	Vertical anchorpoint Z_F	-30.0 m
Geometry	Cable length L	80.0 m
Geometry	Water depth	30.0 m
Cable	Outer diameter D	0.144 m
Cable	Axial stiffness EA	3.88×10^8 N
Cable	Bending stiffness (stick) EI_1	1.75×10^4 N m ²
Cable	Bending stiffness (slip) EI_2	3.29×10^3 N m ²
Cable	Transition curvature κ_{trans}	0.020 m ⁻¹
Cable	Submerged weight W	346.4 N/m
Cable	Buoyant force B_{up}	136.9 N/m
Cable	Friction coefficient μ	0.0
Environment	Fluid density ρ	1025.0 kg/m ³
Environment	Drag coefficient C_d	1.2
Environment	Seabed penalty stiffness k_{bot}	1.0×10^3 N/m
Chute	Radius	5.5 m
Solver	Number of nodes N	81
Solver	Static tolerance	10^{-6}

Appendix B

Tensioner Analysis

B.1 Project Data

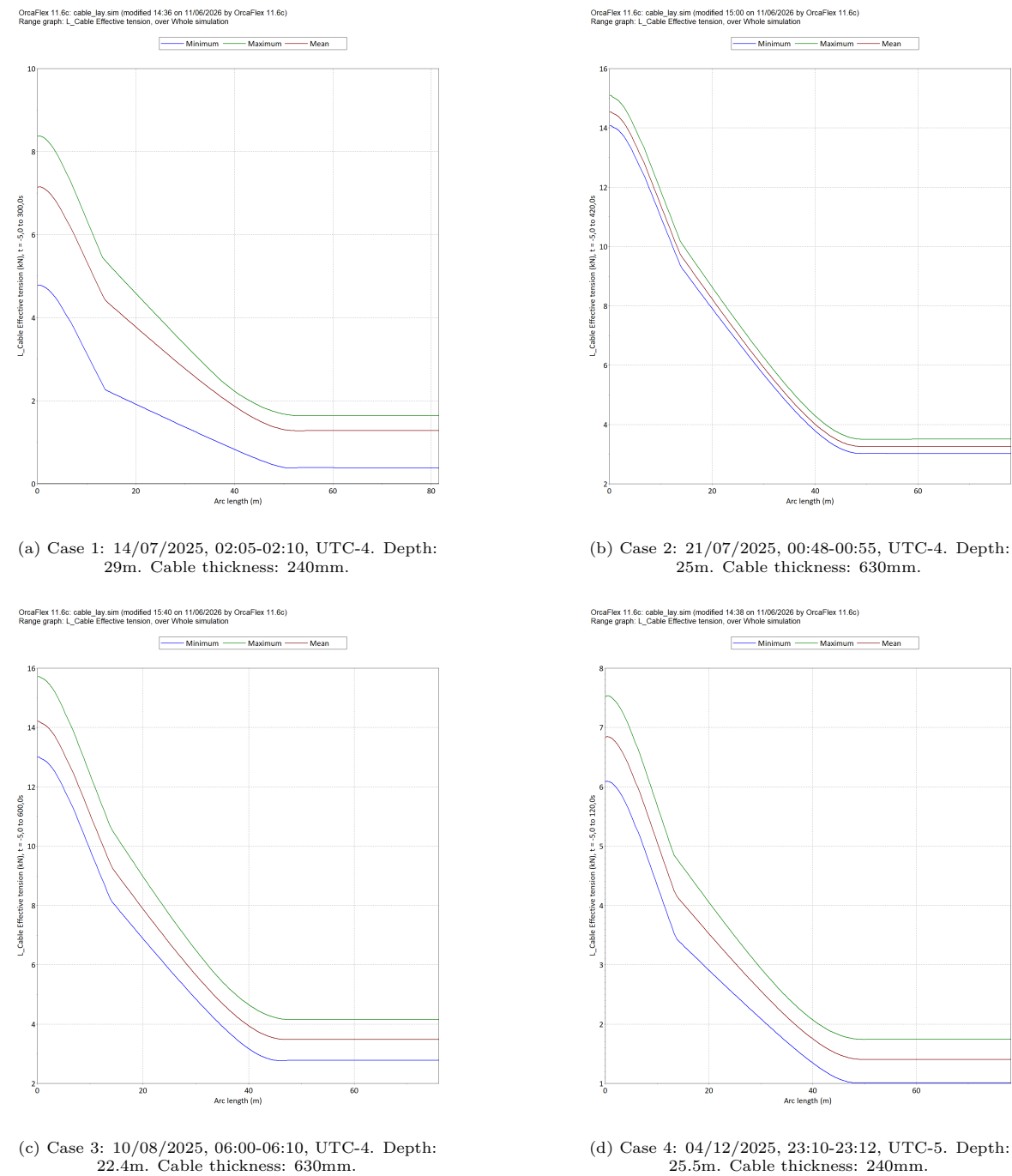


Figure B.1: Project data case 1-4

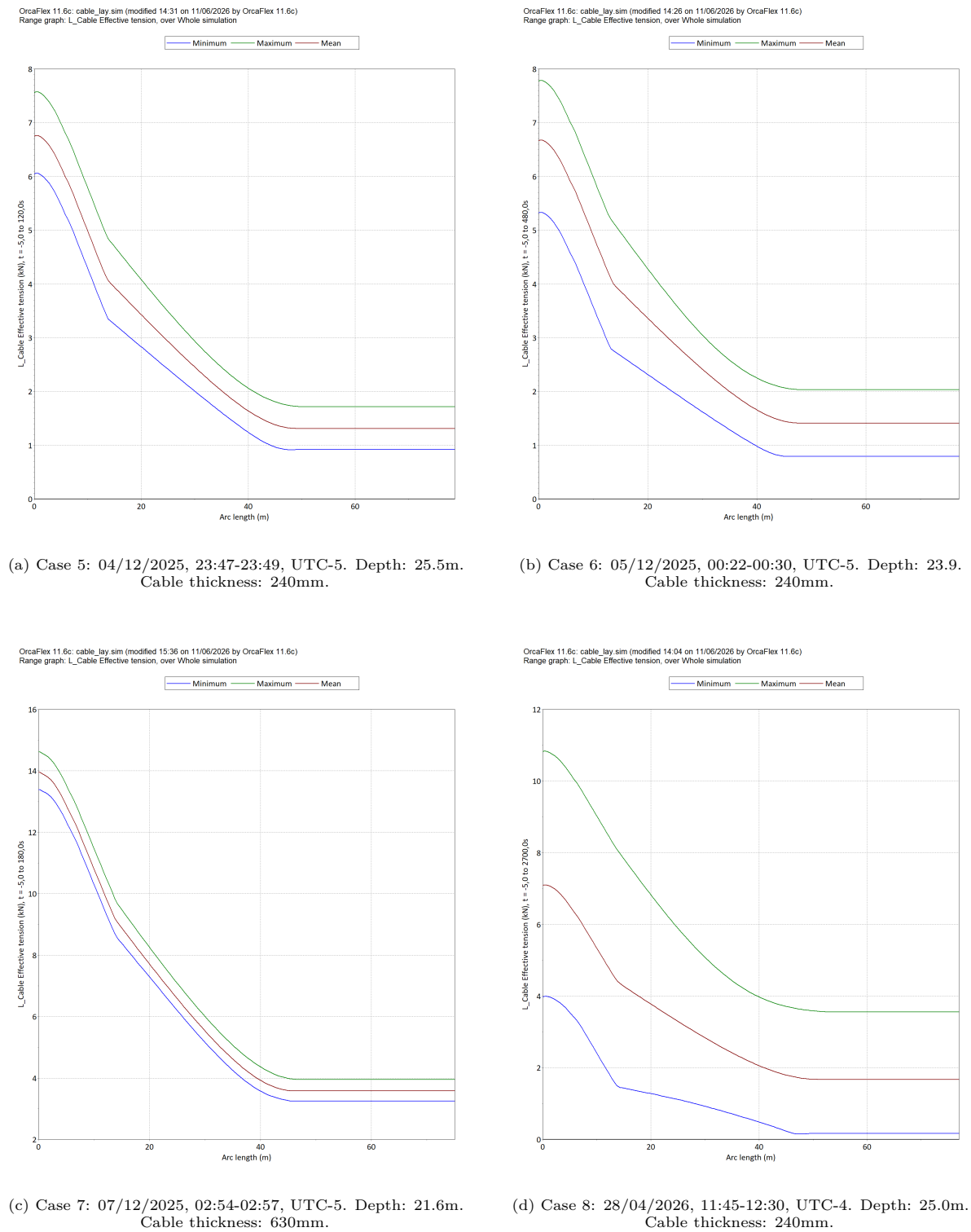


Figure B.2: Project data case 5-8

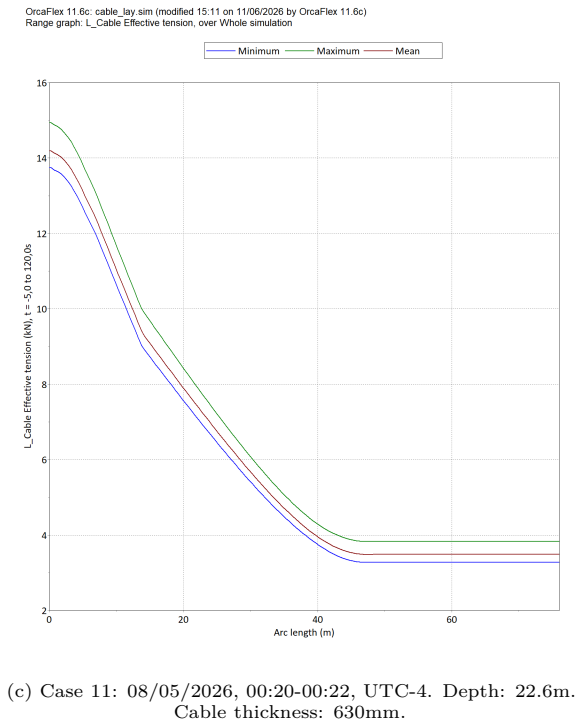
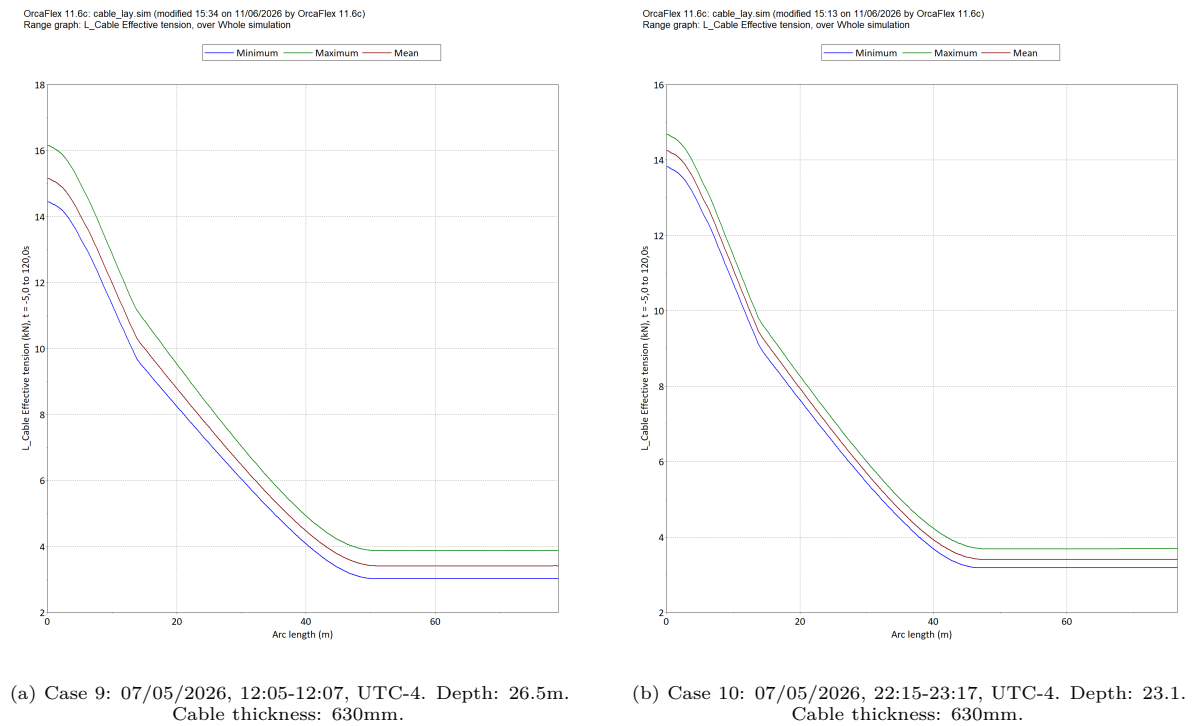
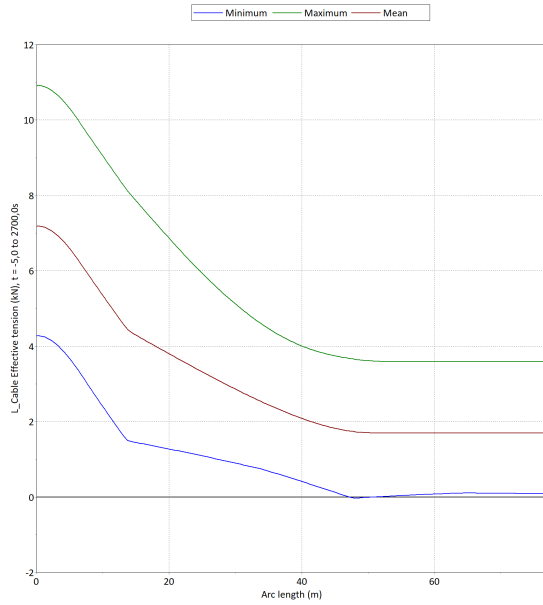


Figure B.3: Project data case 9-11

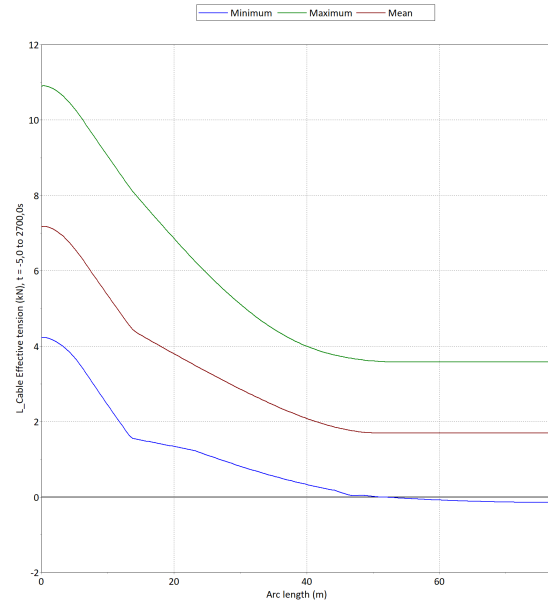
B.2 Bending Stiffness Variation

OrcaFlex 11.6c: cable_laybs0.15.sim (modified 10:27 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



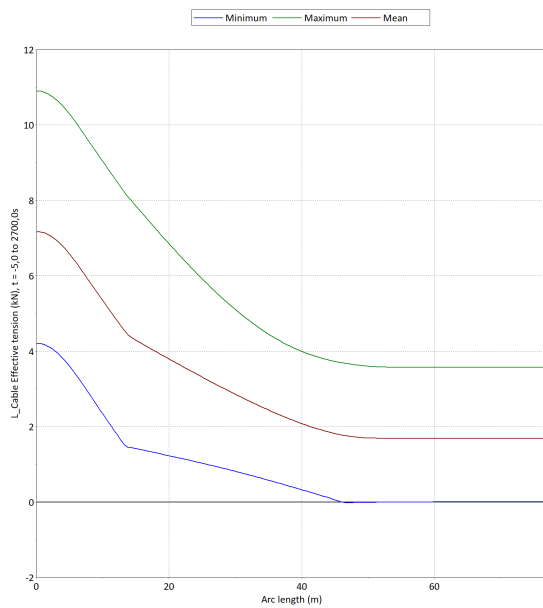
(a) Bending stiffness: 0.15 kNm^2 Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_laybs0.36.dat (modified 09:42 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



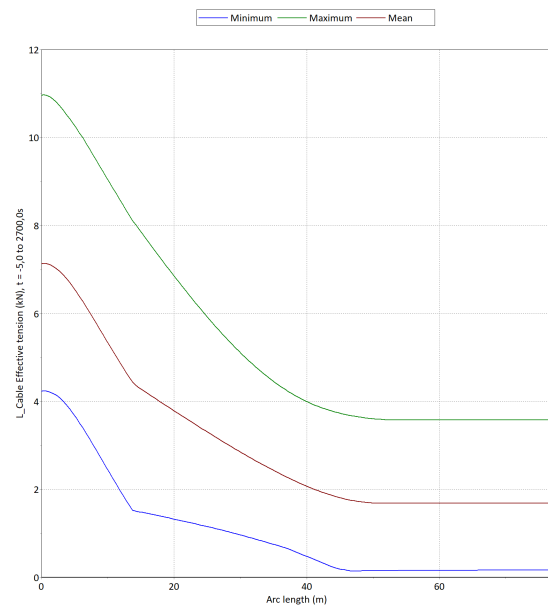
(b) Bending stiffness: 0.36 kNm^2 Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_laybs0.725.dat (modified 09:20 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(c) Bending stiffness: 0.725 kNm^2 Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_laybs1.455.dat (modified 09:20 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(d) Bending stiffness: 1.45 kNm^2 Depth: 25 m. Cable thickness: 240 mm.

Figure B.4: Bendingstiffness variation ($0.15\text{-}1.45 \text{ kNm}^2$)

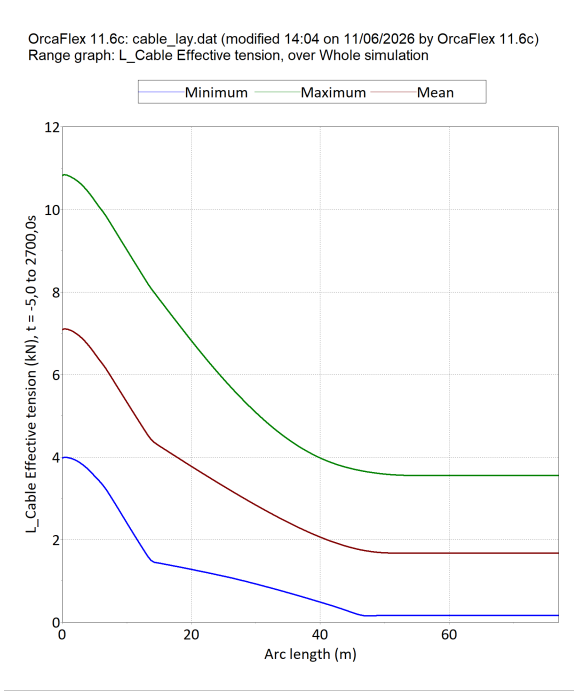


Figure B.5: Bending stiffness: 2.91 kNm^2 Depth: 25 m. Cable thickness: 240 mm.

B.3 Cable Weight Variation

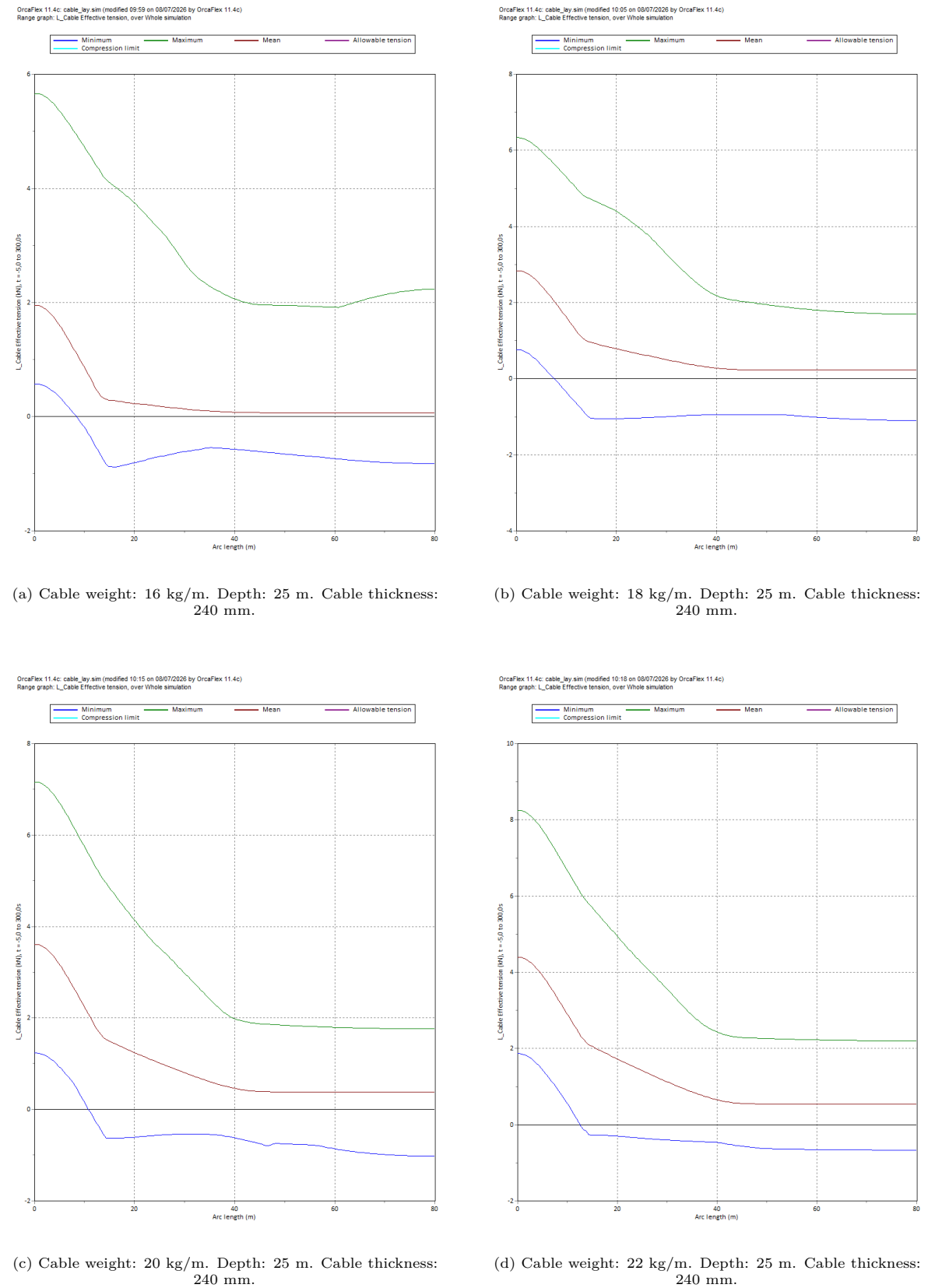
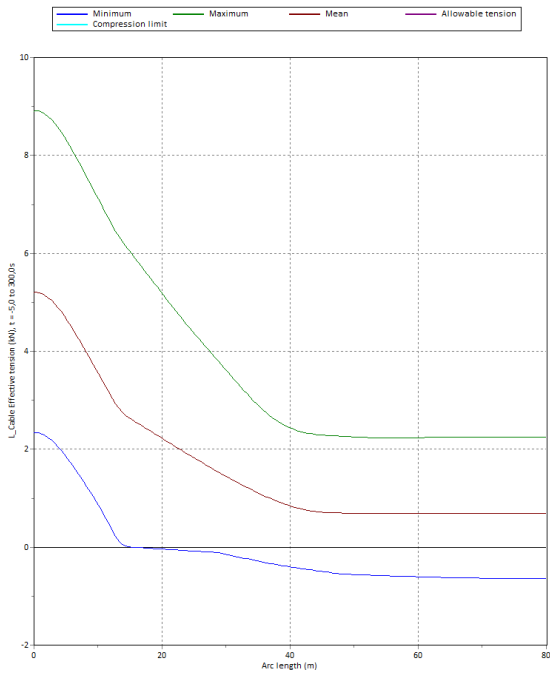


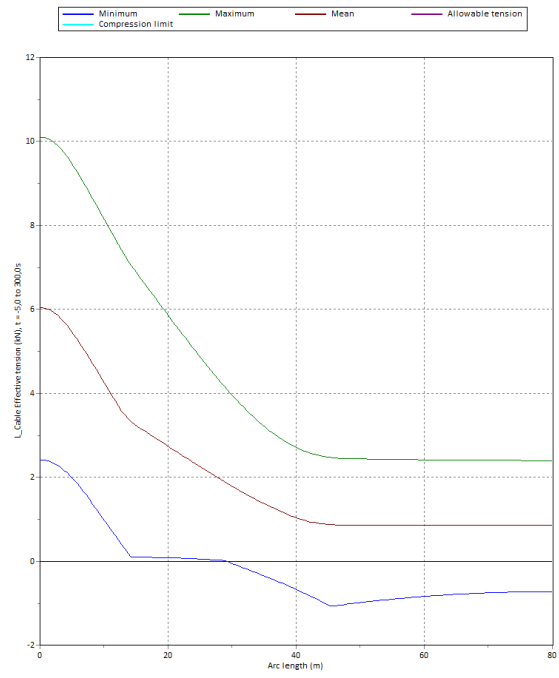
Figure B.6: Cable weight variation (16-22 kg)

OrcaFlex 11.4c: cable_lay.sim (modified 10:22 on 08/07/2026 by OrcaFlex 11.4c)
Range graph: L_Cable Effective tension, over Whole simulation



(a) Cable weight: 24 kg/m. Depth: 25 m. Cable thickness: 240 mm.

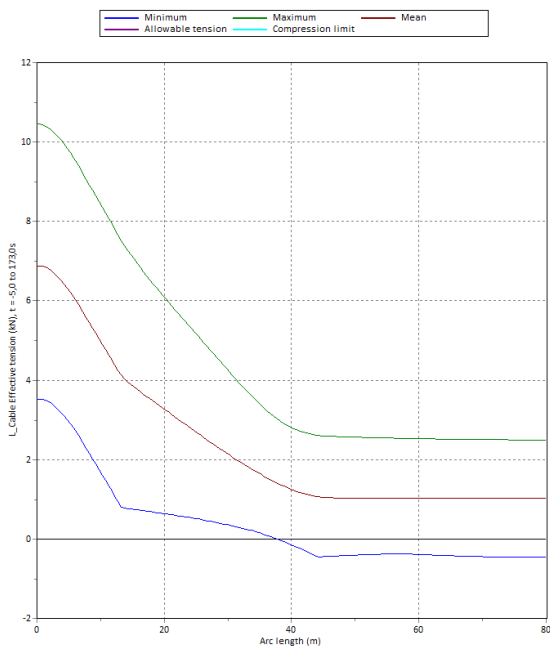
OrcaFlex 11.4c: cable_lay.sim (modified 10:39 on 08/07/2026 by OrcaFlex 11.4c)
Range graph: L_Cable Effective tension, over Whole simulation



(b) Cable weight: 26 kg/m. Depth: 25 m. Cable thickness: 240 mm.

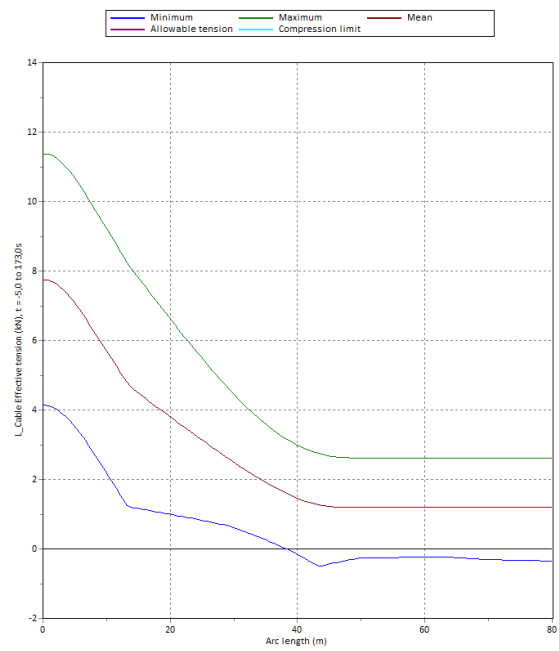
Figure B.7: Cable weight variation (24-26 kg)

OrcaFlex 11.6c: cable_lay.sim (modified 11:41 on 08/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(a) Cable weight: 28 kg/m. Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay.sim (modified 11:42 on 08/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(b) Cable weight: 30 kg/m. Depth: 25 m. Cable thickness: 240 mm.

Figure B.8: Cable weight variation (28-30 kg)

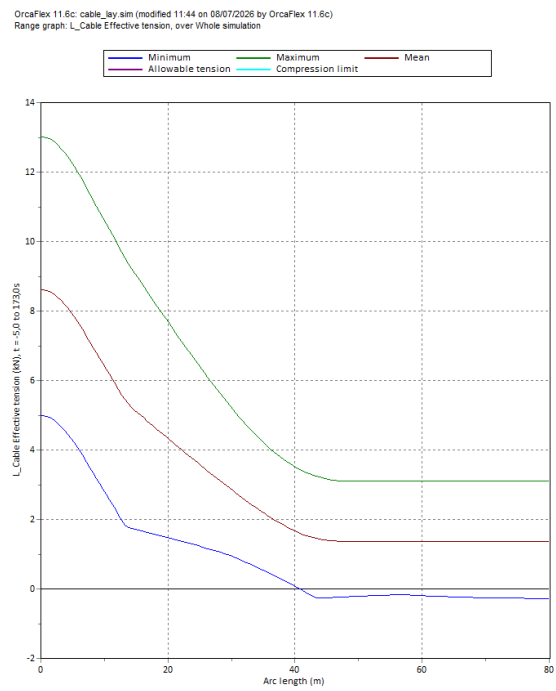
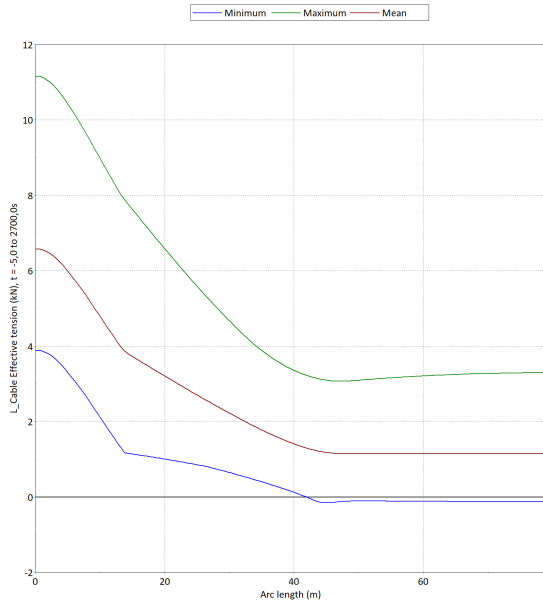


Figure B.9: Cable weight: 32 kg/m. Depth: 25 m. Cable thickness: 240 mm.

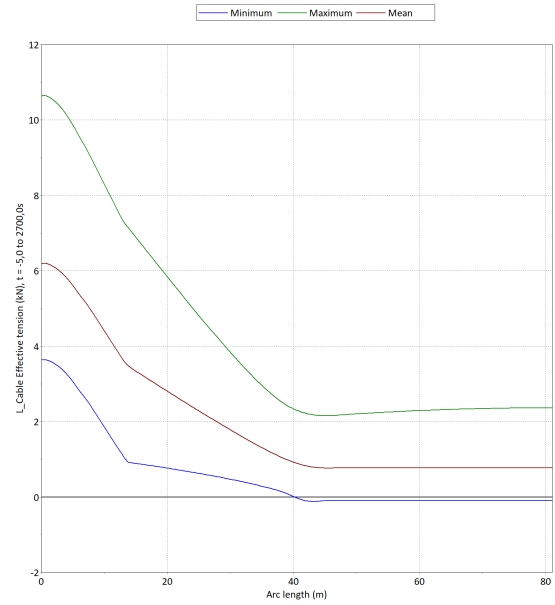
B.4 Touchdown Point Variation

OrcaFlex 11.6c: cable_lay_79m.sim (modified 17:00 on 11/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



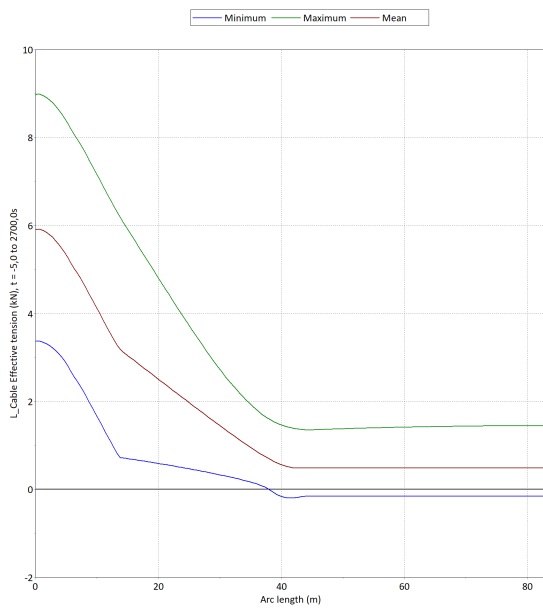
(a) Touchdown point: 79 m Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay_81m.sim (modified 17:07 on 11/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



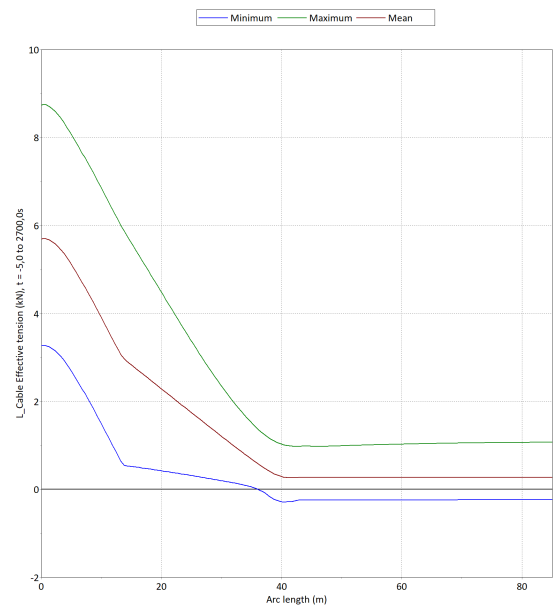
(b) Touchdown point: 81 m Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay_83m.sim (modified 17:21 on 11/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(c) Touchdown point: 83 m Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay_85m.sim (modified 18:08 on 11/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(d) Touchdown point: 85 m Depth: 25 m. Cable thickness: 240 mm.

Figure B.10: Touchdownpoint variation (cablelength 79-85m)

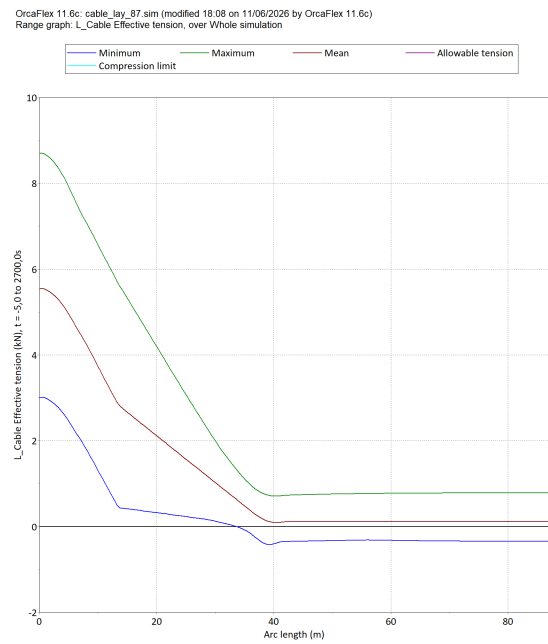
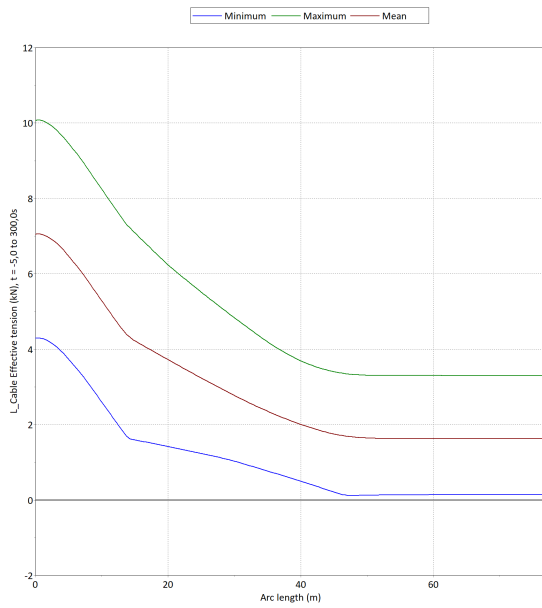


Figure B.11: Touchdown point: 87 m Depth: 25 m. Cable thickness: 240 mm.

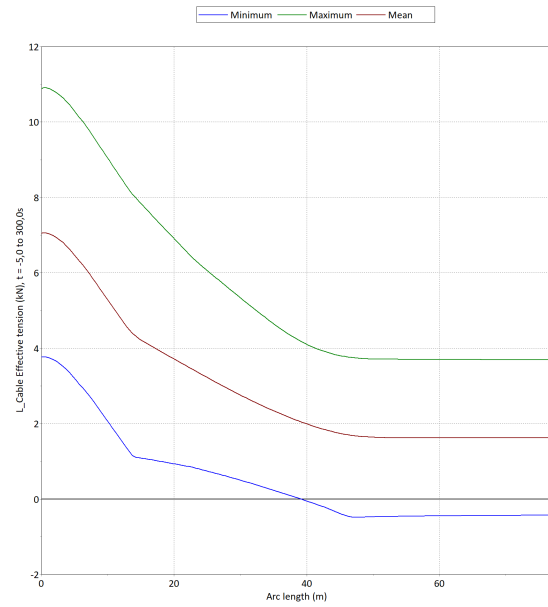
B.5 Period Variation

OrcaFlex 11.6c: cable_lay.dat (modified 14:18 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



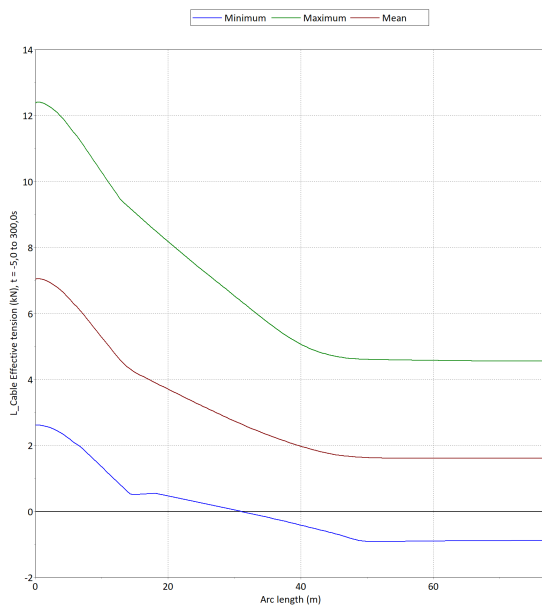
(a) Period: $0.85 * \pi$ s Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay.sim (modified 12:23 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



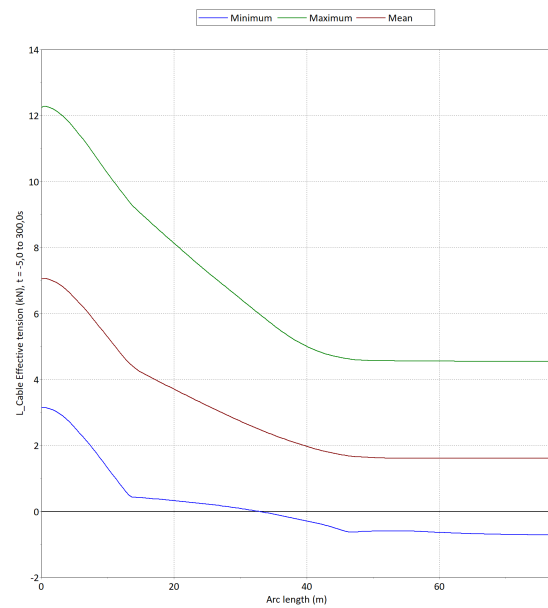
(b) Period: $0.95 * \pi$ s Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay.dat (modified 12:07 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(c) Period: $1.05 * \pi$ s Depth: 25 m. Cable thickness: 240 mm.

OrcaFlex 11.6c: cable_lay.dat (modified 11:57 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(d) Period: $1.10 * \pi$ s Depth: 25 m. Cable thickness: 240 mm.

Figure B.12: Period of motion variation ($0.85\pi - 1.10\pi$)

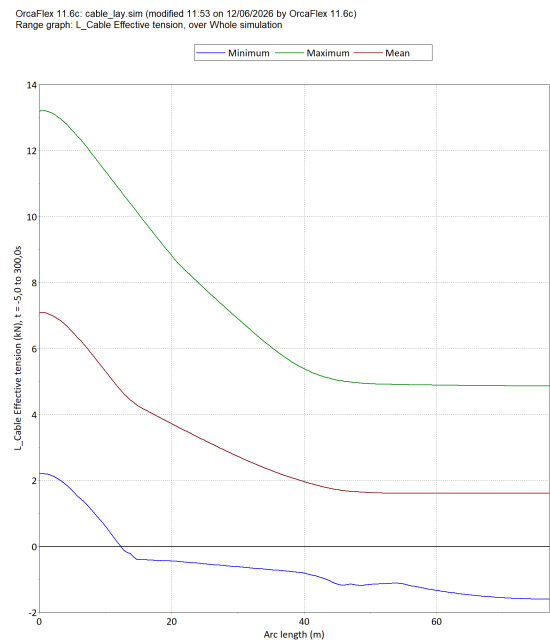


Figure B.13: Period: $1.25 * \pi$ s Depth: 25 m. Cable thickness: 240 mm.

B.6 Water depth Variation

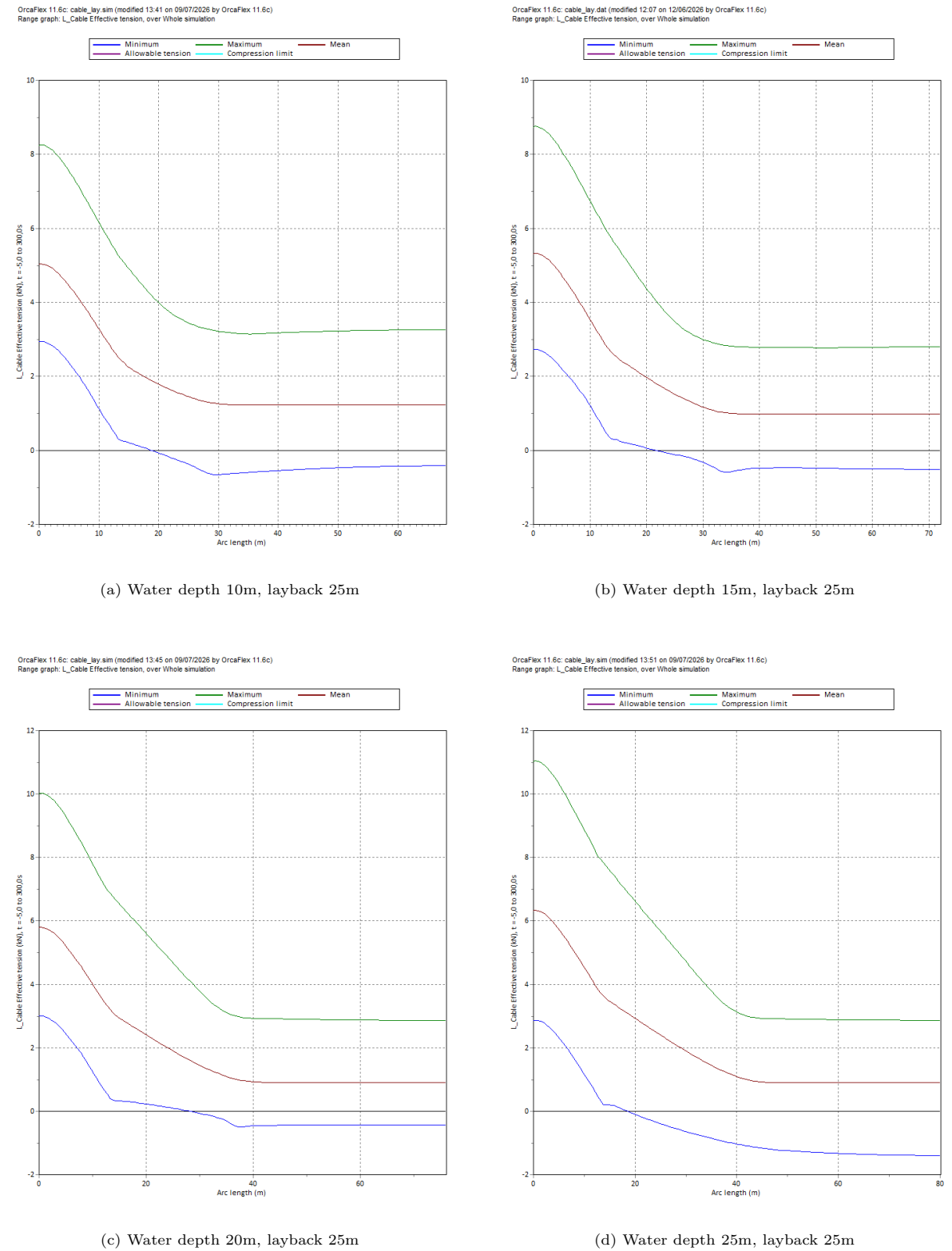
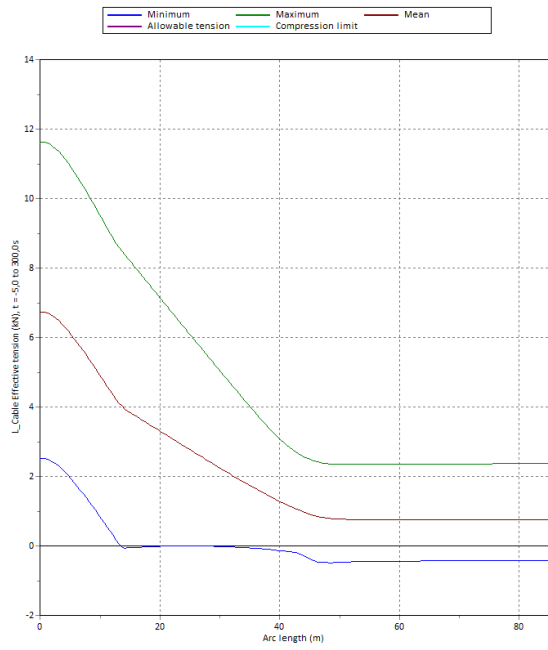


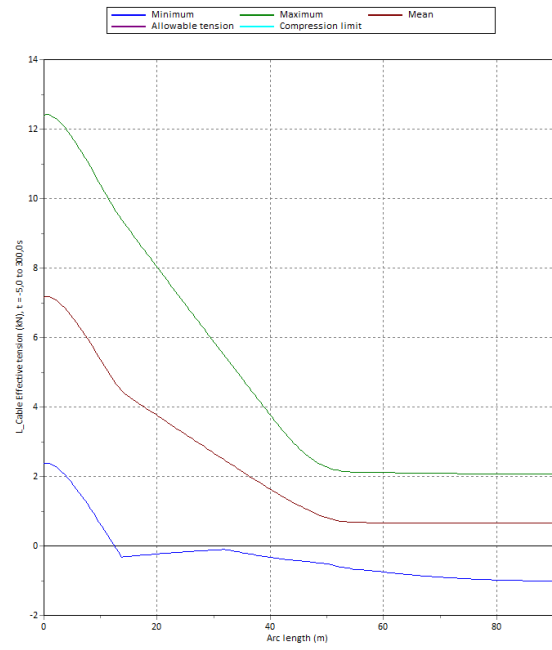
Figure B.14: Water depth 10-25m, layback 25m

OrcaFlex 11.6c: cable_bay.sim (modified 13:54 on 09/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



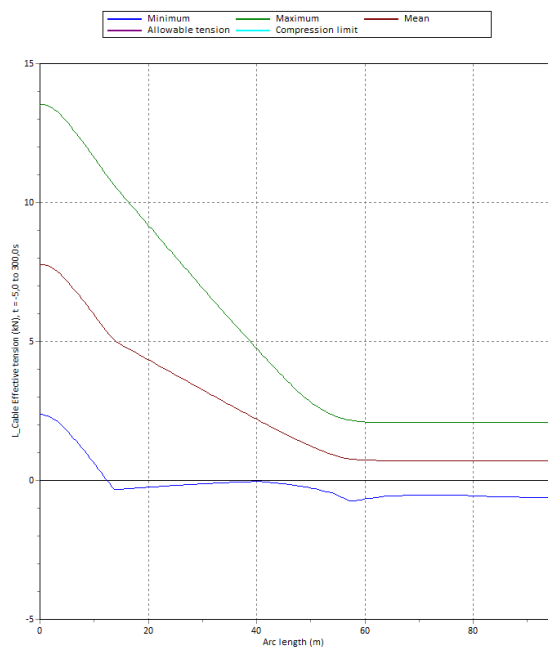
(a) Water depth 30m, layback 25m

OrcaFlex 11.6c: cable_bay.sim (modified 13:58 on 09/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



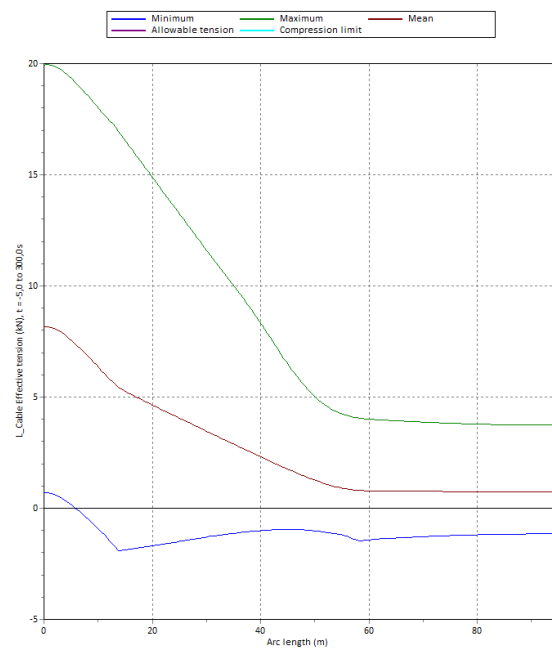
(b) Water depth 35m, layback 25m

OrcaFlex 11.6c: cable_bay.sim (modified 14:17 on 09/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(c) Water depth 40m, layback 25m

OrcaFlex 11.6c: cable_bay.sim (modified 14:33 on 09/07/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation

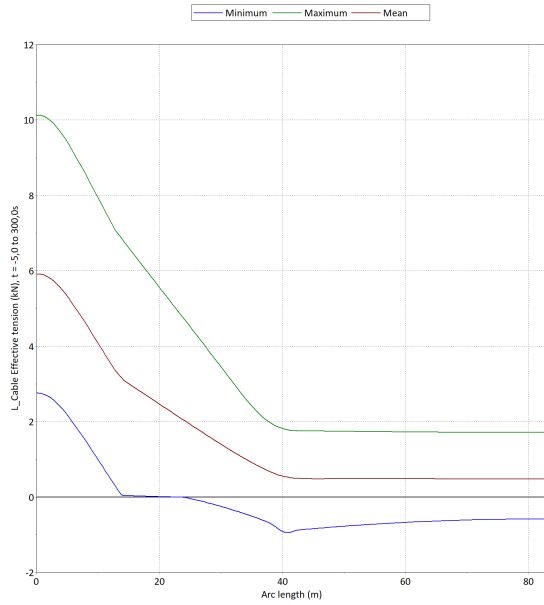


(d) Water depth 40m, layback 40m, amplitude 1.5m

Figure B.15: Water depth 30-40m, layback 25m

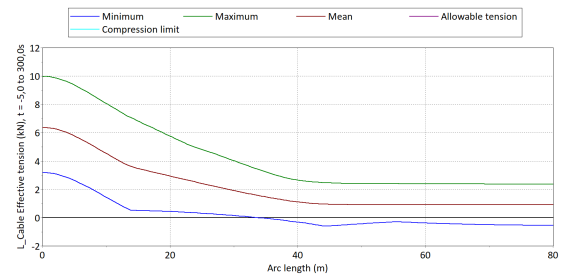
B.7 Combination of Factors

OrcaFlex 11.6c: cable_lay.dat (modified 14:18 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(a) Period: $1.0 * \pi$ s, touchdown: 77-83 m, bending stiffness: 1.5 kNm^2 .

OrcaFlex 11.6c: cable_lay.dat (modified 14:35 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation



(b) Period: $1.0 * \pi$ s, touchdown: 77-80 m, bending stiffness: 1.0 kNm^2 .

Figure B.16: Combination of factors varied (bending stiffness and layback)

OrcaFlex 11.6c: cable_lay.dat (modified 14:35 on 12/06/2026 by OrcaFlex 11.6c)
Range graph: L_Cable Effective tension, over Whole simulation

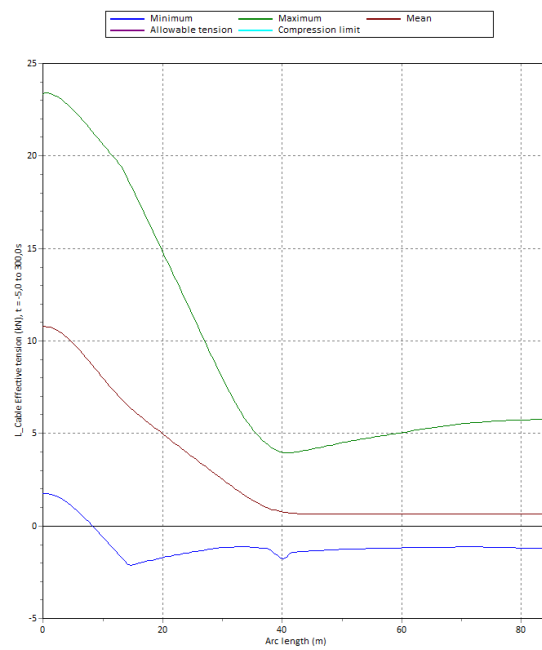


Figure B.17: Period: $2.0 * \pi$ s, cableweight: 40 kg/m , bending stiffness: 1.63 kNm^2 , TDP: 85m