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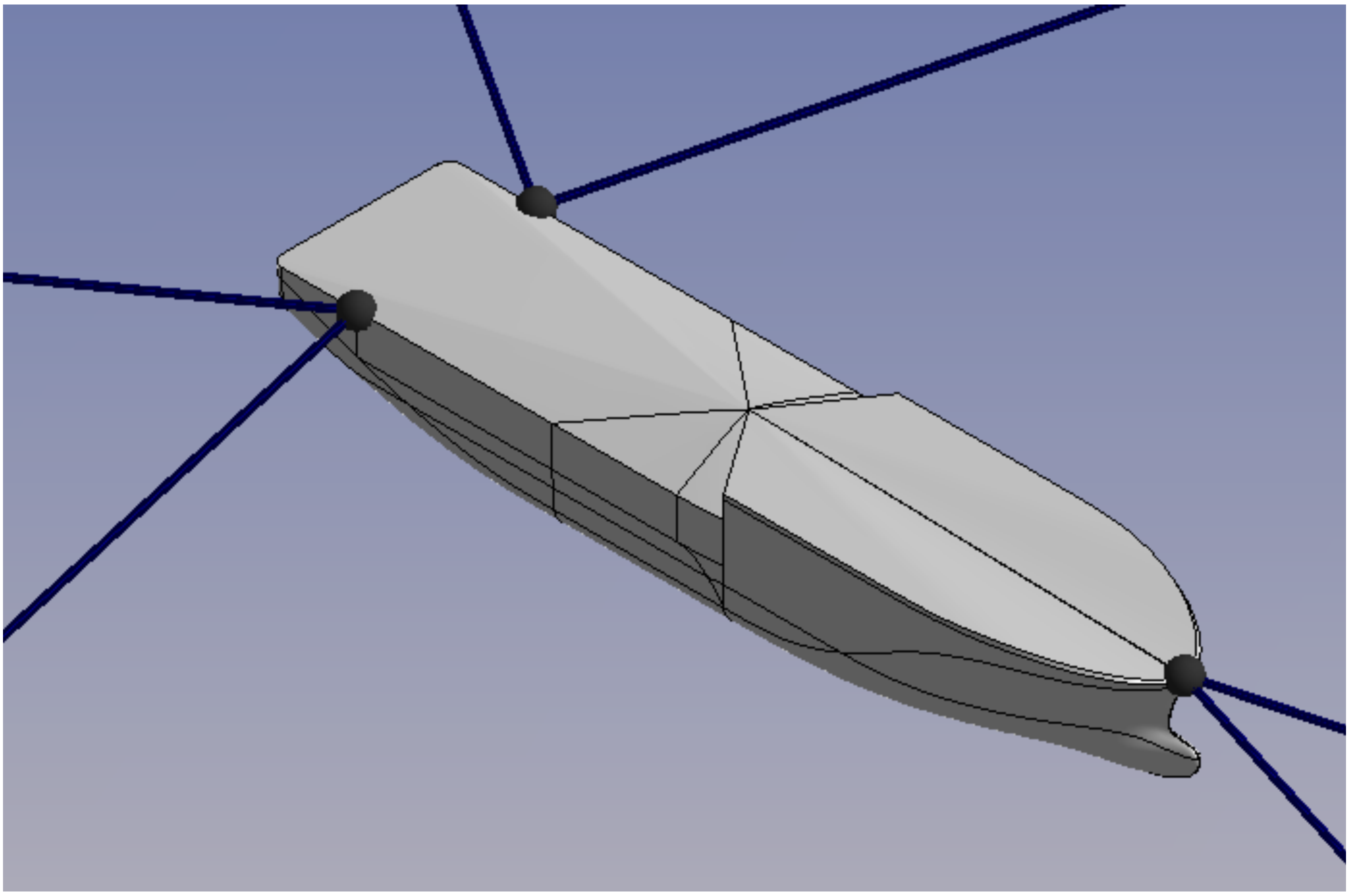

Vessel Motions and Mooring Line Tensions in Very Shallow Water

Study of a Moored Cable Laying Vessel

Master's Thesis in the International Master's Programme
Naval Architecture and Ocean Engineering

JOHAN CAVEFORS AND ANDREAS OSCARSSON

Department of Shipping and Marine Technology
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Göteborg, Sweden 2016

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Hull Model used in Aqwa. Model file received from ABB High Voltage Cables.

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ABSTRACT

This thesis focus on the motions of a vessel operating on a very low keel clearance. To save time and money, it is efficient if one cable laying vessel can get a cable all the way to shore without the need to change vessel. This means that the vessel will operate on very shallow water close to shore with many shallow water effects affecting the movement. No international standard covers movement in very shallow water operations. Therefore, this investigation has been made on a cable laying vessels motions and its corresponding mooring line tensions. A model has been set up in ANSYS Aqwa which has been validated through several steps. The model has been run with various significant wave heights and wave periods as well as analysed with different wave angles. Different parameters, such as wind, current, wave spectra and water depths has been varied and presented in graphs. The results show a small influence from the wind and current on the mooring line tensions but very little on the motions. The wave angle influences the results significantly with peak motions around an angle perpendicular to the vessel and relatively small motions when hitting the vessel from the bow or stern. Due to some limitations and assumptions, the results can be considered slightly conservative. Despite this, they should be used with caution as no verification of the model has been made. During the summertime, operation lasting for several days should be possible since movements resulting in a grounding are very unlikely during this time. Operations in wintertime should also be possible but more caution is needed and shorter time windows are likely. To further investigate the problem, more different simulation cases needs to be run where the different parameters are varied more. A physical model should also be built in order to validate the results. Furthermore, ANSYS Aqwa has some limitations. To receive an even more accurate solution, the model might need to be set up in a more advanced program which allows further adjustment of the model, such as OPENFOAM or similar.

Key words: cable laying vessel, moored vessel, mooring line tension, shallow water effects, ship motions, very shallow water operation

Fartygsrörelser och spänningar i förankringslinor på mycket grunda vatten
Studie på ett förankrat kabelläggningsskepp
Examensarbete inom Naval Architecture and Ocean Engineering
JOHAN CAVEFORS AND ANDREAS OSCARSSON
Institutionen för sjöfart och marin teknik
Avdelningen för Marin teknik
Chalmers tekniska högskola

SAMMANFATTNING

Den här rapporten fokuserar på rörelserna hos ett skepp med väldigt låg frigång. För att spara tid och pengar är det effektivt om ett kabelläggningsfartyg lägger hela vägen in till stranden utan att byta fartyg. Detta innebär att skeppet kommer användas på mycket grunda vatten nära stranden där många extra effekter från grunt vatten uppstår. Inga internationella standarder täcker drift på mycket grunda vatten och därför har en utredning gjorts som fokuserar på ett kabelläggningsfartygs rörelser och ankarlinornas spänningar på mycket grunda vatten. En modell har byggts upp i ANSYS Aqwa som validerats genom många steg. Modellen har körts med varierande signifikanta våghöjder och vågperioder över olika vågvinklar. Olika parametrar, såsom vind, ström, vågspektrum och djup har varierats i olika simuleringar och sedan presenterats i grafer. Resultaten visar på en påverkan från vind och strömmar i ankarlinornas spänningar. Vågvinkeln har en signifikant inverkan på resultaten med toppvärden på rörelserna runt vinklar som är nästan vinkelräta mot skeppets skrovsida. Vågor som träffar skeppet nästan rakt från fören eller aktern resulterar i relativt små rörelser. På grund av vissa begränsningar och antaganden kan resultaten betraktas som något konservativa. De ska trots detta användas med försiktighet då ingen verifikation av modellen har gjorts. Under sommaren borde kabelläggningsfartyget kunna användas under flera dagar i streck då sannolikheten för vågor som skulle resultera i grundstötning är mycket liten. Kabelläggningsfartyget bör också kunna användas under vintern men där bör mer försiktighet åtas och kortare tidsfönster är mer sannolikt. För att vidare undersöka problemet kan mer simuleringsfall göras där de olika parametrarna är varierade ännu mer. En fysisk modell bör också byggas så resultaten kan verifieras. Vidare har också ANSYS Aqwa vissa begränsningar. För att få ännu bättre resultat kan problemet och sättas upp i ett mer avancerat program där modellen kan justeras i en ännu större utsträckning, såsom exempelvis i OpenFOAM.

Nyckelord: användning på mycket grunt vatten, effekter från grunt vatten, fartygsrörelser, förankrat skepp, kabelläggare, spänningar i förankringslinor

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Preface

This thesis is a part of the requirements for the master's degree in Naval Architecture and Ocean Engineering at Chalmers University of Technology, Göteborg. It has been written for, and in cooperation with, ABB high voltage cables and has been carried out at the Division of Marine Design, Department of Shipping and Marine Technology, Chalmers University of Technology between January and June of 2016.

We would like to acknowledge and thank our examiner and supervisor, Per Hogström at the Department of Shipping and Marine Technology, for his guidance, support and patience with us throughout the work of this thesis. We would also like to thank Fabian Karlsson, our supervisor at ABB High Voltage Cables, for providing us with this thesis and the means to complete it.

Furthermore, we would like to thank Johannes Palm at the Department of Shipping and Marine Technology for his time and guidance, and the people at ABB High Voltage Cables, Johan Hedlund, Håkan Sandell and Maurits Smalt for all their support and providing us with the resources needed.

Göteborg, May 2016

Johan Cavefors & Andreas Oscarsson

Abbreviations

CFD	Computational Fluid Dynamics
CLV	Cable Laying Vessel
DNV	Det Norske Veritas
DOF	Degrees of Freedom
FEM	Finite Element Methods
FVM	Finite Volume Methods
HF	High Frequency
JONSWAP	Joint North Sea Wave Project
LF	Low Frequency
MLE	Maximum Likelihood Estimation
Metocean	Metrology and Oceanography
OCIMF	Oil Companies International Marine Forum
PM	Pierson-Moskowitz
WF	Wave Frequency

Notations

Roman Upper Case Letters

A_R	Reference area
A_{kj}	Added mass
A_γ	Normalizing Factor
B	Breadth of Ship
B_B	Breadth of the Bottom of the Hull
B_{kj}	Damping
C_a	Added Mass Factor
C_c	Current coefficient
C_d	Drag coefficient
C_{kj}	Hydrostatic restoring effects
C_w	Wind Shape coefficient
D	Draught
F_c	Current Force
F_k	Wave Exaltation Force
H	Wave Height
H_s	Significant Wave Height
H_{max}	Maximum Wave Height
H_b	Maximum Breaking Wave Height
K_r	Refraction Coefficient
K_{re}	Reflection Coefficient
K_S	Shoaling Coefficient
K_{xx}	Radius of Gyration around x-axis
K_{yy}	Radius of Gyration around y-axis
K_{zz}	Radius of Gyration around z-axis
L	Length of Ship
L_U	Integral Length Scale of Wind Speed Process
L_B	Length of the Bottom of the Hull
M_0	Zeroth Moment

$S(\omega)$	Wave Spectral Density Function
$S_U(f)$	Wind Spectral Density Function
R_e	Reynold's number
RX	Rotation around x-axis (Roll)
RY	Rotation around y-axis (Pitch)
S	Projected area normal to the direction of the force
S_w	Wetted surface
T	Wave Period
T_p	Peak Wave Period
T_R	Return Period
U_{10}	10 Minute Wind Velocity
U_c	Current velocity
U_w	Wind Velocity
Z	Movement in z-direction (Heave)

Roman Lower Case Letters

b	Half Breadth
c	Refraction Phase Velocity
c_g	Wave Group Velocity
d	Water Depth
f	Frequency
g	Gravitational Acceleration
kn	Knots
m	Meters
k	Wave Number
kk	Site and Height Dependent Coefficient
l_z	Total Movement in z-direction
q	Basic Wind Pressure or Suction
s	Seconds
u	Wind Speed
x_c^w	Extreme Wave Response

Greek Upper Case Letters

Θ	Wave Phase
$\emptyset(\omega)$	Depth Function

Greek Lower Case Letters

α	Scale parameter
α	Angle
β	Shape parameter
β	Angle
γ	Location parameter
γ	Non-dimensional Peak Shape Parameter
η	Surface Elevation
λ	Wave Length
π	Pi (3.14)
ω	Angular Frequency
ω_P	Peak Frequency

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1 Introduction

There are a lot of reasons for installing an offshore cable. Some offshore structures need to connect to the mainland, such as a wind park that needs to transfers electricity even if it is several kilometres out to sea. The location can make it difficult to install the cable and it will usually need some kind of protection to avoid damage from maritime operations, such as fishing and anchoring. An example is burying the cable in the seafloor. Laying subsea cables is an expensive operation that requires a vessel designed for it. When connecting the cables to the mainland, at some point the cable will have to be pulled from the vessel to the shoreline. In areas where there is a long shallow coast, it can result in a great distance where the depth is not enough for the draught of the cable laying vessel. Using an additional ship with a lower draught to transport the cable to the shore is an extra cost that is preferable to avoid.

This thesis is made in collaboration with ABB High Voltage Cables in order to determine if a keel clearance of 1 meter could be considered sufficient as a limit. Mooring line tensions will also be investigated. At deep sea, the motions would be checked against a classification society. In this case the DNV standards. Since there is no standard for calculating the motions in shallow water, a further investigation is required.

1.1 Regulatory basis

The DNV GL is an international classification society that is well established and accepted in many countries. Therefore, it will be applied when possible.

The DNV standard states the following regarding shallow water:

7.3.8 Shallow water and restricted areas

7.3.8.1 Special attention should be paid to analysis of wave induced loads in very shallow water and in restricted waters.

7.3.8.2 In cases where the keel of an FPSO or ship is very close to the sea bed, the vertical added mass may change considerably during its motion. Since the narrow gap restricts fluid flow beneath the hull, nonlinear diffraction effects may occur. Similar effects occur for waves over shallow horizontal surfaces, e.g. a shallow pontoon.

7.3.8.3 Since the wave frequency analysis is based on incoming Airy waves, the validity of this wave theory should be checked for the actual wave lengths and wave heights, see Ch.3.

7.3.8.4 Shallow water effects may have a strong influence on mean drift loads, see 7.4.3.

7.3.8.5 For floating structures in shallow water coastal areas where the water depth varies along the length of the structure, this variation should be accounted for in the wave frequency analysis by modelling the sea bed in addition to the wetted surface of the floater.

(DNV, 2014):

1.2 Objective

This thesis is an investigation of the motions of the vessel in shallow water operations. Too large motions could cause the vessel to hit the seabed, potentially damaging the vessel. The purpose of this thesis is to verify that a minimum keel clearance of one meter is sufficient.

During an operation in shallow water, there will also be tension in the mooring lines. It is of importance that these tensions does not reach its limits and an investigation in the mooring lines maximum tension and distribution is thus a necessity. Another purpose of this thesis is therefore an investigation in the maximum tension behaviour on the mooring lines in very shallow water.

Since there will be a number of forces acting on the vessel and on the mooring system, these will have to be combined to get the final motions of the ship. Below follows the main topics and problems that will be discussed.

- Wave spectrum. The shallow water will affect the waves and the wave spectrum. Refraction will occur for waves with a long wavelength and energy will be lost from the waves. The spectrum will therefore not be the same in the shallow water as for deep water.
- Shallow water effects. The water underneath the vessel will work as an added mass in horizontal movements. If water streams underneath the vessel, this will cause a suction.
- Mooring forces. The mooring forces will be affected by all other forces on the vessel. It is therefore important to see how it will affect the motions.
- Current conditions. There are several effects that will cause currents. These will create forces on the hull that can result in roll and pitch of the vessel that will reduce the margin of vertical movement.
- Model building in software. Verification is required to ensure that shallow water effects are being taken into consideration.

There are ships that carry out this kind of operation at present but very little information is available that would assist in this case. Since there is no standard way of calculating the motions it will have to be a done using research about shallow water and combining it to create a model for this case.

1.3 MS Victoria

The MS Victoria is a 140 m long and 30 m wide Cable Laying Vessel (CLV). It is designed to operate in very shallow depths to avoid the need of an additional vessel being used for the attachment to the mainland. It is being built for ABB High Voltage Cables and the expected delivery of the vessel is in 2017 (ABB, 2015). An illustration of the MS Victoria can be seen in *Figure 1.1*. When in shallow water, the vessel will be held in place by the mooring system. This is to reduce the risk of motions since this could damage the cable and ship. The mooring system of Victoria consist of six electrically driven winches. Each winch having a maximum pull of 60 tons and a maximum holding force of 90 tons (NDM, 2015).The operation of the vessel will be on very shallow water depths in relation to the draft of the ship. Many times, the water depth will be less than 10 meters. The MS Victoria will also have a damping system containing passive tanks which will help to stabilize the vessel in roll motions.

Figure 1.1: An illustration of the MS Victoria.

1.4 Methodology

In order to obtain a proper methodology, a literature study will initially be made where important parameters are studied.

This thesis will mainly focus on the motions of the vessel, but the mooring line tensions will also be discussed. All the results will be compared to each other and analysed using external expertise and data.

First, the vessel motions will be calculated. Due to the wide capabilities of ANSYS Workbench with its hydrodynamic response program Aqwa. This will be the main program chosen for the motion analysis (ANSYS, 2013).

A model of Victoria will be imported into Aqwa. All possible parameters, such as current parameters, wind parameters, wave parameters, hull parameters, etc., will be implemented in the program and various simulations will be run. Different validations will be made to validate the setup in the program. These validations will be a mesh validation, a time step validation and a depth validation.

By using site specific metrology and oceanography (metocean) data, a scatter of significant wave heights (H_S) and peak wave period periods (T_P) will be established. The simulations will then be run as simulation series from a matrix of these values.

Initially, some regular wave simulations will be run for various validations. Since irregular waves represent reality to a further extent, the weight of this thesis will be on irregular wave simulations. Various series will be run and then compared to each other.

During these simulations, the maximum tensions of the mooring lines will also be calculated and investigated. In the same manner as for the vessel motions, the results from the mooring line tensions will be compared to each other and discussed. The mooring line tensions will also be compared to the motions in order to further analyse what is of biggest importance during a very shallow water operation with the vessel.

All this will finally be analysed using metocean data received from ABB in order to observe likeliness and return periods of certain motions.

A flow chart of the methodology can be seen in *Figure 1.2*.

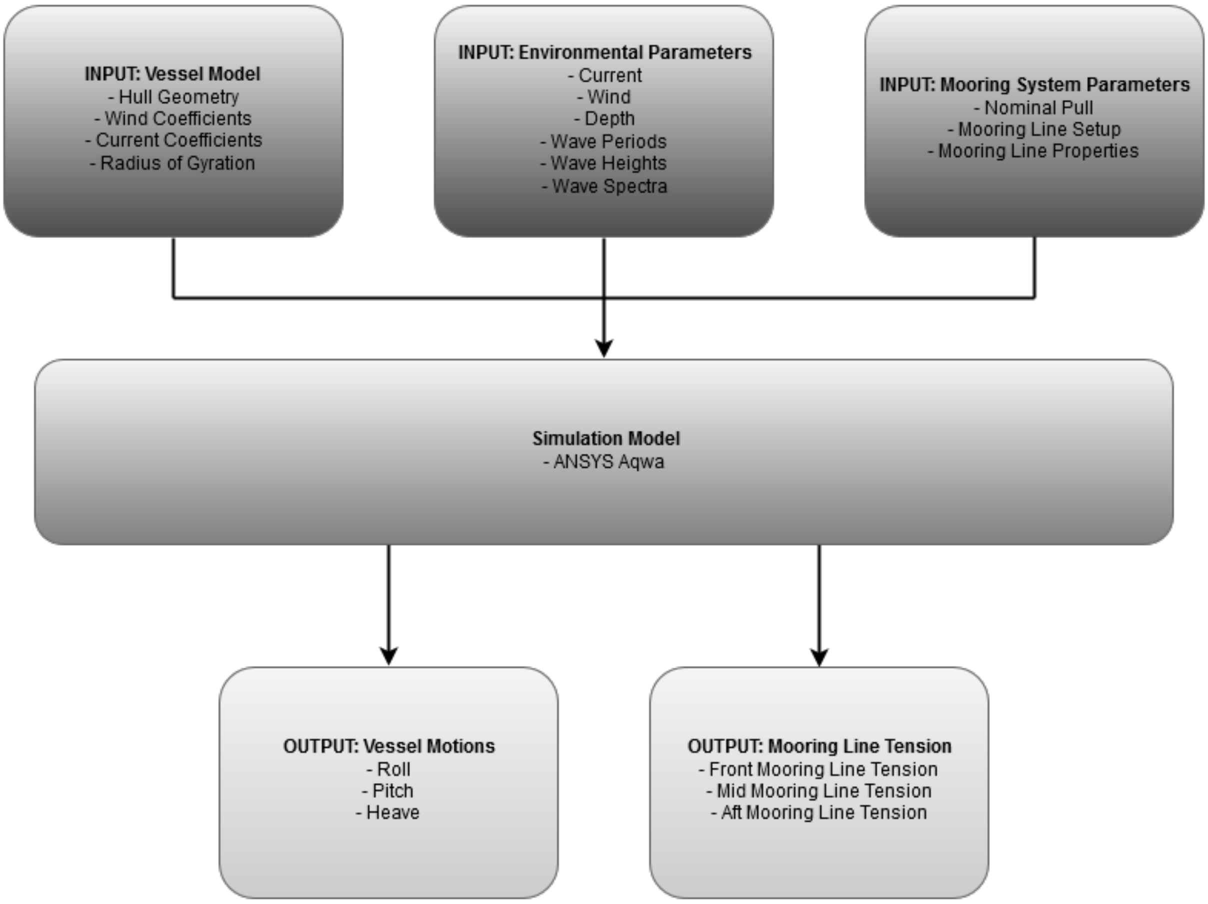

Figure 1.2: Flow Chart of Methodology.

1.5 Limitations

This thesis mainly looks into the conditions in a specific area, with data provided by ABB, and the focus of the discussion will therefore be on these conditions. Even though a rather general model has been made, the simulation analysis, results and conclusions might differ slightly in other areas of operation.

The sea bottom in this thesis is assumed to be strictly flat. In a real life situation, this is very unlikely to be the case. Even though this area consists of sand bottom, random scattered rocks and other small objects are likely to be resting on the sea bottom. This could result in a smaller margin of keel clearance and might thus affect the results.

Due to the limitation of time, no external validation of the results has been made. In order to further confirm the results, preferably a model test should be performed which could verify the results gained from Aqwa. The same calculations could also be run in another model program to verify the results.

Due to limitations in Aqwa, the simulations have only been run with Stokes second order equations. It is arguable if this order is sufficient or if a higher order Stokes equation is necessary in very shallow water, such as a fifth order Stokes equation (Fenton, 1990; Hendrickson, 1961).

In the simulations, a constant wind has been set up without any wind spectrum. This gives rise to a static force which in reality would appear more dynamic. Even though the results are likely to become more conservative, simulations with a wind spectrum would have been more according to real life cases and could thus give a more accurate result.

The low resolution of the spectra which you can import into the Aqwa software will make it hard to get a more precise value around the peaks. With a graph containing maximum 50 values, the graph line will not be very smooth and the final results which are based on this spectrum will accordingly also be less smooth.

1.6 Project outline

Section 2 gives a background on the subject with the literature material necessary to support the different choices made for the simulations.

Section 3 explains how the necessary calculations were made. It contains all necessary equations, the background to them and in what order everything was calculated.

Section 4 shows the simulation procedure in Aqwa, including how the model was built, which simulations that were run and what simulation options that were made. This is followed up by *section 5*, which shows and explains all results received from Aqwa. These results are then discussed and evaluated in *section 6* following with a conclusion in *section 7*.

Section 8 will discuss what future work that could be done on the topic and what further results that could be interesting to study.

2 Literature Study

The purpose of the literature study is to provide a theoretical background to the different effects and forces that need to be taken into consideration when looking at this specific case. It contains substantive findings relevant to the topic, including theoretical and methodological contributions

2.1 Waves

Ocean waves are irregular and random in shape, height, length and speed of propagation (DNV, 2014). Traditionally, they are classified into different categories:

- Wind waves: generated by wind acting on the sea surface.
- Swell: wind waves generated in the deep ocean with a long distance from the current location. Wind has generally stopped blowing by the time they reach the location.
- Seiching (long waves): waves with very long periods, from 30 seconds up to tidal periods of 12 h.
- Waves from passing ships.
- Tsunamis: generated by large sudden impacts such as earthquakes, landslides, etc. Creates very large waves.
- Breaking waves: Short waves creating high pressure impulses to vertical structures. Considerable forces up to 600 kn/m^2 can be observed.

(Thoresen, 2015)

This thesis will focus on swell as this will be the main waves occurring in the shallow water where Victoria will be operating.

2.1.1 Wave Characteristics

Waves are classified according to the ratio of the water depth (d) to the wave length (λ) by the following relationship:

- Deep-water waves for $d/\lambda \geq 0.5$
- Intermediate-water waves for $0.04 < d/\lambda < 0.5$
- Shallow-water waves for $\frac{d}{\lambda} \leq 0.04$

(Thoresen, 2015)

Depending on which classification the waves get, different equations for the calculations are used. The wave height H can be described in different ways, depending on which situation it is used in. Two important definitions are:

$H_S =$ Significant wave height. Arithmetical mean value of the highest one-third of the waves for a certain interval.
$H_{max} =$ Maximum wave height. Is equal to $1.87H_S$ or rounded to $2H_S$ when some safety margin needs to be considered.

(Thoresen, 2015)

2.1.2 Wave Transformation

The waves will be the main cause of vertical movement in the vessel motions. It is therefore crucial to understand and describe what will happen to the waves when they enter a shallow region.

Steepening

When waves propagates towards shore and the water depths becomes smaller and smaller, the waves change its height and length but keeping its periods intact (Thomson, 1981). Contrary to what some believe, this does however not happen immediately. According to studies, there is in fact an initial lowering of the wave height when first hitting the shallower depths (King, 1966). The initial lowering is however usually rather small and never above 10% of the deep water height and after the lowering, the height of the wave is increased. The wave height increases according to the following formula:

$$\frac{\boldsymbol{H}}{\boldsymbol{H_0}} = \boldsymbol{K_s} = \sqrt{\frac{\boldsymbol{c_{g,0}}}{\boldsymbol{c_g}}} \tag{1}$$

Where,

K_s = shoaling coefficient

c_g = group velocity = $\frac{1}{2}\left[1 + \frac{2kd}{\sinh(2kd)}\right]\sqrt{\frac{g}{k}\tanh(kd)}$

(DNV, 2014)

Contrary to the wave height, the wave length tends to decrease when the wave propagates over shallow water at a rate proportional to the lowered wave speed. As a result of these two phenomenon, the waves will steepen and a sharper wave peak will occur. The level of steepening is depending on many factors, such as wave shape, bottom friction and beach slope (Thomson, 1981).

Refraction

Refraction refers to the phenomena that waves tend to bend when going over shallow water. The bending is simply due to the speed differences that occur (Thomson, 1981). When an incoming wave has a crest or through in a deeper part than the adjoining wave crest, this part will move more rapidly and a bend will occur. The bending occurs in such way that the waves will always align accordingly to the bottom contours (DNV, 2014). Therefore, waves which hits a beach is almost always parallel to the beach itself, despite that the original wave direction initially might have a large angle just some kilometres out to sea (Thomson, 1981). Since waves with a bigger wave length gets affected faster by the depth, these waves also tend to be affected faster by refraction. An illustration of refraction can be seen in *Figure 2.1*.

For parallel sea bed contours, Snell's refraction law can be applied:

$$\frac{\sin \alpha}{c(kd)} = constant \quad (2)$$

Where,

c = phase velocity
α = angle between wave ray and normal to the bed contour

(DNV, 2014)

Refraction also affects the height of the waves. The change of wave amplitude is given by the following equation:

$$\frac{H}{H_0} = K_s K_r \quad (3)$$

Where,

K_r = refraction coefficient defined as: $\left[\frac{1-sin^2\alpha_0 tanh^2(kd)}{cos^2\alpha_0}\right]^{-1/4}$

(DNV, 2014)

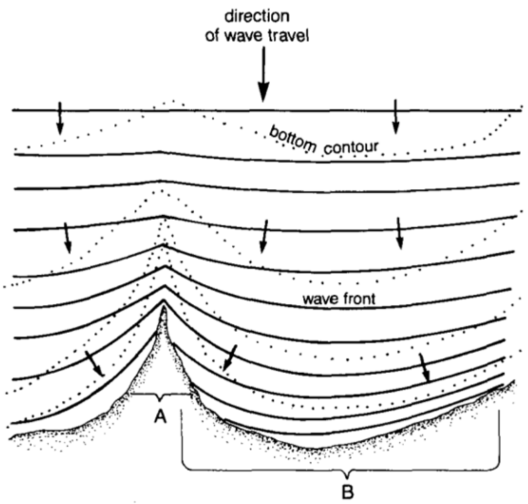

Figure 2.1: Example of refraction along shore (Thomson, 1981).

Reflection

When waves impinges onto shore, a partial or almost full reflection of the waves may also occur. Longer waves gives a higher rate of reflection than shorter wave lengths (Thomson, 1981). The less slope the shore has, the more absorbent will it be to reflection. A beach is for example a very efficient absorbent to wave reflection and with a slope of 10% or less, almost all wave energy is absorbed with only a very small fraction of waves that returns seaward as reflection (Thomson, 1981).

To measure the rate of wave reflection, a wave reflection coefficient (K_{re}) is often used. A simple and common method to measure the wave reflection coefficient is by measuring the minimum and maximum wave height from the combined wave field and then using the following formula:

$$\boldsymbol{K_{re} = \frac{H_{max} - H_{min}}{H_{max} + H_{min}}} \tag{4}$$

(Isaacson, 1991)

Breaking

A shallow-water wave breaks for two reasons:

- The wave is getting too steep. It can no longer withhold the weight from the wave's crest and collapses. This usually occurs when the wave height reaches 1/7 of the wave length.
- The water circle speed in the crest overtakes the wave speed itself which causes the wave to fall over and break

  (Thomson, 1981).

Breaking of waves is usually categorised into four categories; spilling, surging, plunging and collapsing. These categories are illustrated in *Figure 2.2*. In reality, these categories seldom occur by themselves but are usually combined in various ways.

Observations have shown that as the wave height increases, the wave breaking tends to go from surging, to collapsing, to plunging, to spilling. The same trend seems to occur when the slope of the beach decreases (Thomson, 1981). Therefore, spilling is the most common wave break on a beach with very little slope.

The maximum wave height H_b is given by the following equation:

$$\boldsymbol{\frac{H_b}{\lambda} = 0.142\, tanh \frac{2\pi}{\lambda}} \tag{5}$$

(DNV, 2014)

In shallow water, the maximum wave height is 0.78 times the occurring water depth (DNV, 2014). However, for waves propagating over a sea bed which is flat or almost flat, the waves may break in an even lower wave height. Studies have shown that the breaking limit can be as low as 0.55 times the occurring water depth (Nelson, 1994; Massel, 1996).

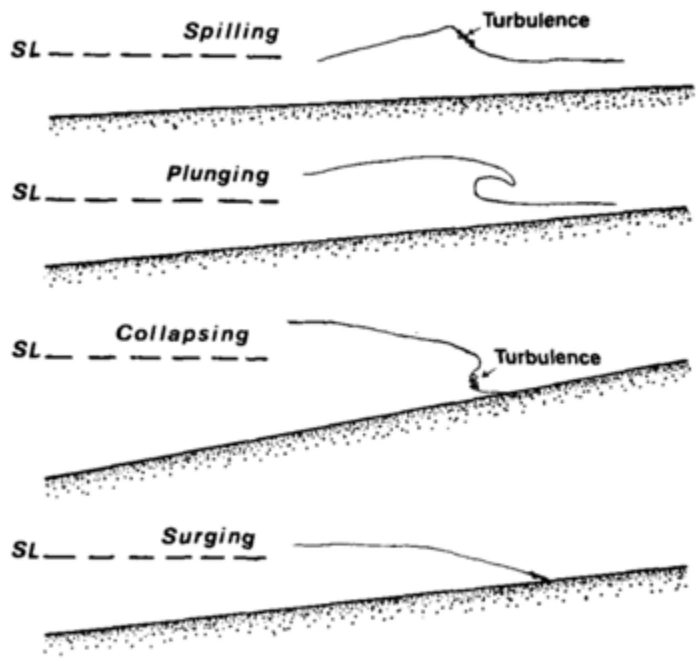

Figure 2.2: Various types of wave breaking (Thomson, 1981).

2.1.3 Wave Spectra

Due to the irregularity of waves, wave spectra are necessary for properly visualising wave heights over a certain time. These spectra are built from frequencies and usually follow a standard formulation:

$$\boldsymbol{S(\omega) = \frac{A}{\omega^5} e^{-B/\omega^4}} \tag{6}$$

$S(\omega)$ = Spectral density function

ω = Angular Frequency

B= breadth of ship

(Techet, 2005)

The area under the spectrum is called the zeroth moment (M_0) and is defined by the terms of H_S. The spectrum describes the likeliness of certain wave heights through and various density of the zeroth moment through equation (Techet, 2005). Since waves are generally generated from wind, a similar spectrum from wind can also be created in order to predict wave heights.

These spectra all takes various parameters into account and it is therefore important to choose the right spectra for the right situation. This section will present a few different wave spectra that will be treated during this thesis.

Pierson-Moskowitz Spectrum

The Pierson-Moskowitz (PM) Spectrum was developed for fully developed seas in the North Atlantic Ocean (Techet, 2005). The waves are assumed to be unidirectional with an unlimited fetch and fully developed wind conditions. Since there are many places in the world where a fully developed sea does not properly represent the ocean conditions, the use of the PM spectrum is limited. The formula is presented below:

$$S(\omega) = \frac{5}{16} \cdot H_S^2 \omega_P^{-5} exp(-\frac{5}{4}(\frac{\omega}{\omega_P})^{-4}) \quad (7)$$

Where,

ω_P = Peak Frequency
H_s = Significant Wave Height

(DNV, 2014)

JONSWAP Spectrum

The JONSWAP spectrum was developed by the Joint North Sea Wave Project and it is a spectrum which is based on the Pierson-Moskowitz Spectra but considers a limited fetch. It is extensively used worldwide in the offshore industry. Over 2000 spectra were measured and by using the least square method, a spectral formulation was obtained (Techet, 2005). This formulation is based on an assumption of near uniform winds. The JONSWAP formula is presented in equation 8:

$$S_j(\omega) = A_\gamma S_{PM}(\omega) \gamma^{exp(-0.5(\frac{\omega - \omega_P}{\sigma \omega_P})^2)} \quad (8)$$

Where:

A_γ = Normalizing Factor
$S_{PM}(\omega)$ = Pierson-Moskowitz Spectra
γ = Non-dimensional Peak Shape Parameter

(DNV, 2014)

TMA Spectrum

In shallow water, the JONSWAP spectrum will unfortunately no longer be as accurate due to the many new parameters that shallow water introduces. To include these parameters, the JONSWAP spectrum can be multiplied with a depth function, $\emptyset(\omega)$ which yields a new spectrum. Such a spectrum is the TMA spectrum. The TMA Spectrum does not however take into consideration factors of bottom effects and distance with a certain depth (Hughes, 1984). The depth function can be written:

$$\emptyset(\omega) = \frac{sinh^2(kd)}{sinh^2(kd) + kd \coth(kd)} \quad (9)$$

Where d is the water depth.

2.1.4 Wave Forces

Ocean waves consist of many different directions and frequencies. All different directions and frequencies interact in different ways and it is thus very difficult to properly simulate. Winds and currents further complicates the wave forces and directions. Through the years, many different numerical methods have been made which purposes are to simulate ocean waves (ANSYS, 2013). In this section, some numerical models used in this thesis will be described.

Regular Wave Theory

The simplest ocean wave theory is the linear regular wave (airy wave) (ANSYS, 2013). This wave theory is based on the assumption of homogenous, incompressible, inviscid fluid and irrotational flow. The amplitude of the wave is considered small compared to the wave length and water depth. Due to this, the linear free surface condition can be used (ANSYS, 2013). However, when it is necessary to observe more advanced waves, non-linear models are necessary. One common non-linear regular wave theory is the Stokes theory. This theory is suitable when the waves are not very long and there is a limited depth (Fenton, 1990).

Three physical dimensions are needed to define a wave train: the mean depth (*d*), the wave crest to trough (*H*) and the wavelength (λ). In many cases, the wave period has been assumed to replace the wave length. It is however sometimes questionable how accurate this is due to the fact that the relative observed speed might be difficult to see because of interruptions of underlying currents (Fenton, 1990).

The surface elevation in linear wave theory is given by:

$$\boldsymbol{\eta(x, y, t) = \frac{H}{2} cos\Theta} \tag{10}$$

Where,

$\Theta =$ the phase $= k(x\ cos\beta + y\ sin\beta) - \omega t$
$\beta =$ propagation angle
$c =$ phase velocity

(DNV, 2014)

The stokes wave theory is a natural approximation which consist of an infinite series. It starts on a linear first order and continues to more non-linear orders (Lautrup, 2011). In deep water, only the first order of Stokes theory is necessary whilst when the water depth gets lower, a higher order of Stokes theory is necessary to accurately model the ocean waves (ANSYS, 2013). It is widely common to calculate with Stokes third order wave theory in waves which propagates over finite depths (Tsuchiya & Yasuda, 1981) even though a Stokes second order wave theory is sufficient in many cases.

For a regular second-order Stokes wave, the surface elevation is given by:

$$\boldsymbol{\eta = \frac{H}{2}\cos\Theta + \frac{\pi H^2}{8\lambda}\frac{\cosh kd}{sinh^3 kd}[2 + cosh2kd]cos2\Theta} \tag{11}$$

(DNV, 2014)

Irregular Wave Theory

Irregular waves can be represented by using various wave spectra (see *section 2.1.3*). These spectra shows the likeliness of certain wave energy occurring on a sea with a frequency that theoretically spreads from zero to eternity. The frequencies does however usually coincide rather well and it is therefore only necessary to plot a limited amount of frequencies (ANSYS, 2013).

The wave frequencies are usually fitted to probability distributions in order to represent how the sea will look over an extended time (DNV, 2014). The most notable techniques used are the Method of Moments (MOM), Least Squares Method (LS) and Maximum Likelihood Estimation (MLE). The MOM typically gives a good fit to the data whilst the MLE has theoretical advantages but can be difficult to use in practice (DNV, 2014). LS is more influenced by the tail of the behaviour than the other two techniques.

The initial distribution is a 3-parameter Weibull distribution:

$$\boldsymbol{F_{H_S}(h) = 1 - exp\left[-\left(\frac{h-\gamma}{\alpha}\right)^{\beta}\right]} \tag{12}$$

Where,

$\alpha =$ scale parameter
$\beta =$ shape parameter
$\gamma =$ location parameter

(DNV, 2014)

To properly model a load case in an irregular wave simulation, a full 3-hour simulation time is recommended. However, if the simulation times are too long for a 3-hours simulation in practice, a method with selection of characteristic wave trains can be applied (DNV, 2011). One common way to do this is to run the simulation for one hour and then apply a Maximum Likelihood Estimation (MLE).

For a JONSWAP spectrum, the location parameter is adjusted so that the number of peaks is 15% of the total number of peaks. For a TMA spectrum however the peaks are reduced. For this reason the appropriate number of peaks to consider for the maximum movement will be tested. If m is the total number of peak responses during the full time simulation, then the extreme response x_c^w during this time can be calculated by:

$$\boldsymbol{x_c^w = \gamma + \alpha \ln m^{\frac{1}{\beta}}} \tag{13}$$

Wave Exaltation Forces

When low keel clearance occurs, most of the wave energy will not pass underneath the hull. When looking at basic ship motion equations in deep water, the small-body approximation is often used ($B < \frac{\lambda}{4}$ where B is the breadth of the ship). Part of the reason for this approximation is the Smith effect where a factor is added since the deeper the draught of the vessel, the less the excitation forces. The particle motion in deep water will extend down a depth where the particles are no longer affected by the surface waves. It will be a greater depth for waves with a long wavelength. In shallow water, the waves motion will be compressed to a more elliptic motion. Close to the bottom the motion will be more or less back and forth. This means that the particle motion will cause very little excitation forces (Bergdahl, 2009). The Smith effect is illustrated in *Figure 2.3*.

The particle movement will however cause a pressure difference in the wave underneath the hull. This pressure difference can give cause to a vertical movement.

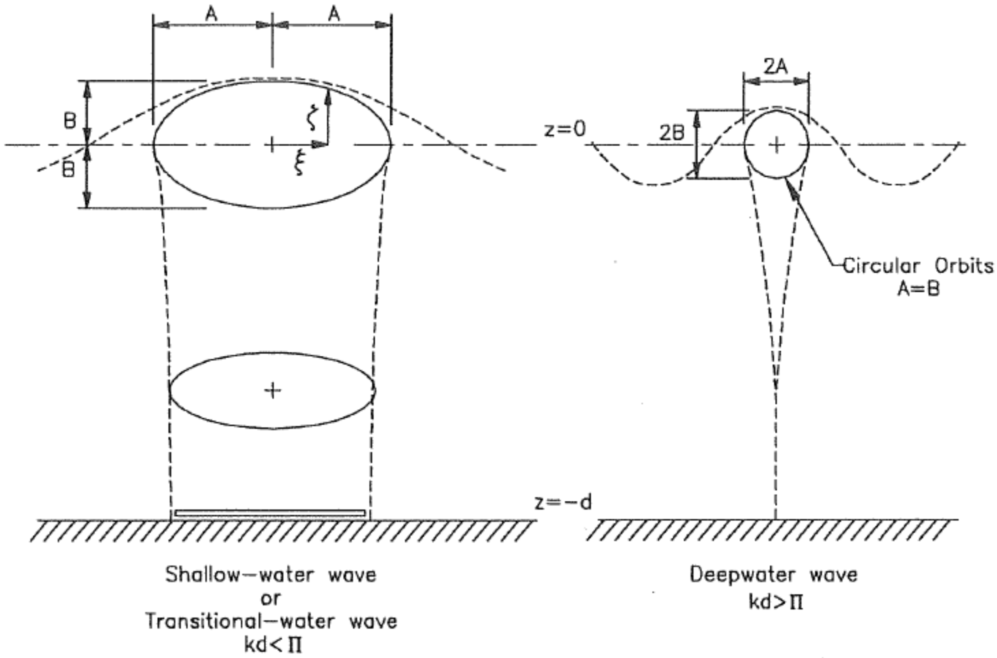

Figure 2.3: Smith effect (Bergdahl, 2009).

2.2 Wind

This section will describe wind in general, i.e. how wind is measured, what parameters that are used, how it can be visualized and how wind forces are calculated.

2.2.1 Wind Conditions

Wind speed varies with time and with height above the sea surface. For these reasons, the wind must always be specified in which time interval it is measured and on which height. A commonly used reference height for the wind is 10 meters and commonly averaged times are 1 minute, 10 minutes and 1 hour (DNV, 2014).

When measuring the wind over a 10 minutes average time and on 10 meter above the mean sea level, the wind forces can be presented using the Beaufort's wind scale in order to more easily visualize the wind intensity (Thoresen, 2015). Another way to visualize wind conditions is by using a wind rose diagram. This type of diagram illustrates the yearly distribution of wind directions and its forces as a percentage of time (Thoresen, 2015). An example of a wind rose diagram is displayed in *Figure 2.4*.

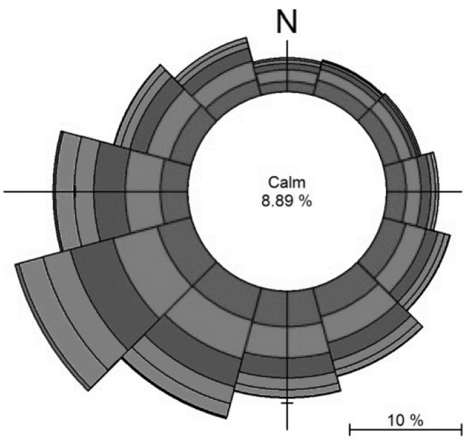

Figure 2.4: Wind rose.

2.2.2 Wind Modelling

To model wind distributions, scatter diagrams can be used. When using these, the wind climate parameters U_{10} (10 minute wind velocity) and σ_U (standard deviation of wind velocity at 10 m height above mean water surface) are derived from available data. Unless the data indicates otherwise, a Weibull distribution is assumed according to the following equation:

$$\boldsymbol{F_{U_{10}}(u) = 1 - \exp\left(-\left(\frac{u}{A}\right)^{kk}\right)} \tag{14}$$

Where A is a scale parameter and kk is a site- and height-dependent shape parameter (DNV, 2014).

To estimate return period T_R, defined as the probability of winds exceeding a certain speed over a defined time period, the following equation can be used:

$$\boldsymbol{U_{10,T_R} = F_{U_{10,max},1\,year}{}^{-1}\left(1 - \frac{1}{T_R}\right)} \tag{15}$$

Where T_R is over 1 year (DNV, 2014).

2.2.3 Wind Spectrum

When simulating wind over a stationary place and under a limited time, the wind may be described as a wind spectrum, i.e. the spectral density of the wind speed (DNV, 2014). When using a wind spectrum, the density $S_U(f)$ shall asymptotically approach following form when the frequency f increases:

$$\boldsymbol{S_U(f) = 0.14 \cdot \sigma_U^2 \left(\frac{L_U}{U_{10}}\right)^{-\frac{2}{3}} f^{-\frac{5}{3}}} \tag{16}$$

Where L_U is the integral length scale of the wind velocity process (DNV, 2014).

There are many different spectra used when modelling wind. Some are presented below:

- The Davenport spectrum: Originally developed for wind over land with $L_U = 1200$ as the proposed value. Not recommended for use in the low frequency range, i.e. for $f < 0.01\ Hz$.
- The Kaimal spectrum
- The Harris spectrum: Also originally developed for wind over land and is neither recommended to use in the low frequency range.
- Simiu and Leigh spectrum: Empirical formula, developed for design of offshore structures. Taking into account the wind energy over a seaway in the low frequency range.
- Ochi and Shin spectrum: Has even more energy content in the low frequency range. Yet, for frequencies less than 0.001, the energy content might not be sufficient.
- Frøya model spectral density: For situations where excitation in the low-frequency range is of importance. Recommended model for wind over water.

(DNV, 2014)

2.2.4 Wind Forces

Wind forces are in general time dependent loads due to fluctuations in the wind velocity (DNV, 2014). The force may vary considerably depending on vessel type and vessel size and is therefore best defined by testing in a hydraulic institute (Thoresen, 2015). There are many standards and recommendations for calculating wind forces, such as the Spanish standard, Eurocode, OCIMF, British standard, DNV, etc. (Thoresen, 2015; DNV, 2014). These standards should however only be used as a guide since they are estimations. The DNV standard recommends the following:

The basic wind pressure is defined by:

$$\boldsymbol{q = \frac{1}{2}\rho_a U_{T,z}^2} \tag{17}$$

Where,

$q =$ basic wind pressure or suction
$\rho_a =$ mass density of air
$U_{T,z} =$ wind velocity averaged over a time interval T at a height z m above the mean water level.

The wind force can then be calculated:

$$\boldsymbol{F_W = C_w\, q\, S \sin\alpha} \tag{18}$$

Where,

$C_w =$ shape coefficient
$S =$ projected area normal to the direction of the force
$\propto =$ angle between direction of wind and axis of the exposed surface

The shape coefficient can either be found in Eurocode EN 1991-1-4 General actions – Wind actions (Eurocode, 2010) or calculated using the shape coefficients in the DNV standard (DNV, 2014).

2.3 Currents

There are many types of currents. The most common types are:

- Wind generated currents
- Tidal currents
- Circulational currents
- Loop and eddy currents
- Soliton currents
- Longshore currents
- Rip currents

(DNV, 2014)

In this thesis, the focus will be on longshore currents in combination with rip currents as this will be the main currents affecting Victoria.

2.3.1 Longshore Currents

When waves break over shallow water, they tend to create currents parallel to the shore. The currents are produced by accumulated breaking waves over time which directly gives rise to a movement of the water. This is the case for waves collapsing to its steepness. In this process, smaller waves create stronger currents as they are less affected by refraction and the water can thus break at a higher angle to the beach and therefore create stronger longshore currents. Currents created this way can get speeds exceeding 0.5 m/s (Thomson, 1981).

2.3.2 Rip Currents

The second way currents can be created from breaking water is through the undivided masses of water. When waves break due to speed differences, water tend to be delegated more towards shore. This causes a current to be set up alongside the shore in order to transport away water from regions with large breakers (Thomson, 1981).

The water being transported along the beach through the longshore currents will eventually have to go back to the sea. This happens through series of strong narrow currents flowing perpendicularly out from shore. These type of currents are called rip currents. Rip currents can sometimes attain speeds up to 1-1.5 m/s (Thomson, 1981).

2.3.3 Current Forces

Just as the wind forces, the current forces can vary considerably with type of vessel and size. If accurate results are needed, the current forces should therefore be established by model testing (Thoresen, 2015). These tests are usually run in either wind tunnels or towing tanks (DNV, 2014).

The low keel depth of this vessel will affect the flow around the ship from currents. The water that flow underneath the ship will be limited which will cause more resistance and the force on the hull will be larger than it would in deeper water. Combining these forces with mooring forces will create a moment that potentially could cause roll and pitch.

The longitudinal current forces are very scale dependent (Thoresen, 2015). The current load and complexity increase with shallow water. Proximity effects should therefore be considered (DNV, 2014; Thoresen, 2015). The effect of the under keel clearance is visualized in *Figure 2.5*.

Another effect that should be considered if the ship is to stay moored in the same place is that the limited flow around the ship will cause an increase in the speed of the water underneath the hull. If the sea bed consists of sand or other sediment it will cause sediment transport. It can also create an increase in the squat effect, mentioned in *section 2.5.2.*

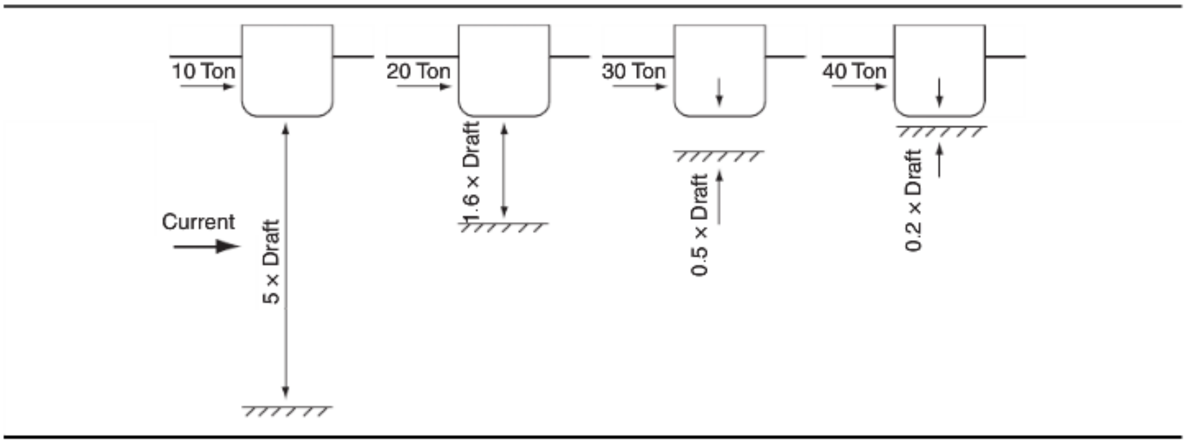

Figure 2.5: Effect of keel clearance on current force (Thoresen, 2015).

Current forces are usually calculated with empirical formulas and normally follows the general form:

$$\boldsymbol{F_c = C_c \cdot U_c^2} \tag{19}$$

Where,dd

C_c = current coefficient
U_c = current velocity

(DNV, 2014)

The current coefficient is obtained from model testing. The current force can also be estimated using various standards. However, this should be done with caution since the estimations might not be accurate (Thoresen, 2015).

According to DNV, the longitudinal current force can be calculated by the formula:

$$\boldsymbol{F_{cx} = \frac{1}{2} \rho\, S\, U_C^2\, C_d(R_e\, d, \beta)} \tag{20}$$

Where,

S_w = wetted surface
C_d = drag coefficient
R_e = Reynold's number
β = angle between current and longitudinal axis of the ship

The transverse current forces can be calculated by the formula:

$$F_{cy} = \frac{1}{2}\rho \left[\int_L dx C_D(x) D(x)\right] U_C^2 \sin\beta \,|\sin\beta\,| \tag{21}$$

Where the integration is over the length of the ship and,

$D(x)$ = sectional draught
$C_D(x)$ = drag coefficient for flow past an infinitely long cylinder with the cross-sectional area of the ship at position x.

2.4 Mooring System

The mooring system can be adjusted to a certain level to compensate for the horizontal forces acting on the ship. The vertical movement is the area of interest in this case, and since the horizontal forces can give a moment from the mooring lines it can cause a roll of the vessel that should be considered.

When mooring a ship in very shallow water, the behaviour gets complex due to all the nonlinearities and dynamic effects (Oortmerssen, 1988). To achieve fairly accurate solutions to these type of problems, you must either perform model tests or calculate with CFD. To achieve as accurate solution as possible it is preferable to perform both, but in the initial phase CFD calculations are usually used as they save both time and costs and still gives fairly accurate results. The mooring lines are usually exposed by the following forces (Oortmerssen, 1988):

- Wave loads and wave drift forces
- Hydrodynamic forces, damping (Oortmerssen, 1988)
- Wind and currents
- Combined loads
- Static and dynamic mooring loads

2.5 Bottom Effects

There are three main categories of forces from nature that will act on the ship: waves, wind and currents. Mooring forces will counter these forces to prevent horizontal movements, but heave, roll and pitch of the vessel will not be countered. The close proximity of the bottom will cause effects that would not have to be considered in deep water.

2.5.1 Added Mass

The forces needed to accelerate a floating ship has to take added mass into consideration. In deep water it will represent the water moving with the ship as it is being pushed aside. Far from the free surface only the shape of the hull will affect the added mass as it will remain constant. (Bergdahl, 2009)

The added mass is a hydrodynamic characteristic that play an important role when determining the motions of a body. When looking at frequency dependant added mass of a floating cylinder with a simple shape, there are a lot of literature on the subject. However, looking at the same topic in shallow water there is considerably less material. When the ship moves in a horizontal direction in shallow water there will be a restriction in the flow for the water underneath the ship. This will cause an added mass effect that will vary depending on how close to the bottom the ship gets. (Z.X. Zhou, 2003)

The added masses for sway, heave and roll for a body in shallow water can be numerically analysed. There are reports on the subject that look at different shapes and how the added mass is affected depending on its proximity to the sea bed. A rectangular shape will be greatly affected, and as the MS Victoria has a relatively flat bottom it will mean this will be the case here. The shallow water will have the greatest effect on sway motions. (Z.X. Zhou, 2003)

Looking at the heave motions from the report *Effect of shallow and narrow water on added mass of cylinders with various cross-sectional shapes* (Z.X. Zhou, 2003) the added mass factor C_a for a rectangular cross section will be around 7.5 for a depth to draft ratio of 1.2. In deep water it will be closer to 2.4. However, the ration will be even lower in this.

When looking at the added mass in deep water for a rectangular cross-section the DNV standard uses the following formulas:

Added mass (m_A) per meter rectangular cross section:

$$\boldsymbol{m_A = \rho C_A A_R} \tag{22}$$

Where,

$$C_A = \frac{b}{d*\varepsilon} - \frac{2}{pi} * log(4*\varepsilon) + \frac{2}{pi} - 2*\frac{b}{d} + \varepsilon * \frac{b}{d} + \frac{2}{3*pi} * \varepsilon^2$$

$b = half\ breadth$

$D = draught$

$d = depth$

$1 - \varepsilon = \frac{D}{d}\ where\ \varepsilon \ll 1$

$A_R = 2c^2$ – *reference area*

However, this is only for a rectangular cross section. It will only give an indication if the value from the CFD is in a reasonable range.

2.5.2 Squat Effects

The difference in speed between the water and the hull in shallow water will create a suction effect. This is called the squat effect and needs to be taken into consideration when a vessel is moving in shallow water. For example, when a ship moving in a channel or canal. It will be affected by the speed of the vessel and how close to the sea bed the ship is.

The low keel depth of this vessel can cause a squat effect of the MS Victoria while moving, or if there is a flow underneath the hull from currents or waves. (DNV, 2011)

The squat effect can cause a pitch or roll if the water has a speed underneath the ship. It is important to consider the speed of the water underneath the ship to get an accurate value for the potential suction this could cause. See *section 2.3.3.*

$$\frac{z_{max}}{D} = 2.4 * \frac{C_b}{L/B} * \frac{F_h^2}{\sqrt{1 - F_h^2}} \tag{23}$$

Where,

$zmax$ = squat (combined sinkage and trim at bow or stern [m]
L = length of object [m]
B =beam of object at the maximum area [m]
D = draught of object [m]
$C_b = \frac{\nabla}{LBT}$ [−], where ∇ is the displaced water volume.
$F_h =$ the depth Froude number: $F_h = \frac{V}{\sqrt{gd}}$ [−]
$V = U - U_c$ is the relative speed [m/s]
g = gravitational acceleration [m/s2]
d = water depth [m]
U = towing speed [m/s]
U_c = current velocity (in e.g. a river) being positive in the direction of the tow route [m/s]

A higher speed will increase the effect, as well as lower depth. For this reason, ships will usually decrease their speed when going into more shallow water. If the current starts causing squat effects then it should increase as the depth decreases.

2.6 Simulation Methods

Environmental loads can generally be divided into three frequency ranges; low frequency (LF), wave frequency (WF) and high frequency (HF) (DNV, 2011). Steady-state loads also occur from current forces, mean wind forces and mean wave drift forces (Kwan & Bruen, 1991). LF usually consist of non-linear load effects due to slowly varying wave and wind loads. It is sometimes also named slow-drift motions (DNV, 2011) and could in a simulation often be considered as a steady-state load due to its long motion periods (Kwan & Bruen, 1991). HF usually consist of elastic responses from wave induced loads and causes effects such as springing and whipping (DNV, 2011). WF are induced by large wave loads (DNV, 2011) and can be predicted by two methods; a quasi-static analysis or a dynamic analysis (Kwan & Bruen, 1991).

In a quasi-static analysis, the wave induced loads are accounted for by statically offsetting the vessel horizontally depending on the wave induced motions. All vertical motions are thus neglected and the analysis does therefore not include effects such as damping, added mass and fluid acceleration effects (Kwan & Bruen, 1991).

The dynamic analysis calculates the dynamic responses from the vessel in all six degrees of freedom (DOF) (surge, sway, pitch, roll, heave and yaw) and this analysis type includes effects such as damping, added mass and fluid acceleration effects (Kwan & Bruen, 1991).

Since the quasi-static method neglects many important effects and is also less reliable in the WF, a dynamic analysis is to prefer in order to achieve a better accuracy. Several dynamic analysis methods are available and can be done using for example a time domain analysis or frequency domain analysis (Kwan & Bruen, 1991).

2.6.1 Frequency Domain Analysis

The frequency domain analysis is always a linear method and all nonlinearities must thus be eliminated. This can be done by either using a direct linearization or by an iterative linearization process (Kwan & Bruen, 1991).

Within a frequency domain analysis, the hydrodynamic problem is usually divided into two sub-problems:

- Radiation problem – The vessel oscillates with the WF in a rigid body motion and with no incident waves. Resulting loads are formulated as added mass, damping and restoring loads:

$$\boldsymbol{F_k^{(r)}} = -\boldsymbol{A_{kj}}\frac{\boldsymbol{d^2\xi_j}}{\boldsymbol{dt^2}} - \boldsymbol{B_{kj}}\frac{\boldsymbol{d\xi_j}}{\boldsymbol{dt}} - \boldsymbol{C_{kj}\xi_j} \tag{24}$$

  Where,

  A_{kj} = Added mass

  B_{kj} = Damping

  C_{kj} = Hydrostatic restoring effects

  $k, j =$ 1,6, the six DOF.

- Diffraction problem – The structure is restrained from motions and is excited by incoming waves. Resulting loads are wave exaltation loads:

$$\boldsymbol{F_k^{(d)}} = \boldsymbol{f_k(\omega)e^{-i\omega t}} \tag{25}$$

  (DNV, 2011)

A big advantage of the frequency analysis compared to a time domain analysis is that the frequency analysis is considerably faster and simulations can thus be done more efficiently (Kwan & Bruen, 1991).

2.6.2 Time Domain Analysis

In many cases, a linear assumption works well but when highly non-linear effects are of importance, a frequency method is not sufficient enough. A time domain analysis can properly calculate all non-linear effects at each time step. It is however a lot more time consuming and complex (Kwan & Bruen, 1991).

During a time domain analysis, the equations of motions are numerically integrated over each time step and are often used for extreme load cases. In case of modelling critical events, it is of importance that the simulation is run for a sufficient amount of time (DNV, 2011).

2.7 ANSYS Aqwa

ANSYS is a software suite which contains various finite element method (FEM) and finite volume method (FVM) programs. Aqwa is a part of this suite which provides a toolset to investigate effects from wind, waves and currents on marine structures. Including ships and breakwater designs. It uses equations for calculating motions in both deep and shallow water and also include important parameters such as damping effects and added mass (ANSYS, 2013).

By combining the hydrodynamic parameters, a three-dimensional non-linear analysis can be obtained where motions can be observed on the vessel in all six degrees of freedom (DOF). The results can be obtained either as a frequency analysis or a time step analysis.

The wave parameters can be inserted either as regular waves or as irregular waves with a chosen wave spectrum and wave angle. The wind parameters can also be inserted either as a constant wind or with a wind spectrum of choice. The currents can be inserted as constant with a certain angle.

To further extend the possibilities of Aqwa, a wide range of physical connections can also be attached, such as mooring lines, fenders and articulations. These connections will contribute with restraints of the model and thus affect the hydrodynamic motions (ANSYS, 2013).

In addition to this, Aqwa can also investigate slow-drift effects and extreme-wave conditions.

3 Calculations

Various wave spectra are needed to be calculated for the necessary combinations of H_S and T_p for the simulations. Matlab is used to calculate these values efficiently with the possibility to change the input parameters in order to obtain different desired results. (Matlab, 2016)

3.1 Wave Spectrum Calculations

When calculating the different wave spectrum for the analysis, the TMA spectrum is used, using actual data from the metocean data, obtained from ABB to decide relevant H_s and T_p. To calculate the TMA spectrum, the method explained in the DNV standard (DNV, 2014) has been used.

Three input parameters are used: a matrix of all desired H_S, a matrix of all desired T_p and the depth. Matlab is then set to run all following calculations with all combinations of H_S and T_p.

The TMA spectrum is as mentioned in *section 2.1.3* given as the JONSWAP spectrum multiplied by a depth function $\emptyset(\omega)$, where ω is the wave frequency. The JONSWAP spectrum is in turn a modification of the PM spectrum. The calculations is done in the following order:

The wave length L is obtained for deep water

$$\mathbf{L} = \frac{\boldsymbol{gT^2}}{\boldsymbol{2\pi}} \tag{26}$$

Where g is the acceleration of gravity (m/s^2)

If $d/L < 0.5$

L is changed to:

$$\mathbf{L} = \frac{\boldsymbol{gT^2}}{\boldsymbol{2\pi} \cdot \mathbf{tanh}\left(\frac{\boldsymbol{2\pi d}}{\boldsymbol{L}}\right)} \tag{27}$$

If $d/L < 0.04$

L is changed to:

$$\mathbf{L} = \boldsymbol{T\sqrt{gd}} \tag{28}$$

With the wave length, the wave number k can be calculated:

$$\boldsymbol{k = 2\pi/L} \tag{29}$$

With k, the depth function $\emptyset(\omega)$ can be obtained:

$$\emptyset(\boldsymbol{\omega}) = \frac{\boldsymbol{sinh^2(kd)}}{\boldsymbol{sinh^2(kd) + kd}\ \mathbf{coth}\ \boldsymbol{(kd)}} \tag{30}$$

Afterwards, the peak shape parameter γ for the JONSWAP equation is calculated:

$\gamma = 5$ when $T_P/\sqrt{H_S} > 5$

$\gamma = 1$ when $T_P/\sqrt{H_S} \leq 3.6$

Otherwise,

$$\boldsymbol{\gamma = \exp\left(5.75 - 1.15 \cdot \frac{T_P}{\sqrt{H_S}}\right)} \tag{31}$$

Next, some values necessary for the JONSWAP formula are calculated.

The peak frequency ω_P:

$$\boldsymbol{\omega_P = 2\pi/T_P} \tag{32}$$

The normalizing factor A_γ:

$$\boldsymbol{A_\gamma = 1 - 0.287 \cdot \ln(\gamma)} \tag{33}$$

The spectral width parameter σ:

$\sigma = 0.07$ for $\omega \leq \omega_P$

$\sigma = 0.09$ for $\omega > \omega_P$

With these values, the PM $S_{PM}(\omega)$ and JONSWAP $S_J(\omega)$ spectrum can be obtained:

$$S_{PM}(\omega) = \frac{5}{16} \cdot H_S^2 \omega_P^{-5} exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_P}\right)^{-4}\right) \tag{34}$$

$$S_J(\omega) = A_\gamma\, S_{PM}(\omega)\, \gamma \cdot exp\left(-0.5\left(\frac{\omega-\omega_P}{\sigma\omega_P}\right)^2\right) \tag{35}$$

Which finally yields the TMA spectrum through:

$$\boldsymbol{S_{TMA}(\omega) = S_J(\omega) \cdot \emptyset(\omega)} \tag{36}$$

These spectra are then individually saved as point values in separate .csv files in order to be easily imported into Aqwa.

3.2 Maximum Vertical Movement Calculations

Since a quantity of analysis are of importance in this thesis and a full 3-hour simulation of the analysis would not be time efficient, an approximation of the wave train has been made from a 1-hour simulation accordingly to *section 2.1.4*.

For each time step in the analysis, the maximum movement (l_Z) in z-direction (movement towards the sea bed) is calculated using a simplistic method by applying Pythagoras theorem:

$$\boldsymbol{l_Z = Z + \sin(RX) \cdot B_B/2 + \sin(RY) \cdot L_B/2} \quad (37)$$

Where,

Z = initial movement in z-direction (Heave)
RX = rotation around x-axis (Roll)
RY = rotation around y-axis (Pitch)
B_B = breadth of the bottom of the ship
L_B = length of the bottom of the ship

The bottom length and breadth of the hull is measured from the bottom area of the hull. The values measured are:

$B_B = 20\ m$
$L_B = 115.5\ m$

A comparison of the measured rectangle and the actual area can be seen in *Figure 3.1*.

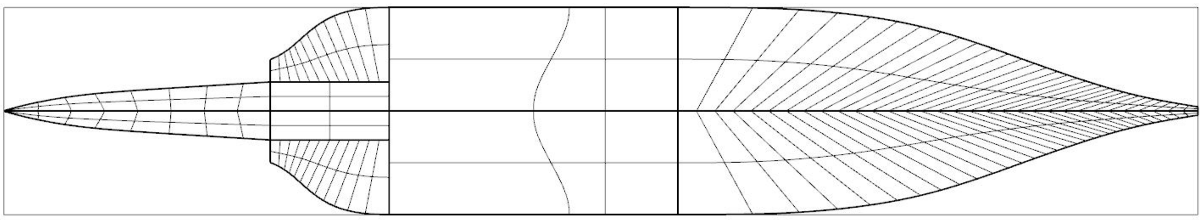

Figure 3.1: Bottom area of the hull compared to estimated lengths (rectangle).

This data needs to be fitted and adjusted to a Weibull plot. The same amount of peaks as used for the JONSWAP spectrum (15%) cannot be used because of the TMA spectrum's properties. Compared to the JONSWAP Spectrum, a TMA spectrum has a blunter peak and will thus consist of less peak values. Two full length simulations are therefore run in order to verify how big percentage of the peaks from l_Z that should be taken into consideration in order to receive a reliable result.

A value of 5% is chosen. This percentage is then applied on all simulations and its value for each simulation chosen as the simulations peak parameter. The scale (α) and shape (β) parameter is fitted from the peak values using the built-in command "wblfit" in Matlab.

m is then chosen as the number of peaks for the full 3-hour simulation:

$$\boldsymbol{m = n_{15\%,peaks} \cdot 3} \quad (38)$$

The extreme response x_c^w is calculated:

$$\boldsymbol{x_c^w = \gamma + \alpha \ln m^{\frac{1}{\beta}}} \quad (39)$$

Each extreme response value is then stored and represented in a diagram showing the extreme responses for various significant wave heights and wave periods. This will be further discussed in *section 6*.

3.3 Mooring Line Calculations

The tension from the mooring lines are given from Aqwa. Since the simulation has only been run for 1 hour, a 3-hour approximation of the results need to be done. This is made in the same manner as for the movement calculations as seen in *section 3.2*.

Since the vessel is identical on starboard and port side with the mooring lines arranged in the same way, the tension in the lines are only calculated on the side which causes the most critical values. The values for the front-, mid- and aft-lines are then stored and presented as maximum tension for various significant wave heights and wave periods.

4 Simulations in ANSYS Aqwa

The simulations for the motions of the vessel are as mentioned in section 2.7 is made in the software Aqwa. This section explains how the simulations were set up, which simulations that were chosen and why. In Aqwa, one base setup is made where the model of the vessel is imported and adjusted to work well with the ANSYS Work bench.

When the base model is setup and all parameters adjusted to get an acceptable result, different simulations are run according to a simulation schedule.

4.1 Base Model Setup

A model needs to be set up to solve the problems using Aqwa, containing two models: the hull of the vessel and the mooring lines attached to the hull.

4.1.1 Base Hull Model

A file containing the geometry of the hull of the MS Victoria was obtained from ABB. This hull needed to be slightly modified in a software called Rhino 3D (McNeel, 2016) in order to smoothly be imported into ANSYS Workbench. In Rhino, the following modifications to the hull are made:

- Ship hull is mirrored in order to obtain a full hull. This is necessary since Aqwa cannot run analysis on a half hull.
- The hull deck is closed by adding surfaces on top of the hull model to simplify for Aqwa.
- The hull is lowered in the coordinate system so the z-axis cuts through the hull on draught level (6.7 m). The hull is then separated into two surfaces with the z-axis separating the two. This is also necessary in order to allow Aqwa to easier analyse the hull body.

The model is then imported into Aqwa which can be seen in *Figure 4.1*. On the model, a point mass is added, containing all necessary mass data. The mass data is also based on data from ABB. The loading conditions used on the vessel assumes that the vessel is operating in shallow water (1-3 m depth) with fully loaded cargo (6000 tonnes). The data inserted into the model can be seen in *Table 4.1*.

Table 4.1 Mass properties inserted into Aqwa.

Radius of Gyration

Kxx	9.36 m
Kyy	30.65 m
Kzz	30.71 m

Center of Gravity

z-axis	2.58 m

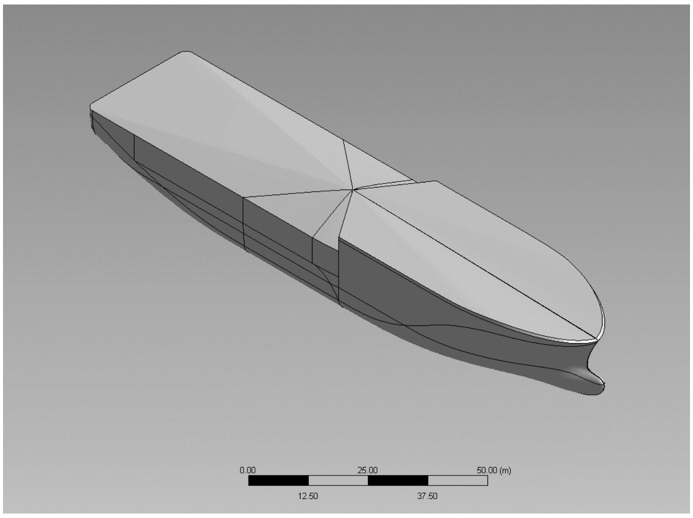

Figure 4.1: Hull model in ANSYS Aqwa

Aqwa is thereafter calculating the rest of the hydrostatic properties from these values. The hydrostatic properties are then compared to the given properties from ABB to verify that the model hydrostatics corresponds well. The comparison can be seen in *Table 4.2*.

Table 4.2 Compared Hydrostatic values.

	Hydrostatic values obtained from Aqwa	***Hydrostatic Values obtained from ABB***	***Difference (%)***
Displacement	19737 t	19594 t	0.7
Center of Buoyancy			
x-axis	58.44 m	58.49 m	0.01
z-axis	-3.04 m	-3.04 m	0
Center of Gravity			
x-axis	58.44 m	58.49 m	0.01

In order to properly model the effects from wind and currents, model specific wind and current coefficients has been received from ABB. These coefficients are then applied to the model hull through two extensions on the surface properties.

4.1.2 Base Mooring Cables Model

To model the mooring cables in Aqwa, values obtained from ABB are used in as large extent as possible. The mooring cables are attached and modelled according to *Figure 4.2*. This attachment setup is based on information from ABB. The mooring lines have an angle according to *Table 4.3*.

Table 4.3 Mooring line angles.

Mooring Line	Angle (Degrees)
Front	14
Mid	78
Aft	145

Maximum allowed length of the mooring lines are 800 meters. To give a slight span to this length, the initial cable length is set to about 700 meters. To obtain the desired initial towing tension of the cables received from ABB, the initial cable stretch is calculated in Microsoft Excel and subtracted from the unstretched length. This value is then inserted into the model as the initial cable length.

The mooring cables in this analysis also assumes to function as linear springs (Zhang, et al., 2011). Therefore, only the spring stiffness is inserted into the model, which is obtained from ABB. However, when the mooring cables become slack, the program assumes the stiffness to be 0.

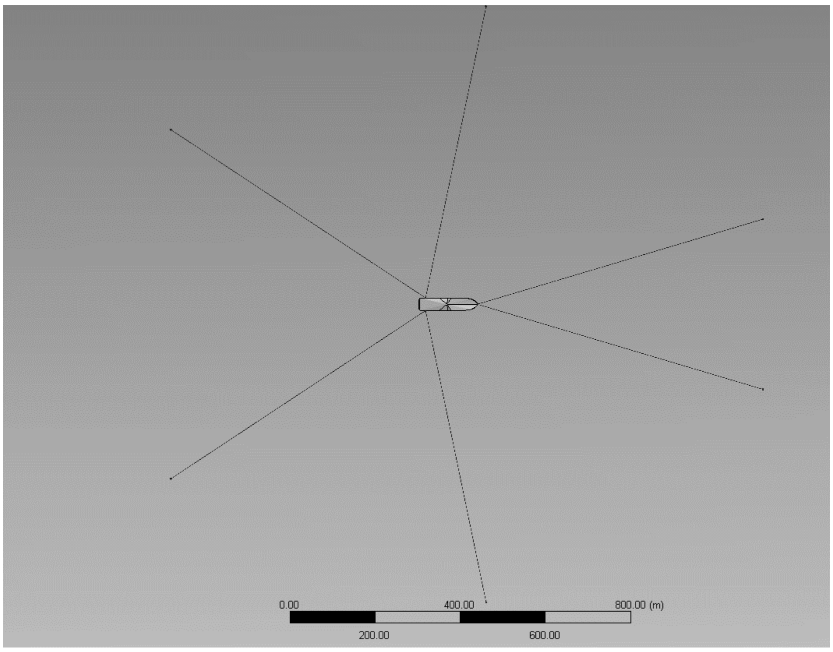

Figure 4.2: Mooring cables model setup.

4.2 Mesh Validation

In order to obtain a good result from the model, a sufficient mesh must be used. A more detailed mesh density does however also mean longer simulation times and since many simulations need to be run, as short simulation time as possible is sought after.

Initially, Aqwa already has some limitations itself on the choice of mesh density. The simulations can be run with a maximum of 40 000 elements, which corresponds with a maximum mesh element size of 1 meter and a tolerance of 0.5 meters on the vessel model. Due to the shallow depth of the simulations and thus the importance of a rather detailed mesh, Aqwa does not allow a bigger mesh element size than around 2 meters.

In order to better visualize how the mesh affects the results, large waves are used on a seabed where the vessel with certainty would have sufficient depth to not hit the bottom. Regular waves with the second order Navier Stokes theory are used for a better comparison of the results. The simulation was tested and set to a sufficient duration to balance the motions. The settings used for the mesh validation can be seen in *Table 4.4*.

Table 4.4 Settings for mesh validation.

Mesh element size span	1-2 m
Depth	20 m
Period	10 s
Amplitude	2 m
Time step	0.1 s
Duration	200 s
Wave Angle	150°

In order to get an approximate of how the mesh size affects the simulation, heave, roll and pitch were observed and compared for each time step. The mesh sizes were compared from the finest mesh. Graphs are shown in *Figure 5.1*, *Figure 5.2*, *Figure 5.3* and *Figure 5.4*.

Since the mesh does not seem to fluctuate very much with varying mesh size and since the values does not vary very much, an acceptable mesh element size of 2 m is chosen with a defeaturing tolerance of 1 m. This result in a mesh with 9157 elements.

4.3 Time Step Validation

A smaller time step will mean that more data is presented and the simulation time will increase. To ensure that the time step used does not give a large error on the final results, different time steps were compared to each other. In this case, the maximum movements are the areas of interest and therefore the peaks are compared for a regular wave, starting with a small time step. The difference is then compared as the time step is increased, looking at the difference in motion for every wave.

Aqwa also has a built in function to show how big the error is from the time step size. After testing, the final time step used is 0.2 seconds.

4.4 Depth Validation

The simulations in this thesis are very dependent on the water depth and its effects of the ships motions. It is therefore crucial that the depth variance has valid impact on the results. To verify this, a depth validation is made where the same parameters are put in with only a varying depth. The depth is varied from 100 meters to 7.2 meters (a keel clearance from 93.3 to 0.5 meters). The parameter settings for the depth validation can be seen in *Table 4.5*.

Table 4.5 Settings for depth validation.

Mesh size	9157 $Elements$
Depth span	20- 7.7 m
Period	10 s
Amplitude	2 m
Time step	0.2 s
Duration	400 s
Moored	Yes
Regular	Yes
Cable Length	700 m

Since the added mass is highly affected by the depth of the simulation, these are the values that are compared. The added mass gained from the simulations are then divided by the initial displacement of the vessel (19737 tonnes). The comparison can be seen in *Figure 5.5*. As can be observed, the added mass is highly related to the depth and the simulated depth field does thus seem to be accurate.

Looking back to *section 2.5.1* that showed an added mass factor of 7.5 for a rectangular cross section at keel clearance to depth ratio of 1.2, the results in the graph seem close to this estimation when looking at a 1 meter keel clearance, which further confirms a reasonable result.

4.5 Irregular Wave Simulation Models

The irregular wave simulations are where the focus of this thesis will be. Even though it is very unlikely that wave trains will hit the vessel in less than 90° from the bow in the areas where it will operate, this will still be investigated in order to achieve a more complete analysis. All simulations are therefore run with wave angles from 0° - 180° from the bow with a 30° interval. Each of these simulations are run with various H_s and T_P, where H_s will vary from 0.5 – 2.5 meters with 0.5 meters intervals and T_P will vary from 4 – 20 seconds with 2 seconds intervals.

From these simulations, results from maximum movement in z-direction (movement towards the sea bed) and maximum tension in the front, mid and aft mooring line are calculated according to *section 3.3.* Each simulation case will thus consist of 135 results of 18000 values each which are presented in diagrams and graphs.

The following simulation cases are run:

1. No wind and no current.
2. A current of 1 knot and a wind of 10 m/s. Both with an angle of attack of 90° from the bow.
3. A current of 2 knots and a wind of 10 m/s. Both with an angle of attack of 90° from the bow.
4. No wind and no current, using a JONSWAP spectrum instead of a TMA spectrum.
5. No wind and no current and with a keel clearance of 0.5 m (draught of 7.2 m).

On the simulation with no wind and no current, two different types of graphs are presented; one which follows the same calculations as the others and one to which some values will be re-calculated to simulate the effect from the damping system which is installed on the MS Victoria. This estimation is made by using a graph obtained from ABB. The original maximum motions are reduced with a percentage according to *Table 4.6* for each specific T_p extracted from the graph.

Table 4.6: Motion variation with and without roll damping system.

Tp (s)	Diff (&)
6	13.7
8	44.8
10	51.4
12	27.5
14	14.9
16	6.9

4.6 Matlab Automatization

The simulation cases run in Aqwa consist of 45 different simulations per case. To start up, run, save and export values from each case manually would not be time efficient. Therefore, a Matlab script has been made where this process is automated. It is thus possible to run as many simulations in a row as preferred without having to interfere manually.

Initially, a simple Matlab script is made where it only loads and runs an ANSYS Workbench Journal. This journal is in turn programmed to open the current simulation, run it, save it and close it. These simulations contains either four or five different T_P with a constant H_S. This Matlab script is thus used when the simulations are run over several computers. If nine computers are used, the total simulation time will be approximately 15 hours.

For the times when it is necessary to run the simulations with fewer computers, another Matlab script has been made. Here, different simulations from Aqwa are set in a certain folder, containing the name of the H_S (05, 10, 15, 20, 25) they contain. Matlab is then set to open the ANSYS Workbench journal file and change the settings of which analysis to run. When it has executed one simulation, it is set to look for a specific folder, which only exist while the simulation is running. When this folder no longer exist, Matlab restarts the process by changing the journal file to execute the next simulation and again look for the corresponding folder. When all simulations are run, Matlab exports all simulation values and closes down.

5 Results

This section presents the results received from Aqwa, which are displayed in various graphs. The first subsections present some results which validates the Aqwa model. Afterwards, the different results of the vessel motions are presented followed by the results of the different mooring line tensions.

5.1 Mesh Validation

The difference in results for each time step in a simulation is very small, as seen in *Figure 5.1*. The maximum difference in heave is slightly less than 5 millimetres, the roll about 0.025° and the pitch is almost equivalent to none. Looking at *Figure 5.2*, *Figure 5.3* and *Figure 5.4*, it can be seen that the fluctuations tend to grow linearly with a bigger and bigger mesh size. For the rolling motions (roll and pitch), the mesh size of 1.8 meters seems to be the least profiting for the model while the heave motions seem to have the biggest fluctuations at a mesh size of 2 meters.

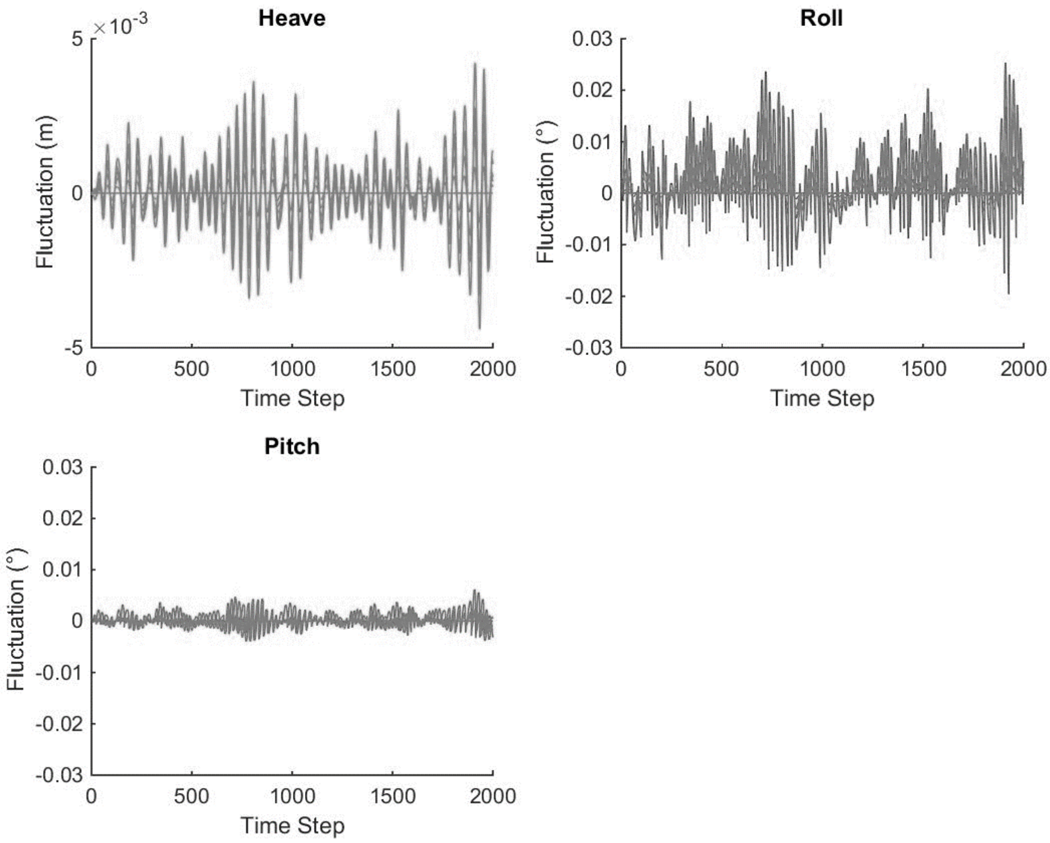

Figure 5.1: Mesh affecting the total results on vessel motions.

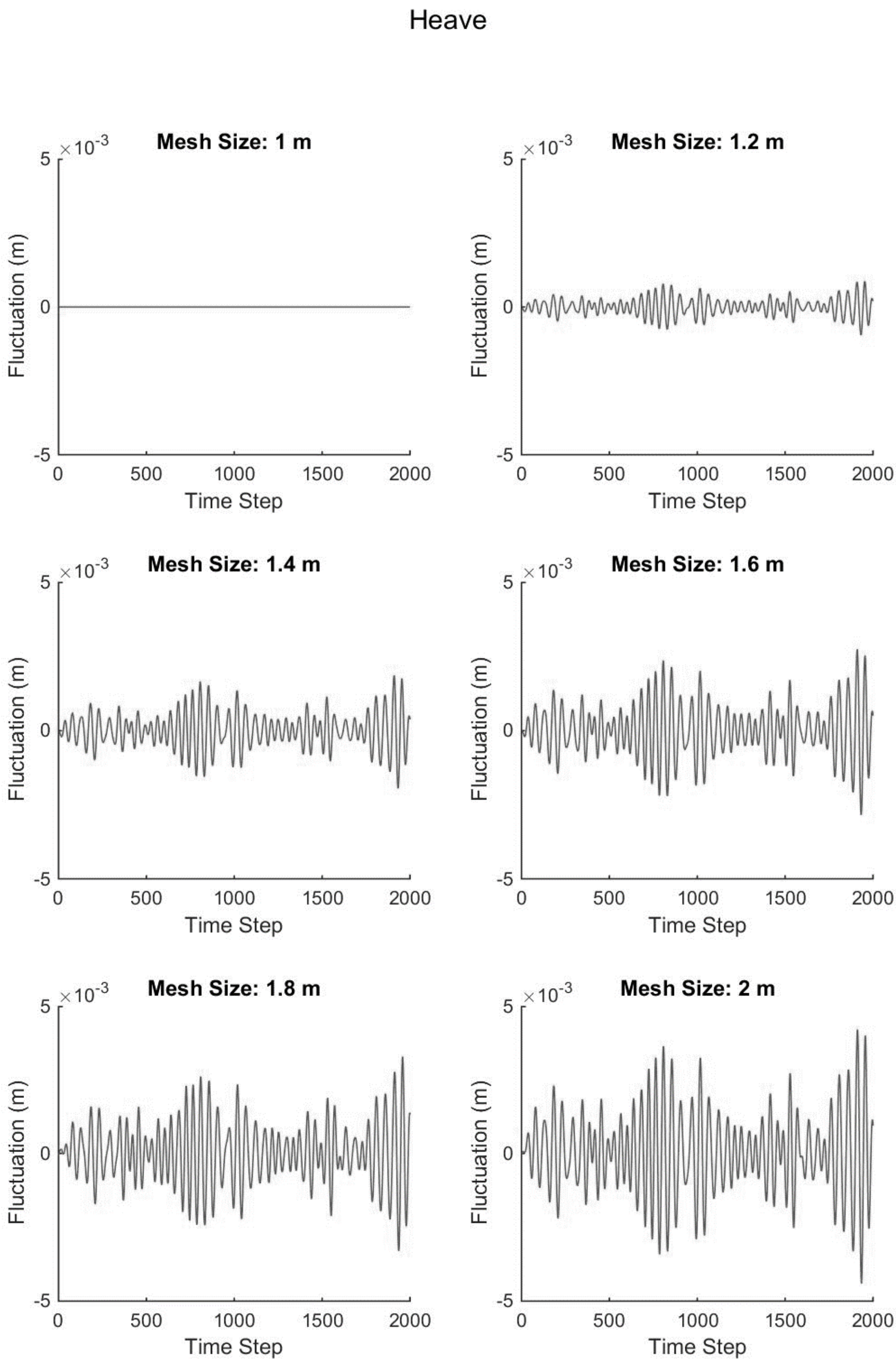

Figure 5.2: Mesh affecting the results of heave motions.

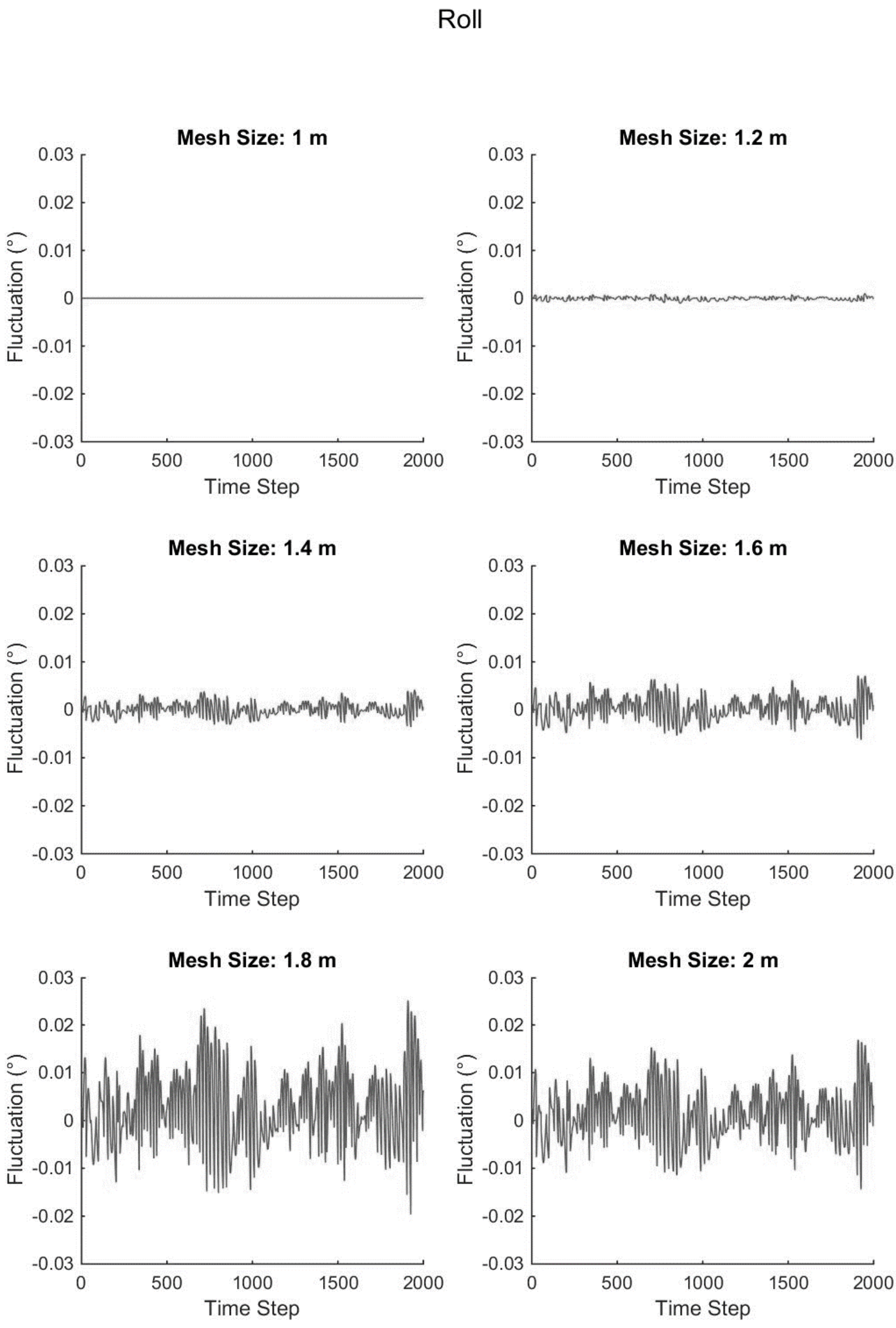

Figure 5.3: Mesh affecting the results of roll motions.

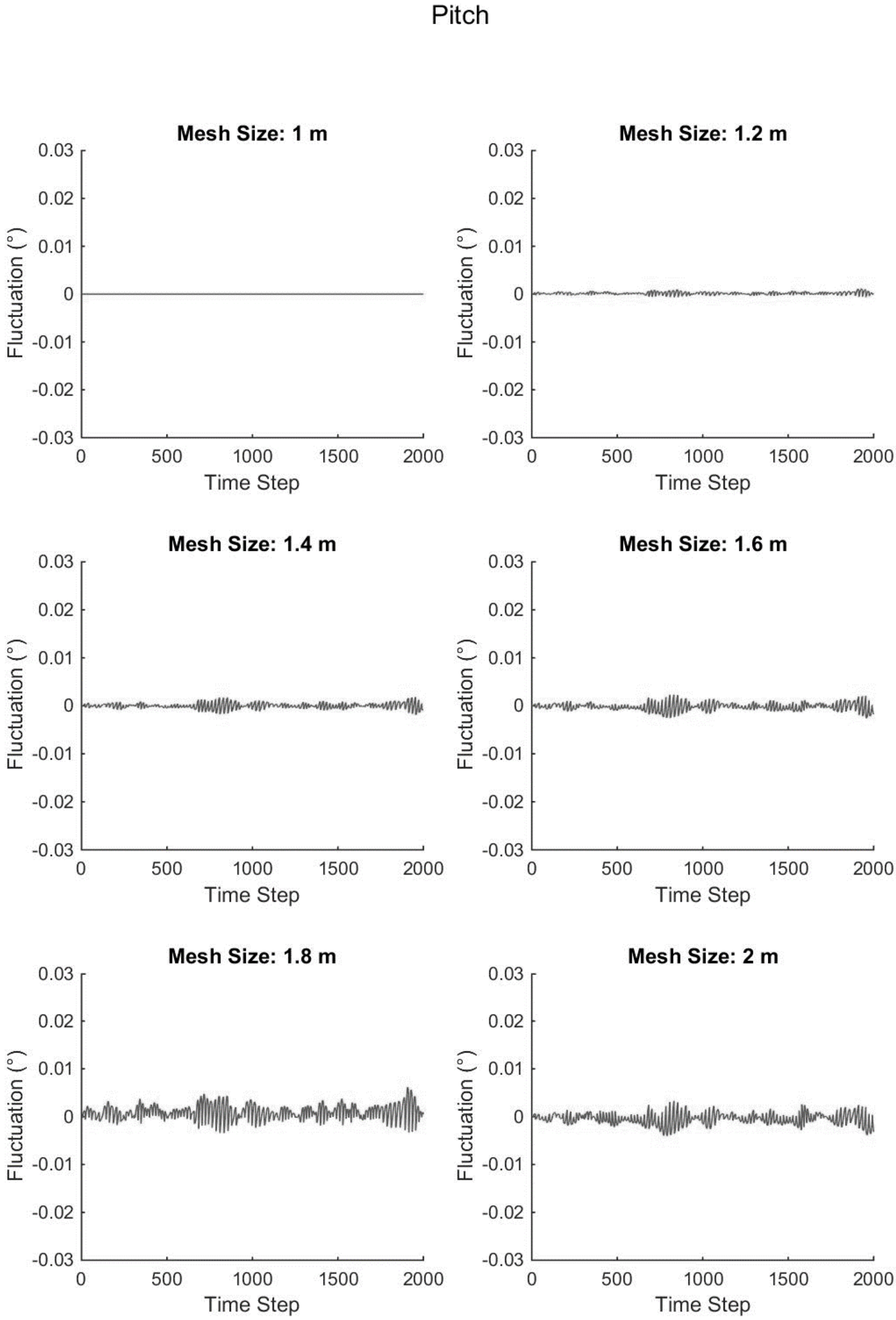

Figure 5.4: Mesh affecting the results of pitch motions.

5.2 Depth Validation

The added mass/vessel displacement can be seen in *Figure 5.5*. Here, the added mass/vessel displacement is plotted for various keel clearances over a frequency. The added mass tends to be higher and higher with a lower keel clearance. In higher keel clearance, the exaltation of added mass seems to be almost linear while it is highly non-linear with a lower keel clearance. This is especially clear in the region less than 3 meters.

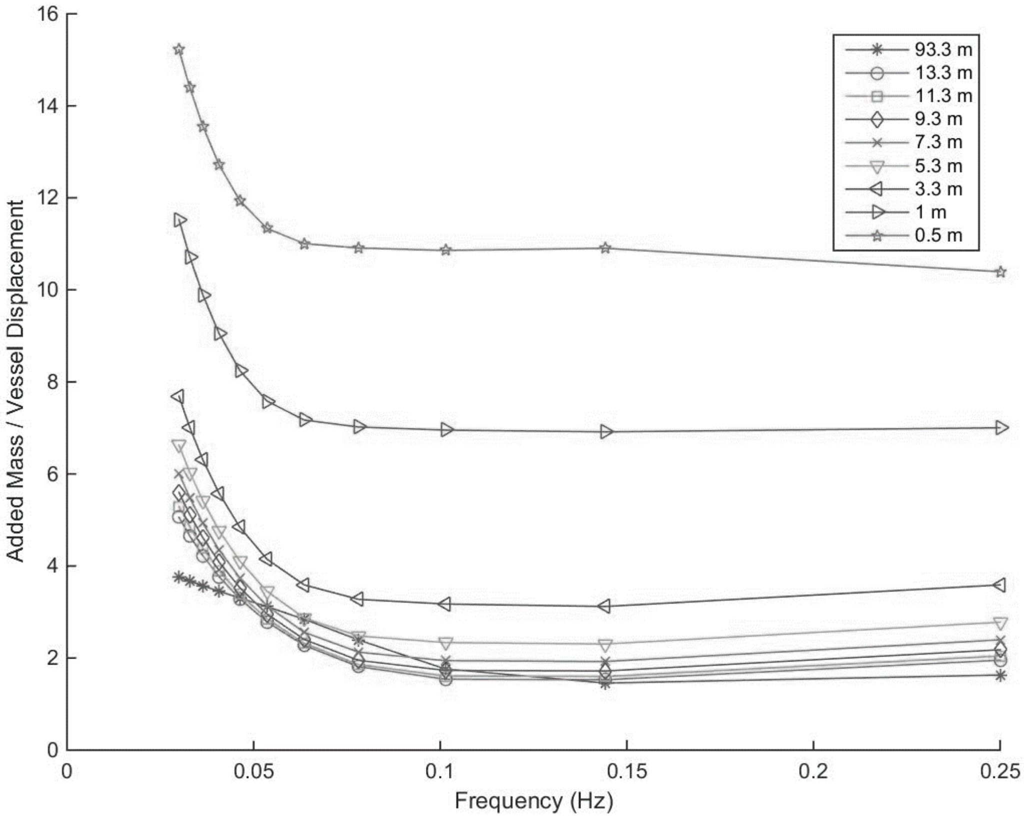

Figure 5.5: Added mass variation over depth

5.3 Vessel Motions

The results of the maximum vessel motions in z-direction (movement towards the sea bed) are presented in this subsection. Each angle of the wave trains has been sorted in separate graphs, with wave periods on the x-axis and the maximum motions on the y-axis. Each significant wave height has been designated a separate line. A limit line has been inserted in the graphs to visualize the maximum depth (1 meter). This representation of the results has been made for all different simulation cases. The observed angles can be seen in *Figure 5.6*.

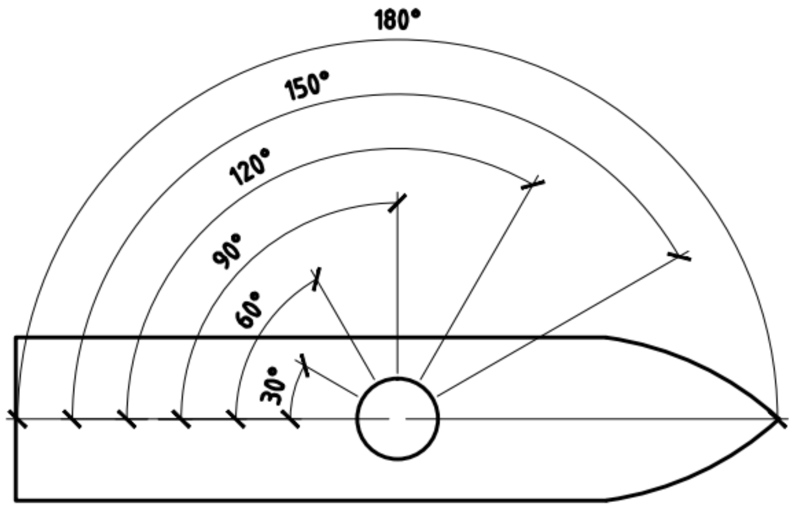

Figure 5.6: Wave angles

As can be seen in *Figure 5.7-Figure 5.12*, the movement in z-direction (movement towards the bottom) is highly affected both by wave period and significant wave height. The movement seems to increase almost linearly with the significant wave height while the movement tends to follow a more non-linear approach with varying wave periods. The movements tend to follow the same trend on opposing sides from 90^{o} with just a small disparity.

The effect of the wave period is more distinctive in wave angles more towards the side of the vessel. Here, the non-linearity of periods is increased with an escalation of movement around the 8-10 second period.

The movement due to a higher significant wave height also tends to escalate quicker with a higher angle of attack. Around 90^{o}, the escalation is very quick and the vessel can therefore not withstand high values of H_s at all.

A significant wave height of 0.5 meters (which yields a maximum height of 0.9 meters) can be considered rather safe, except when the waves are hitting with an angle of attack normal to the vessel. With waves approaching the vessel straight from the bow or stern can also be considered rather safe, except when both the significant wave height and wave period reaches very high values.

The same trend can be seen in *Figure 5.8* with slightly higher values when moving towards a wave angle of 90^{o}. The affection of the small current with the constant wind seems very small and almost negligible.

Again, the same trend as the aforementioned graphs can be noticed also in *Figure 5.9*. The effect of the 1 m/s current is there but hardly noticeable. The effects can be noticed mostly around 90^{o}, where the motions are the biggest.

As can be seen in *Figure 5.10*, the values from the simulation case with no wind and current and a depth of 0.5 meters follows the same trend as the previous graphs. The movements tend to be slightly larger in higher periods, from about 12-14 seconds and up.

In *Figure 5.11*, the effect of a JONSWAP spectrum can be observed. The lines follow the same trend but reaches much higher movements compared to the TMA spectrum simulations. A $H_s$of 0.5 meters is still within safe margins but the motions from a H_s of 1 meter grounding may occur around 5-6 seconds in wave angles closer to 90°. The JONSWAP spectrum receives higher values overall and not only around a wave angle close to 90°. However, these values are again most affected.

In *Figure 5.12*, the effects from roll damping can be observed. Since the roll motions are the only ones damped, it is especially efficient for the wave trains around 90°. The roll damping system works best for wave periods around 6-12 seconds.

A more perspicuous view over how the results vary can be seen in *Figure 5.13*-*Figure 5.14*. Here it is more observable that the JONSWAP spectrum highly affects the motions and that the roll damping is especially effective with wave angles around 90°.

In *Figure 5.15-Figure 5.21,* the windows for where the movement does not exceed 1 m can be observed underneath the plotted lines. Here, it is even more noticeable that much harsher wave conditions can be allowed with a wave angle more towards the bow or stern. The effect of the roll damping system can also be observed, which is efficient around a 90° wave angle.

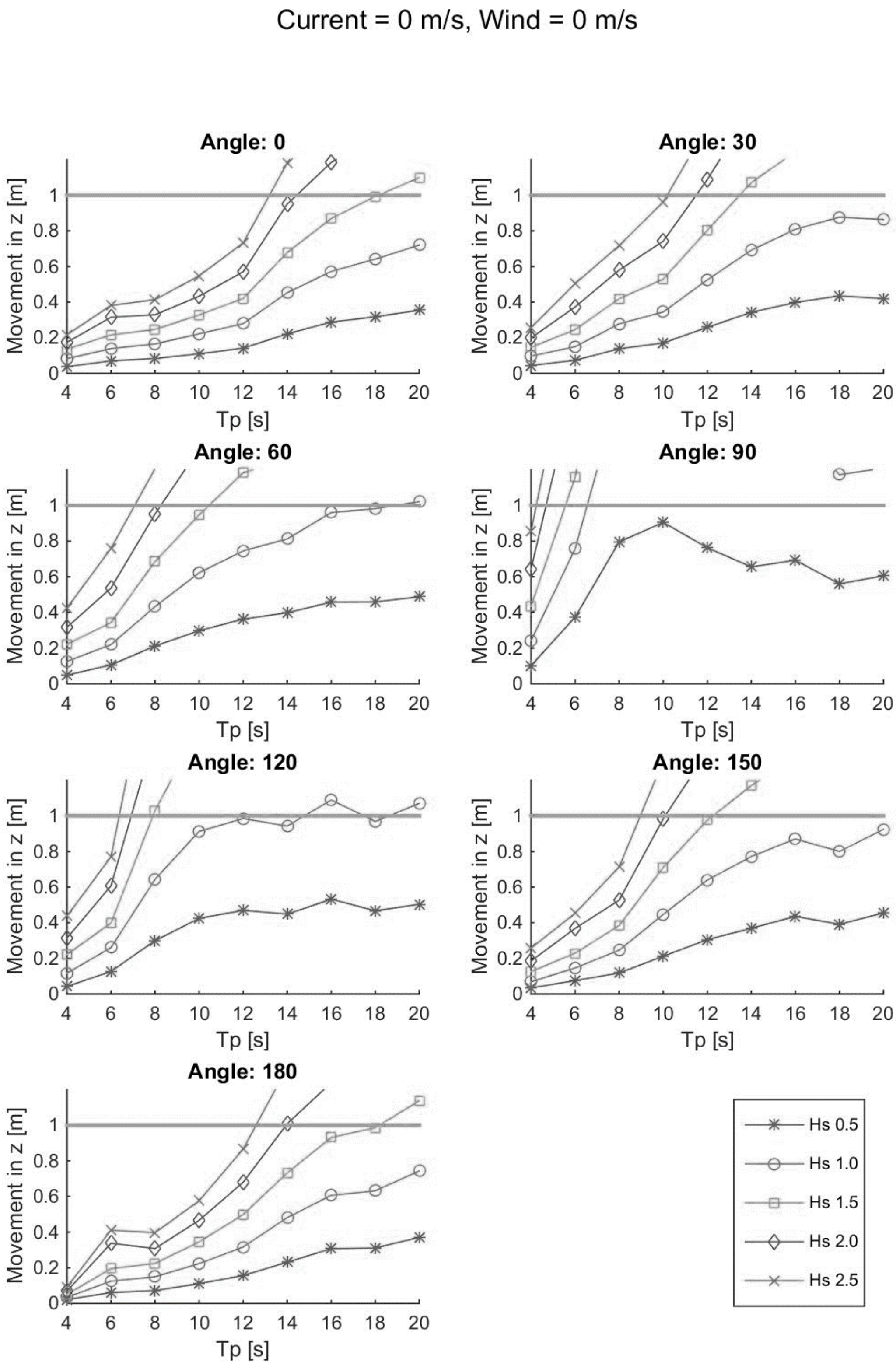

Figure 5.7: Vessel motions with no currents and no wind.

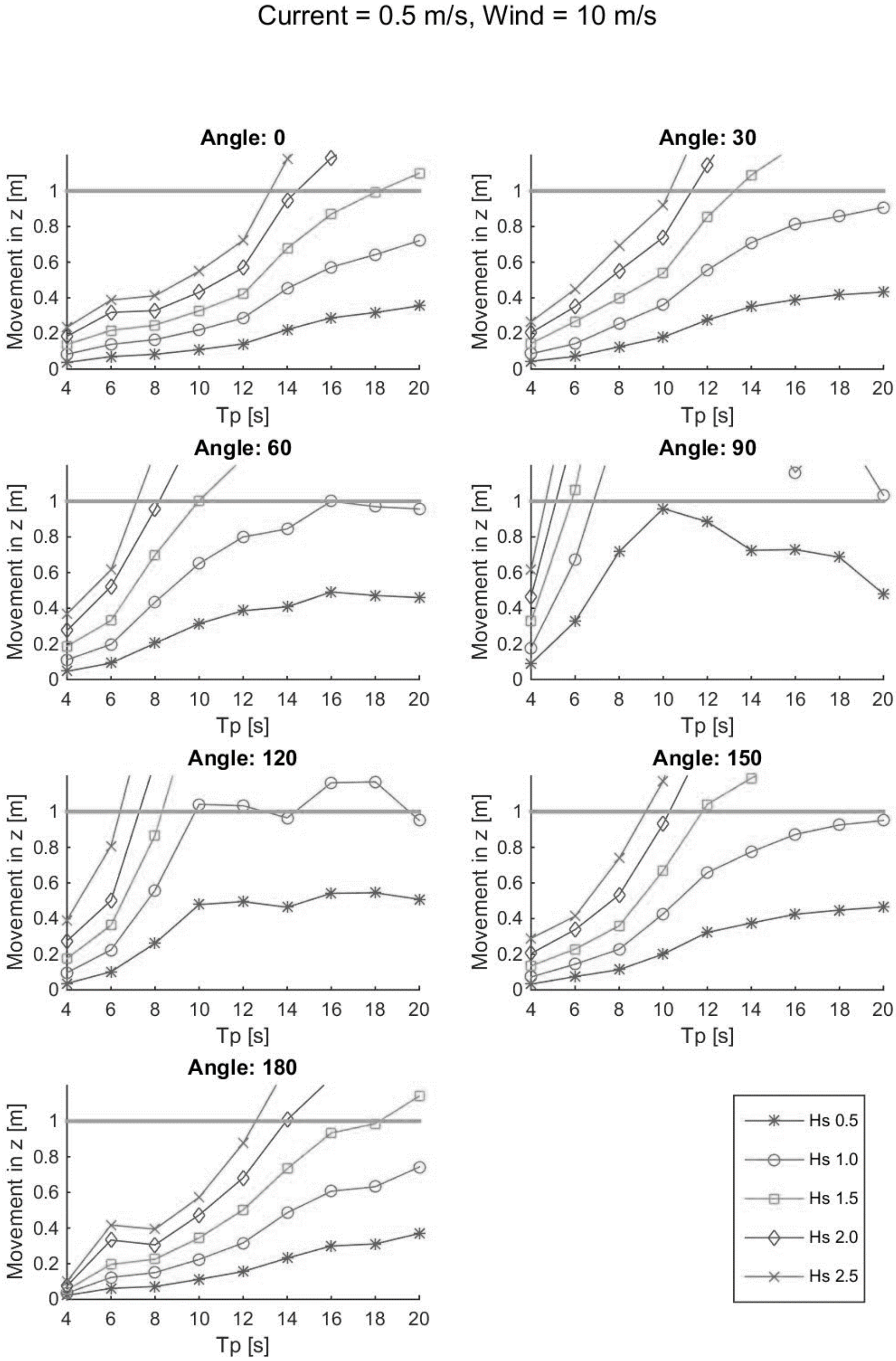

Figure 5.8: Vessel motions with 0.5 m/s current and 10 m/s wind.

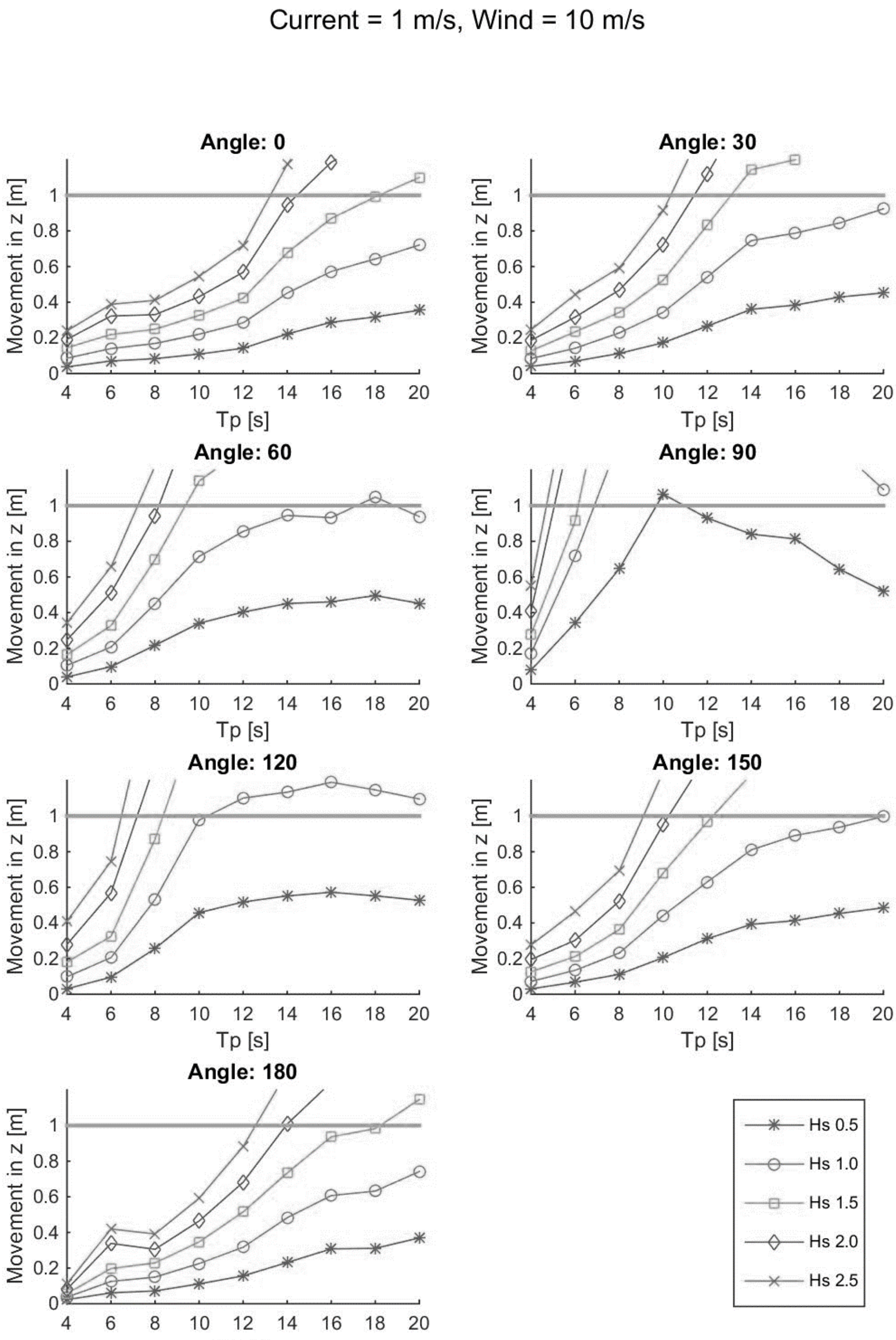

Figure 5.9: Vessel motions with 1 m/s current and 10 m/s wind.

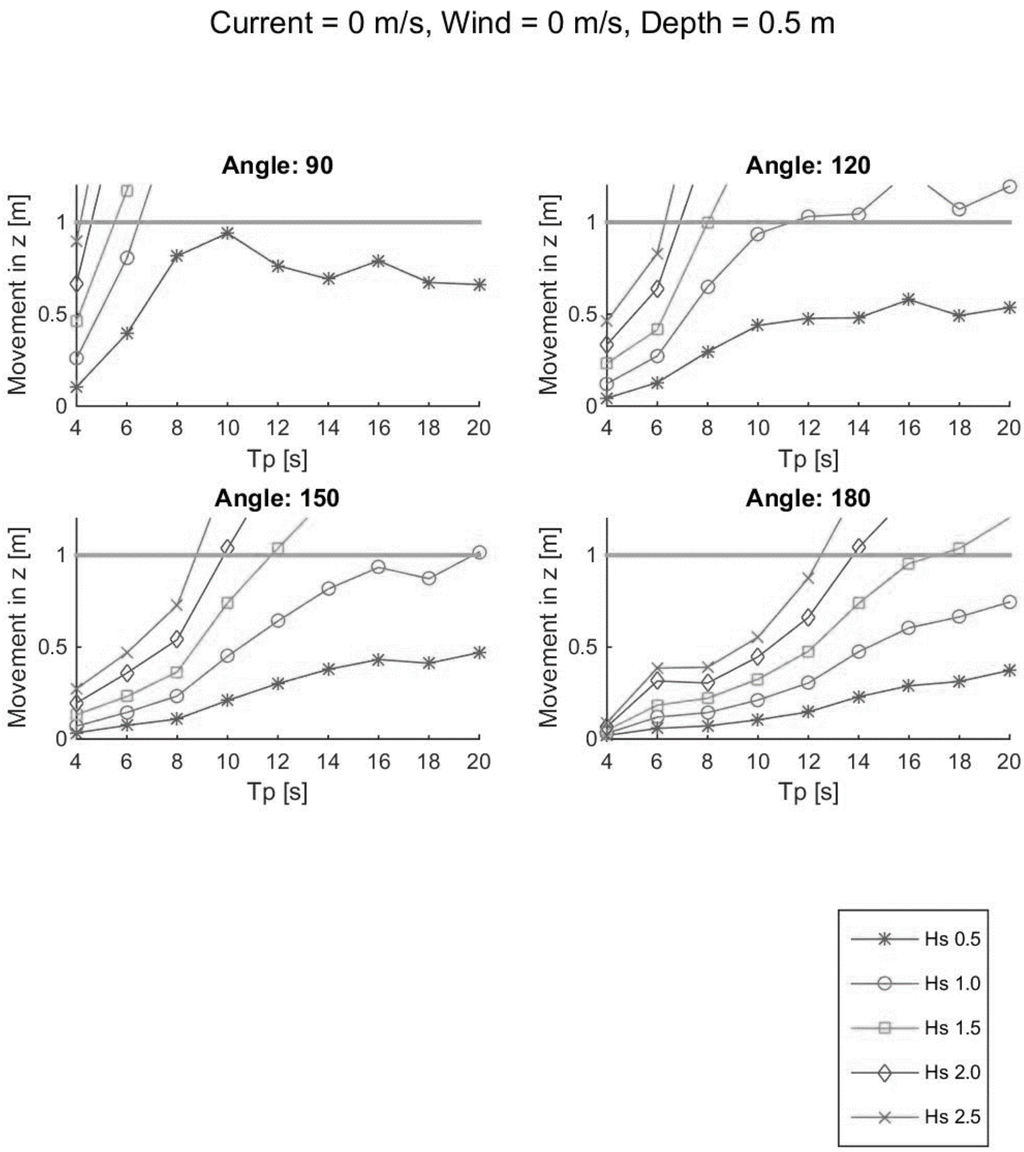

Figure 5.10: Vessel motions with no current, no wind and a depth of 0.5 m.

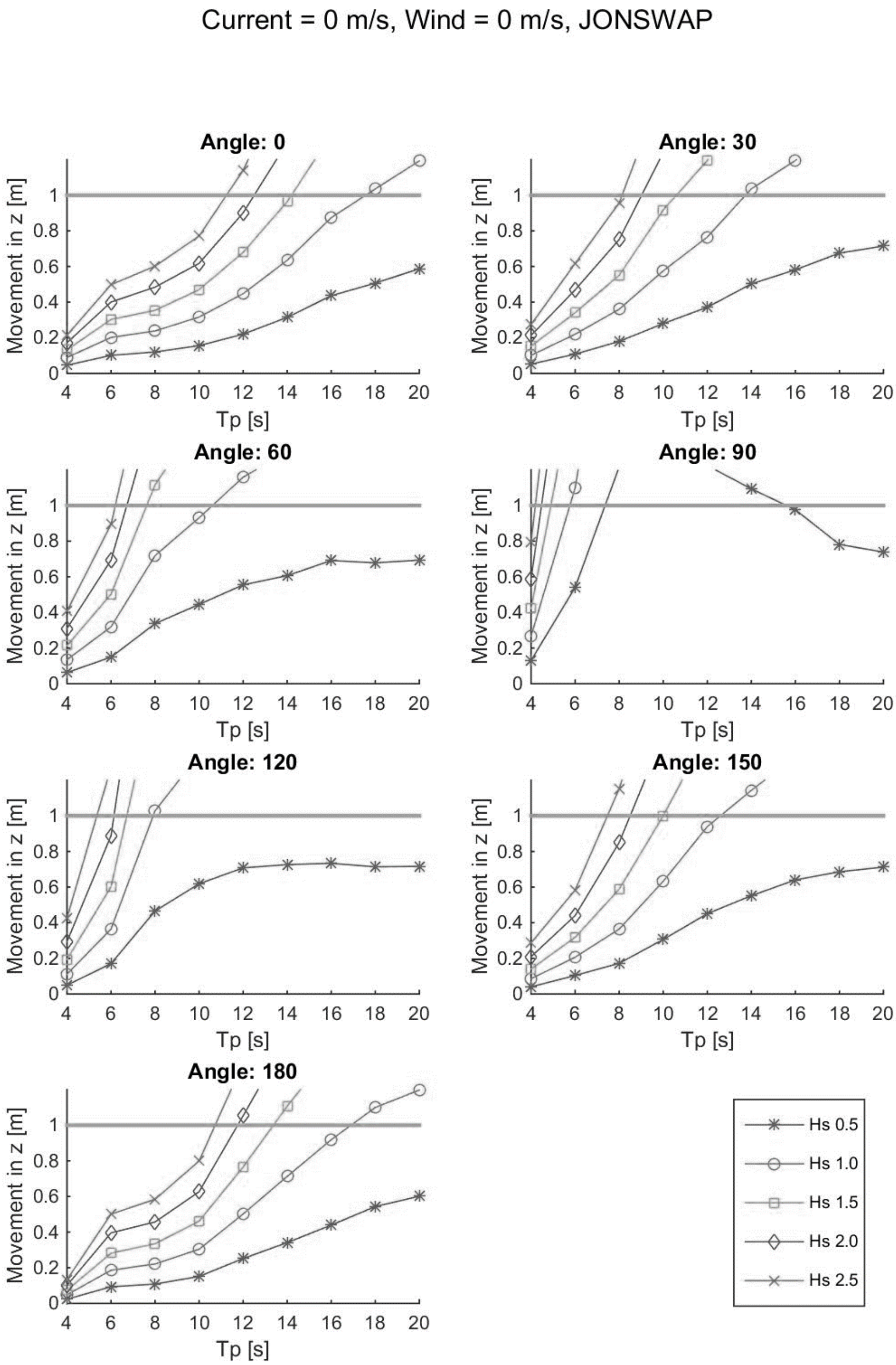

Figure 5.11: Vessel motions with no current, no wind and JONSWAP spectrum.

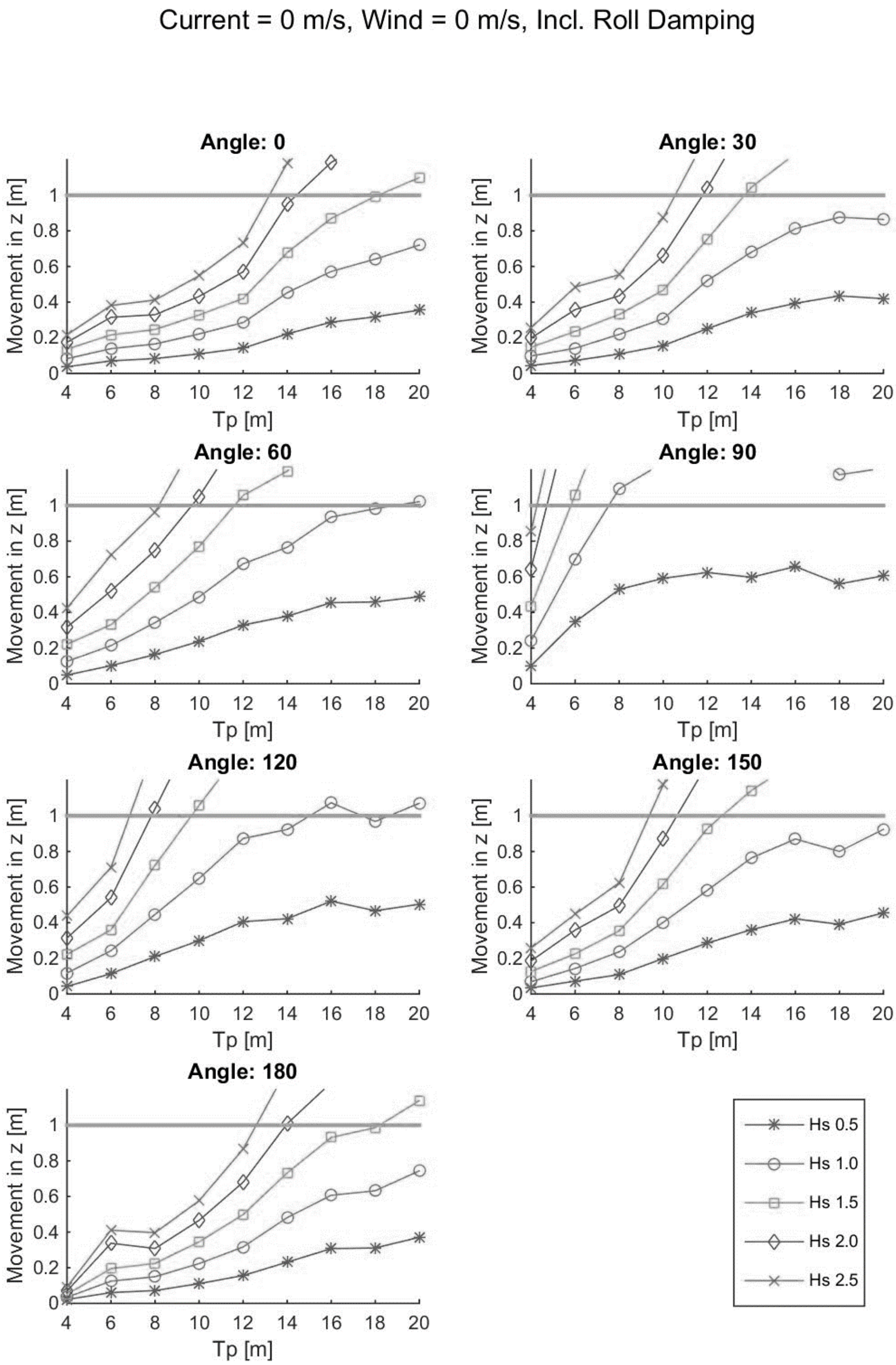

Figure 5.12: Vessel motions with no current, no wind and roll damping included.

5.3.1 Comparison from Effects of Various Parameters

In *Figure 5.13-Figure 5.14*, the different simulation cases are compared to each other. By using the case with no current and no wind, the difference in meters is plotted over the different time periods.

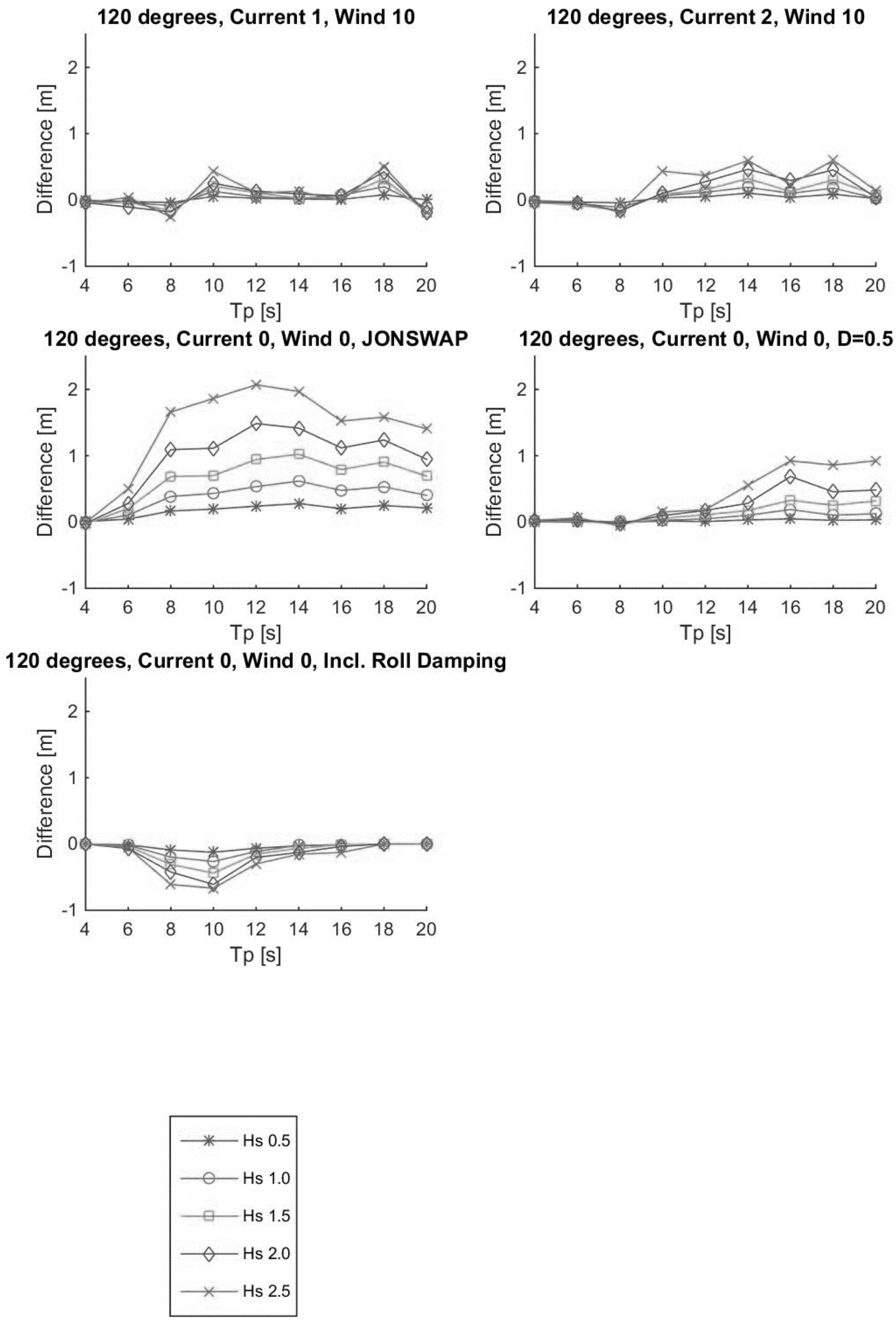

Figure 5.13: Difference from the simulation with 0 m/s wind and 0 m/s currents. Waves with an angle of 120°

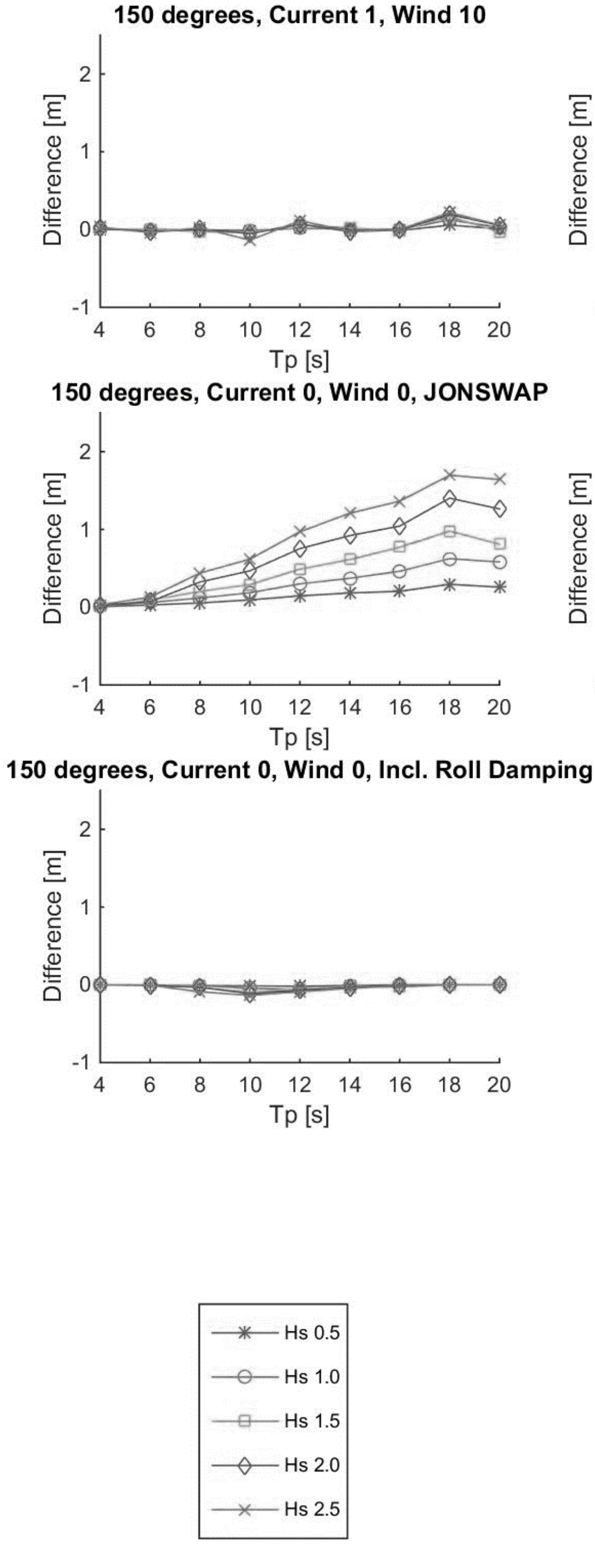

Figure 5.14: Difference from the simulation with 0 m/s wind and 0 m/s currents. Waves with an angle of 150°

5.3.2 Motion Comparison over 1 m Depth

In *Figure 5.15* - *Figure 5.21*, the values where the movement exceeds 1 meter for different simulation cases and wave angles are plotted. This makes it easy to follow where the vessel is safe and where it hits the bottom.

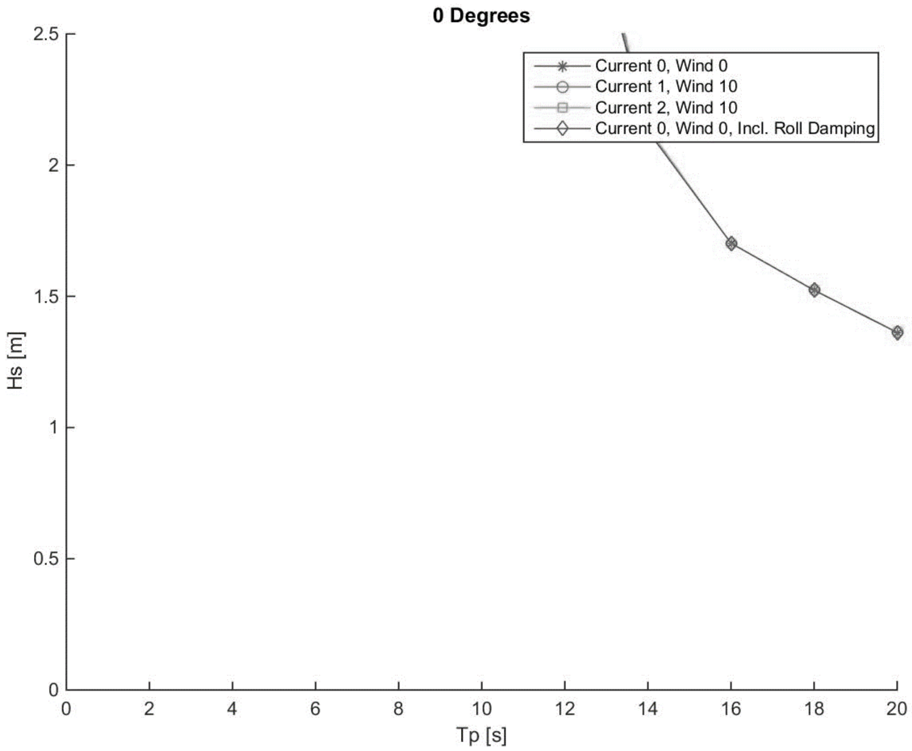

Figure 5.15: Values where grounding occurs for a wave angle of 0 degrees.

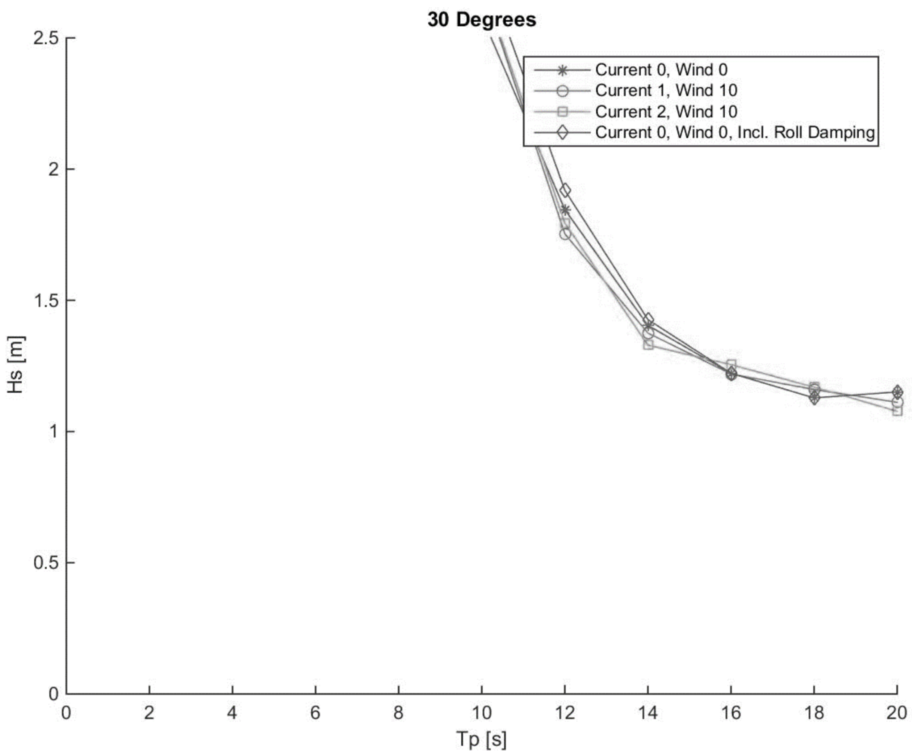

Figure 5.16: Values where grounding occurs for a wave angle of 30 degrees.

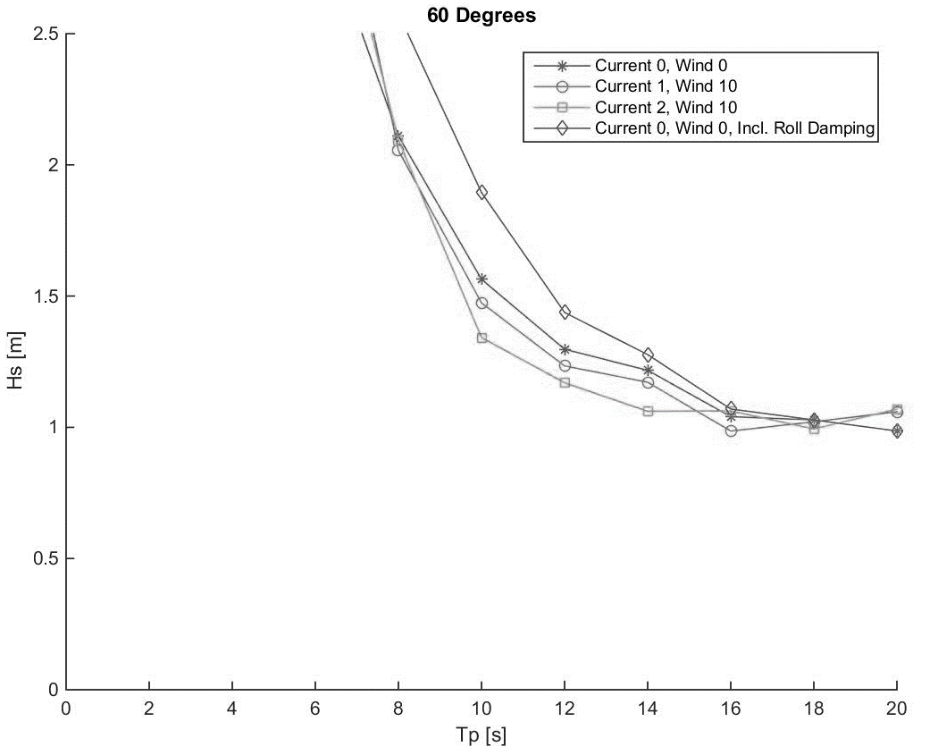

Figure 5.17: Values where grounding occurs for a wave angle of 60 degrees.

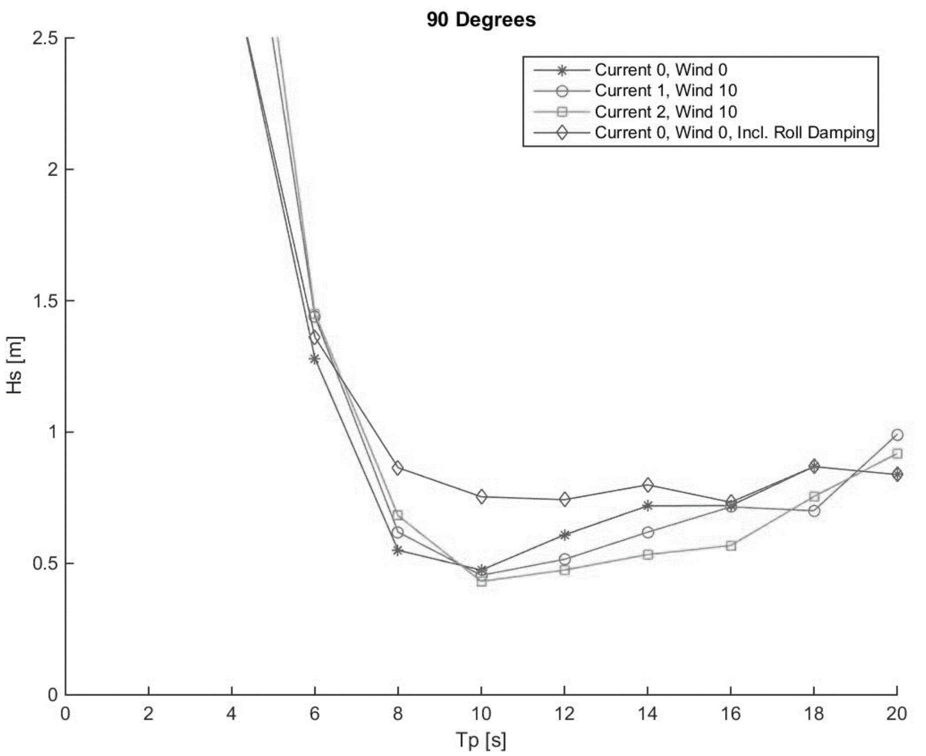

Figure 5.18: Values where grounding occurs for a wave angle of 90 degrees.

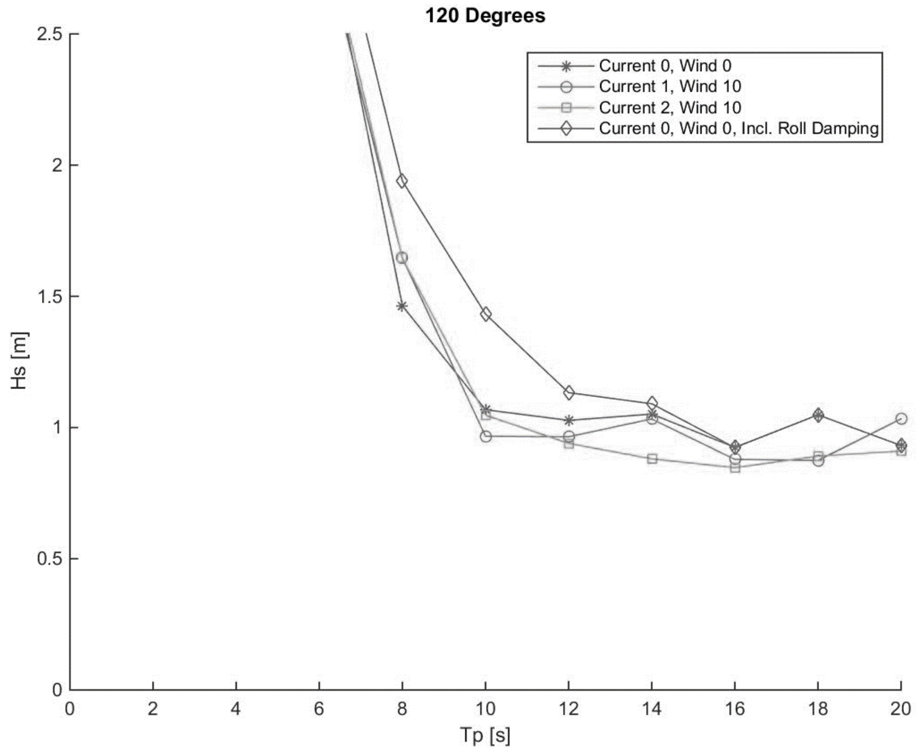

Figure 5.19: Values where grounding occurs for a wave angle of 120 degrees.

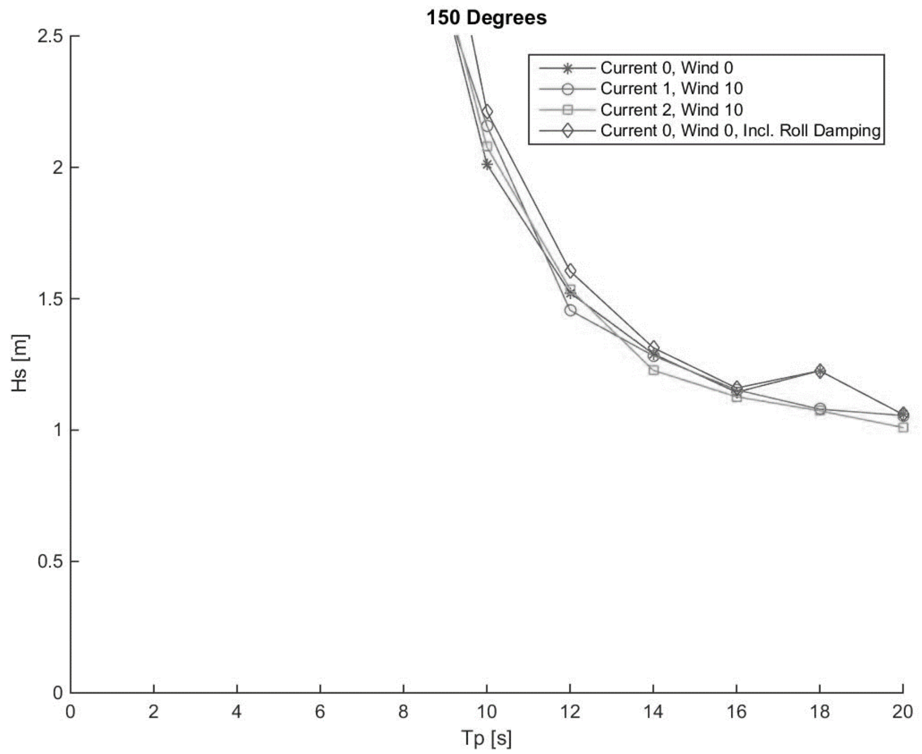

Figure 5.20: Values where grounding occurs for a wave angle of 150 degrees.

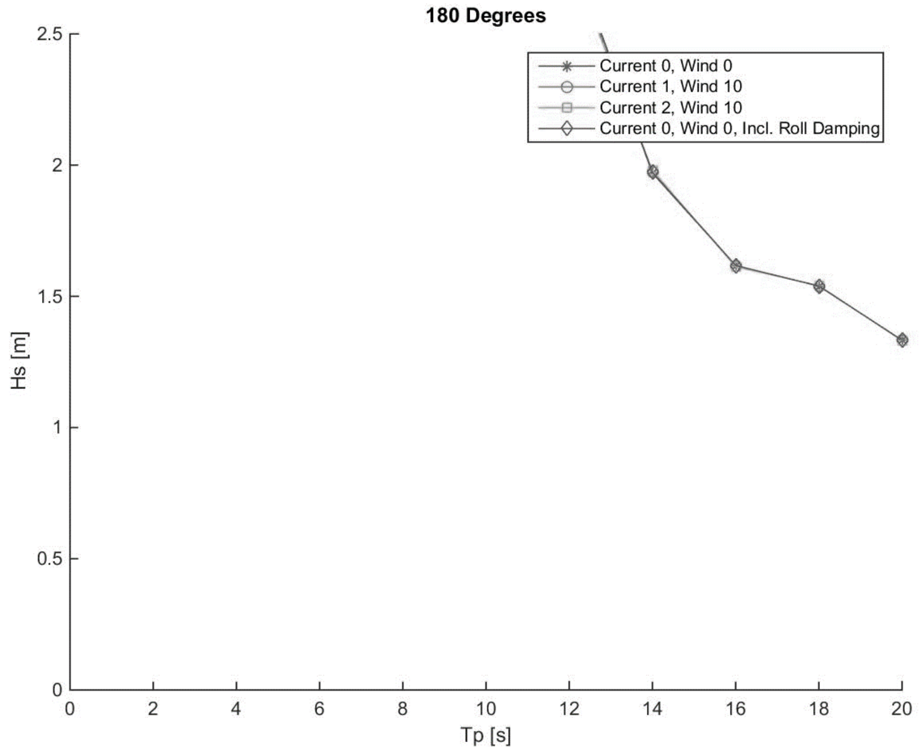

Figure 5.21: Values where grounding occurs for a wave angle of 180 degrees.

5.4 Mooring Line Tensions

The results of the maximum mooring line tensions are presented in this subsection. Each angle of the wave trains has been sorted in separate graphs, with the wave periods on the x-axis and the maximum tensions on the y-axis. Each significant wave height has been designated a separate line. A limit line has been inserted in the graphs to visualize the maximum allowed tension in the mooring lines (60 tonnes). This representation of the results has been made for all different simulation suites and for all different mooring lines (front, mid and aft mooring line).

The tension in the front mooring lines can be observed in *Figure 5.22*, *Figure 5.25* and *Figure 5.28*. Just as for the vessel movement, the tension in the mooring line is well within limits when the waves hit either the bow or the stern. When the wave angle gets closer to 90°, the tension in larger significant wave height exceeds its maximum with a limit around 1.5 meters. With wave angles closer to 90°, the shorter periods has larger impact on the front mooring lines compared to the longer ones. With waves more towards the bow or stern however, the trend is the opposite even though the fluctuation is smaller.

The tension in the mid mooring lines can be observed in *Figure 5.23*, *Figure 5.26* and *Figure 5.29*. For wave angles more towards the bow or stern, the tension is very small. The tension rises with an almost linear trend when the wave angle move towards 90° with maximum tensions when the wave angle is perpendicular towards the vessel. In all different simulation cases, a significant wave height of 1 meter is where the tensions exceeds its limit with wave angles closer to 90°.

The tension in the aft mooring lines can be observed in *Figure 5.24*, *Figure 5.27* and *Figure 5.30* . The tensions in the aft mooring lines are very similar to the front mooring lines with about the same tension limits and with a large impact of shorter periods around a wave angle of 90°. The values overall tends to be slightly higher compared to the front mooring lines.

The effect from the wind and current is especially noticeable on wave angles closer to 90° with the current effecting the results more than the wind. The affection from current and wind is the highest when the significant wave height is higher but also noticeable on smaller heights.

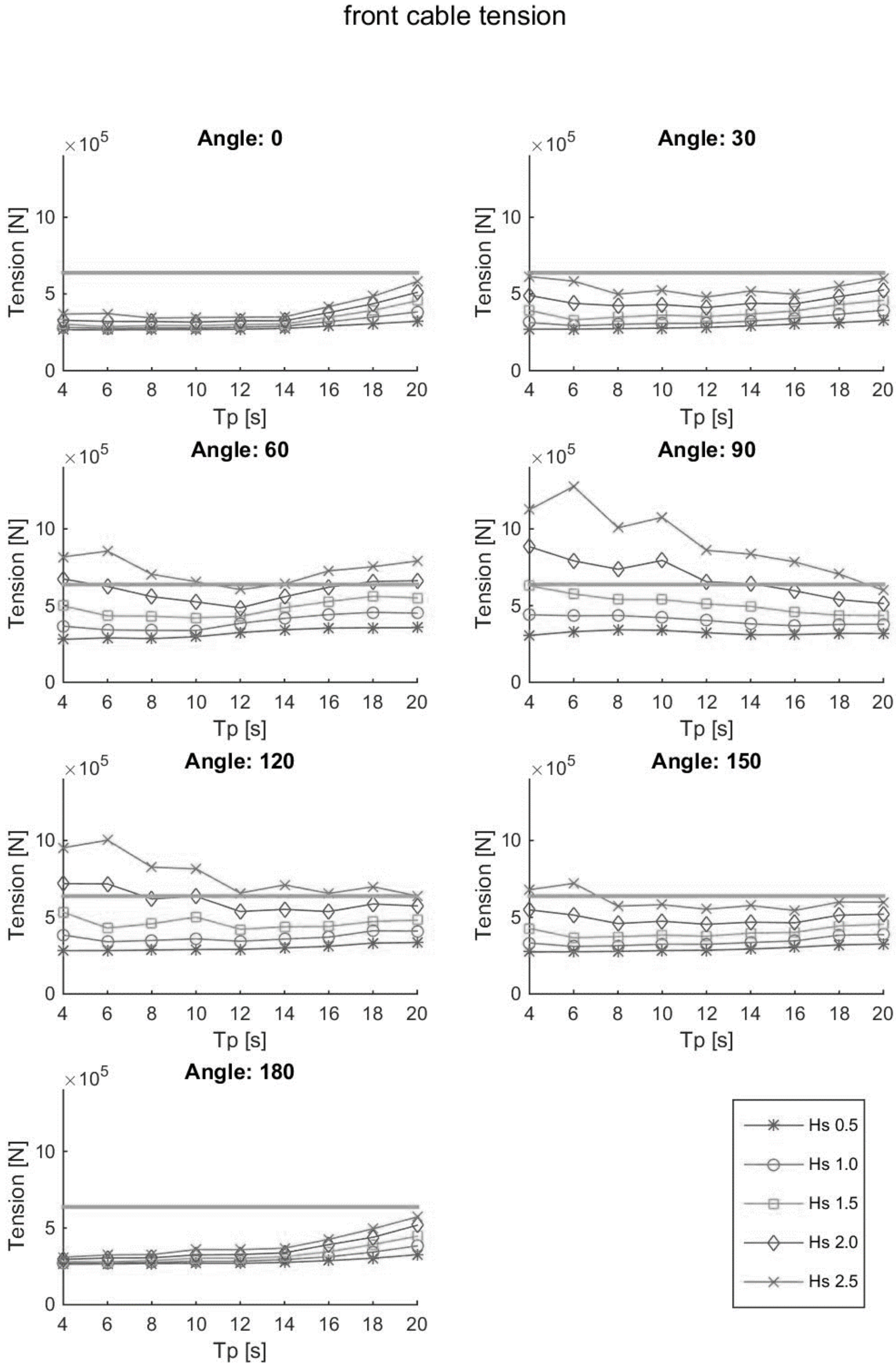

Figure 5.22: Front mooring line with no currents and wind.

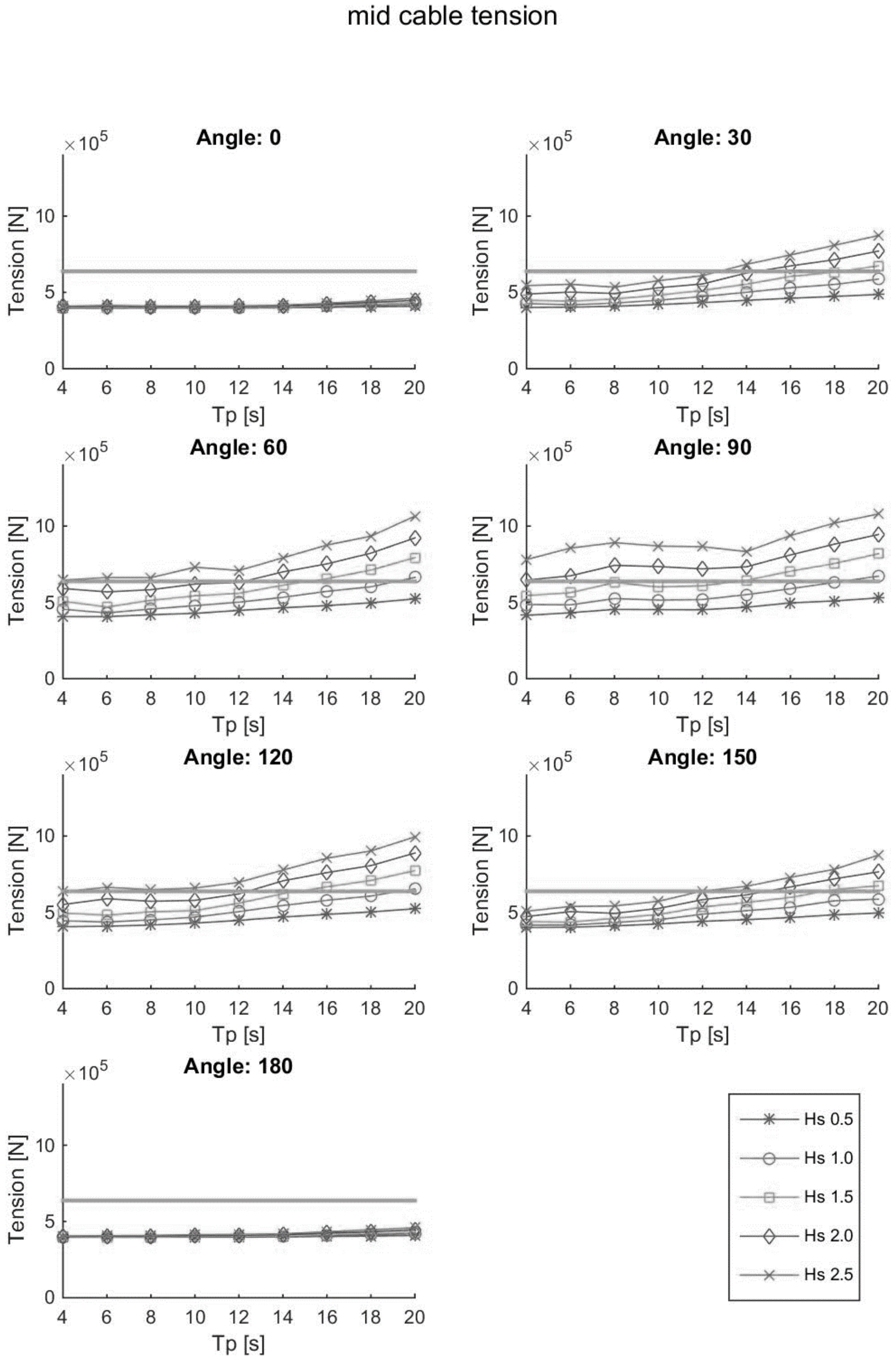

Figure 5.23: Mid mooring line with no currents and wind.

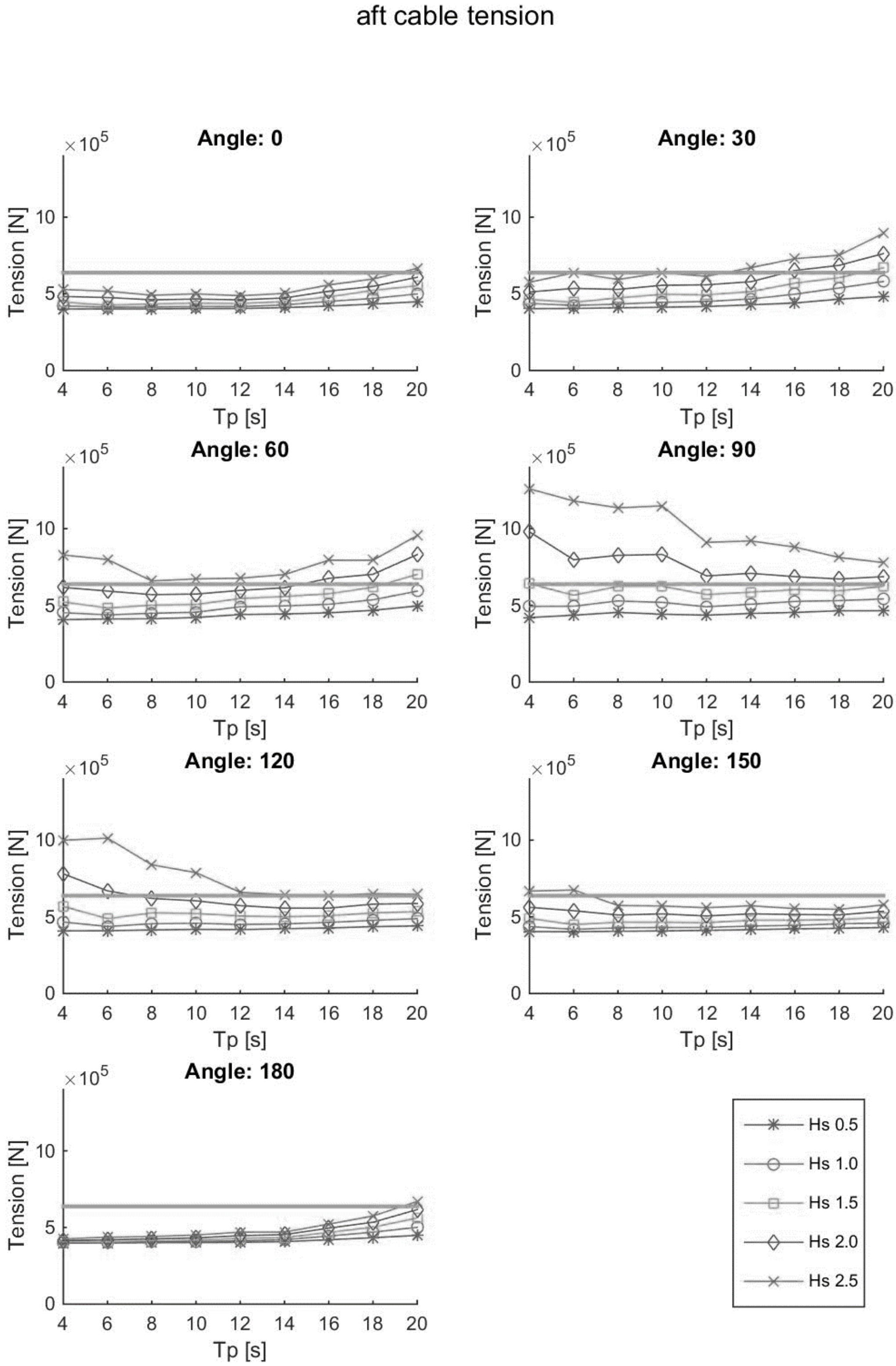

Figure 5.24: Aft mooring line with no currents and wind.

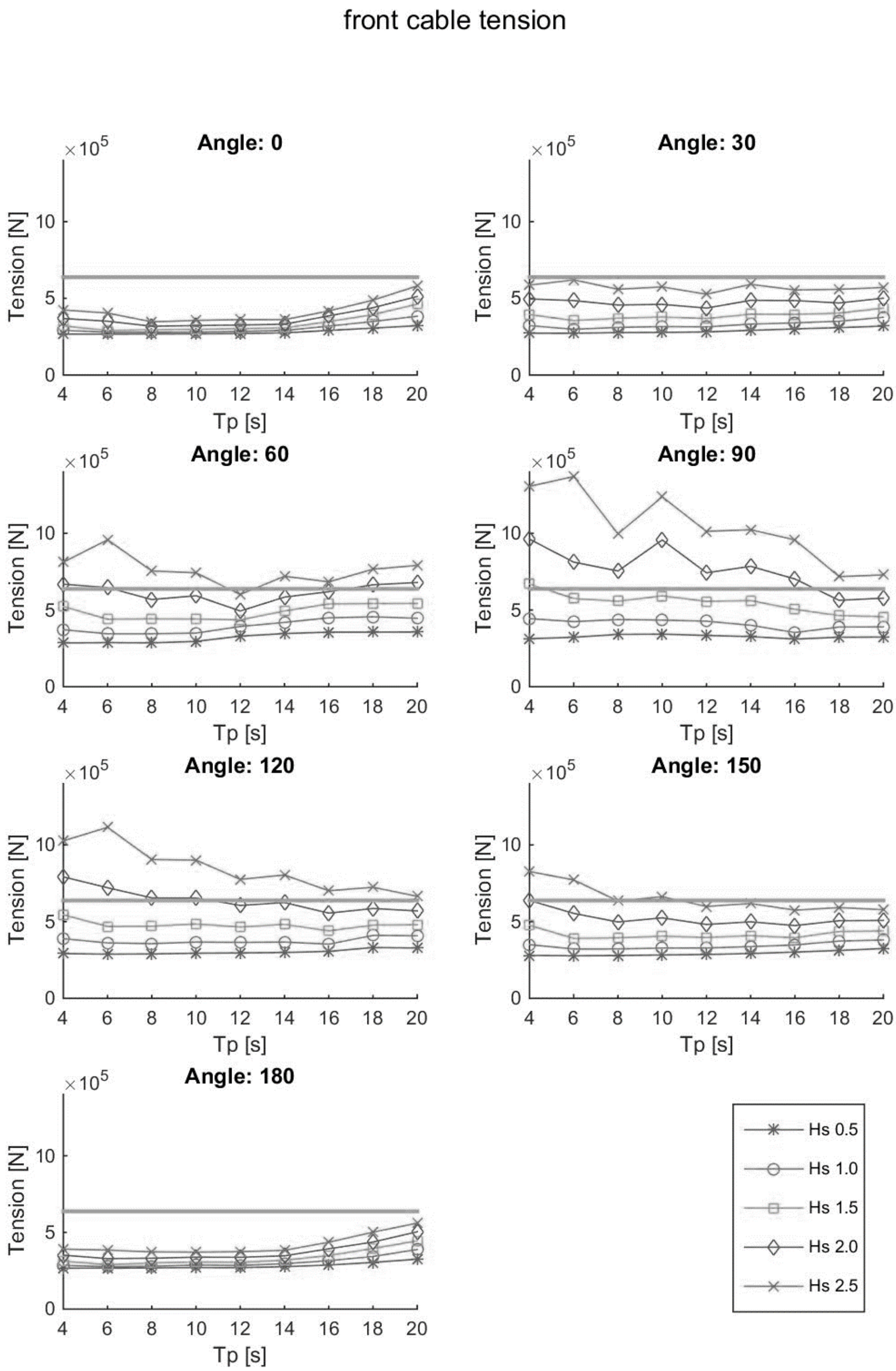

Figure 5.25: Front mooring line with 0.5 m/s currents and 10 m/s wind.

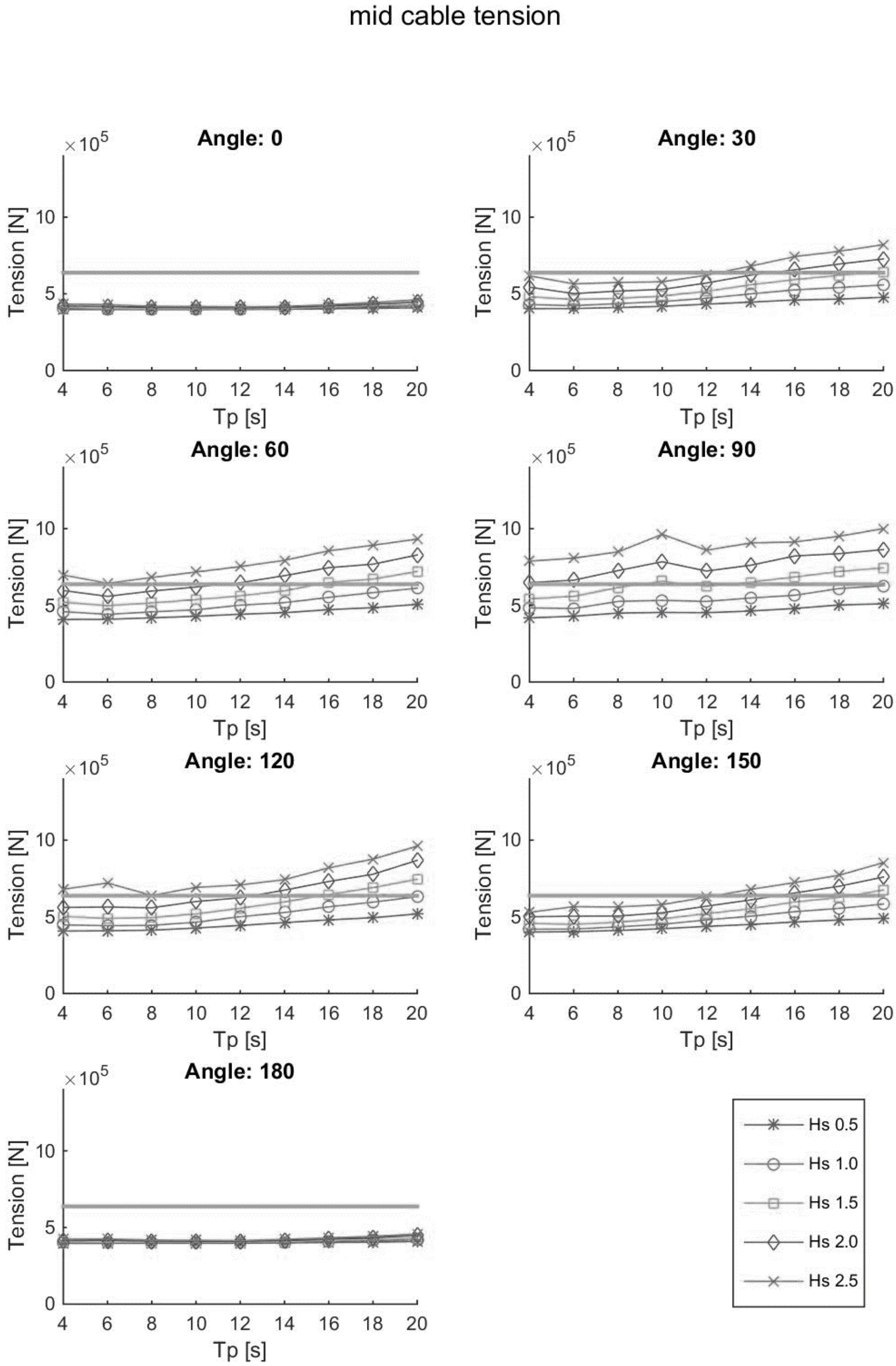

Figure 5.26: Mid mooring line with 0.5 m/s currents and 10 m/s wind.

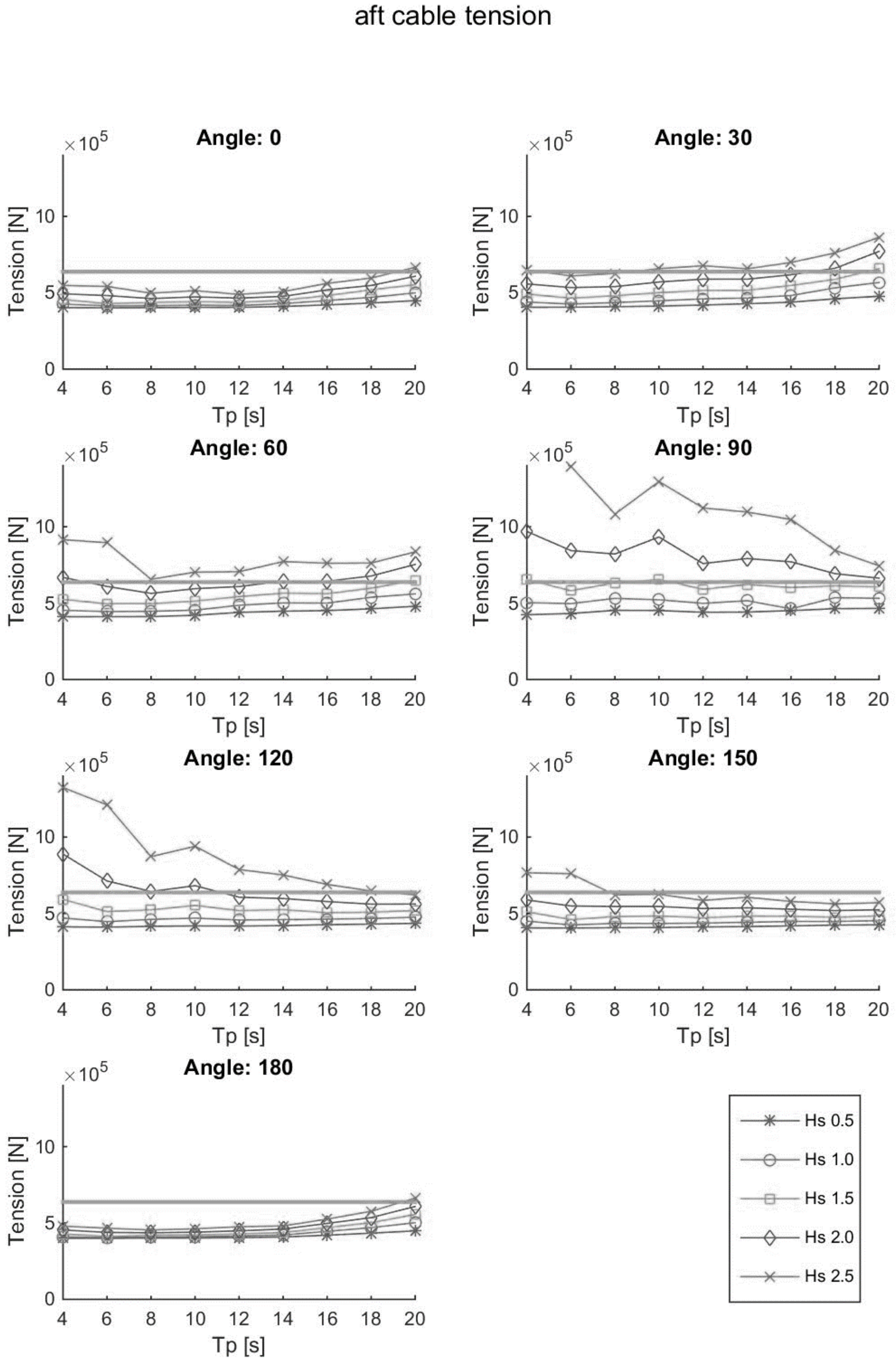

Figure 5.27: Aft mooring line with 0.5 m/s currents and 10 m/s wind.

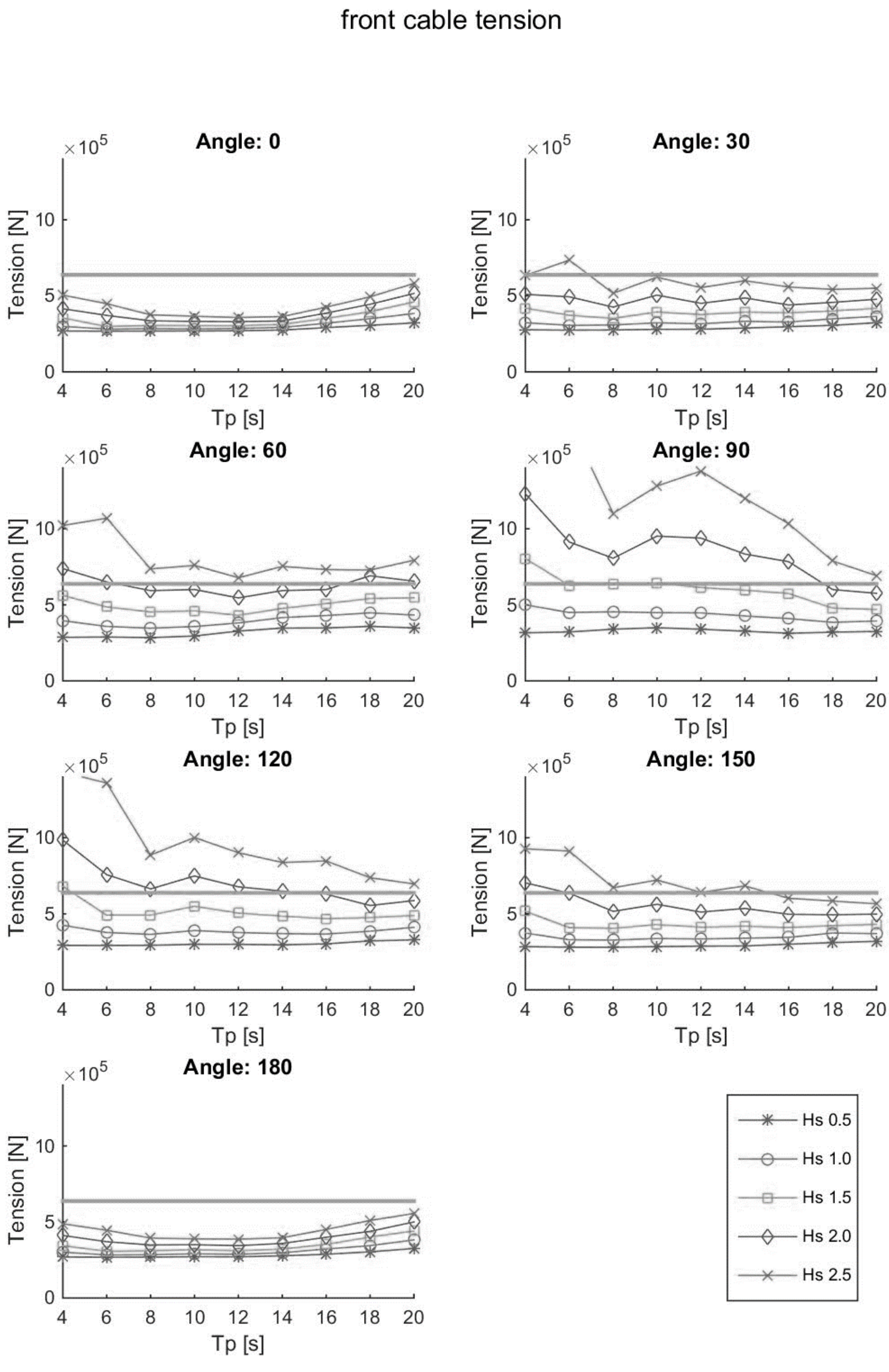

Figure 5.28: Front mooring line with 1 m/s currents and 10 m/s wind.

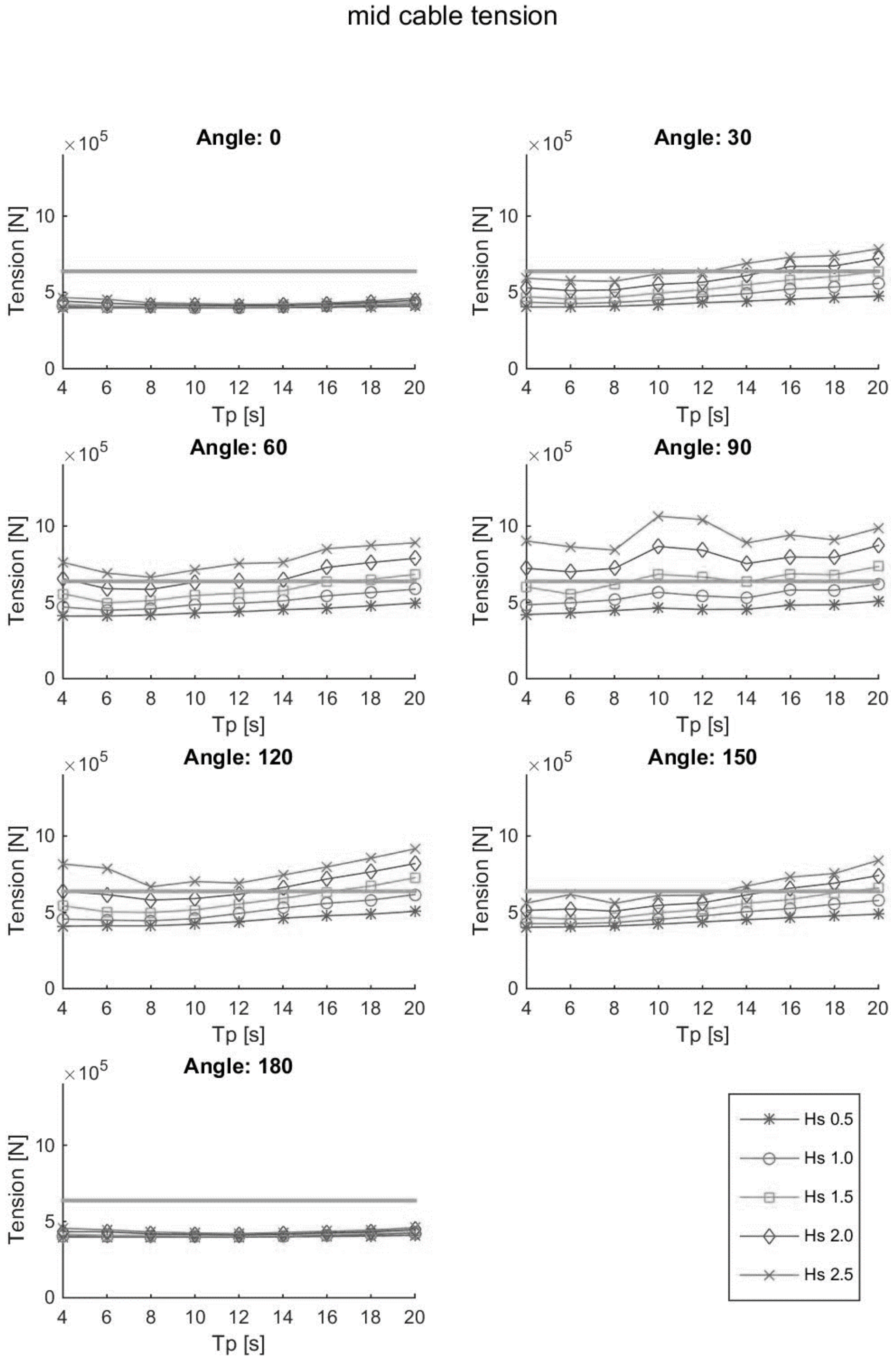

Figure 5.29: Mid mooring line with 1 m/s currents and 10 m/s wind.

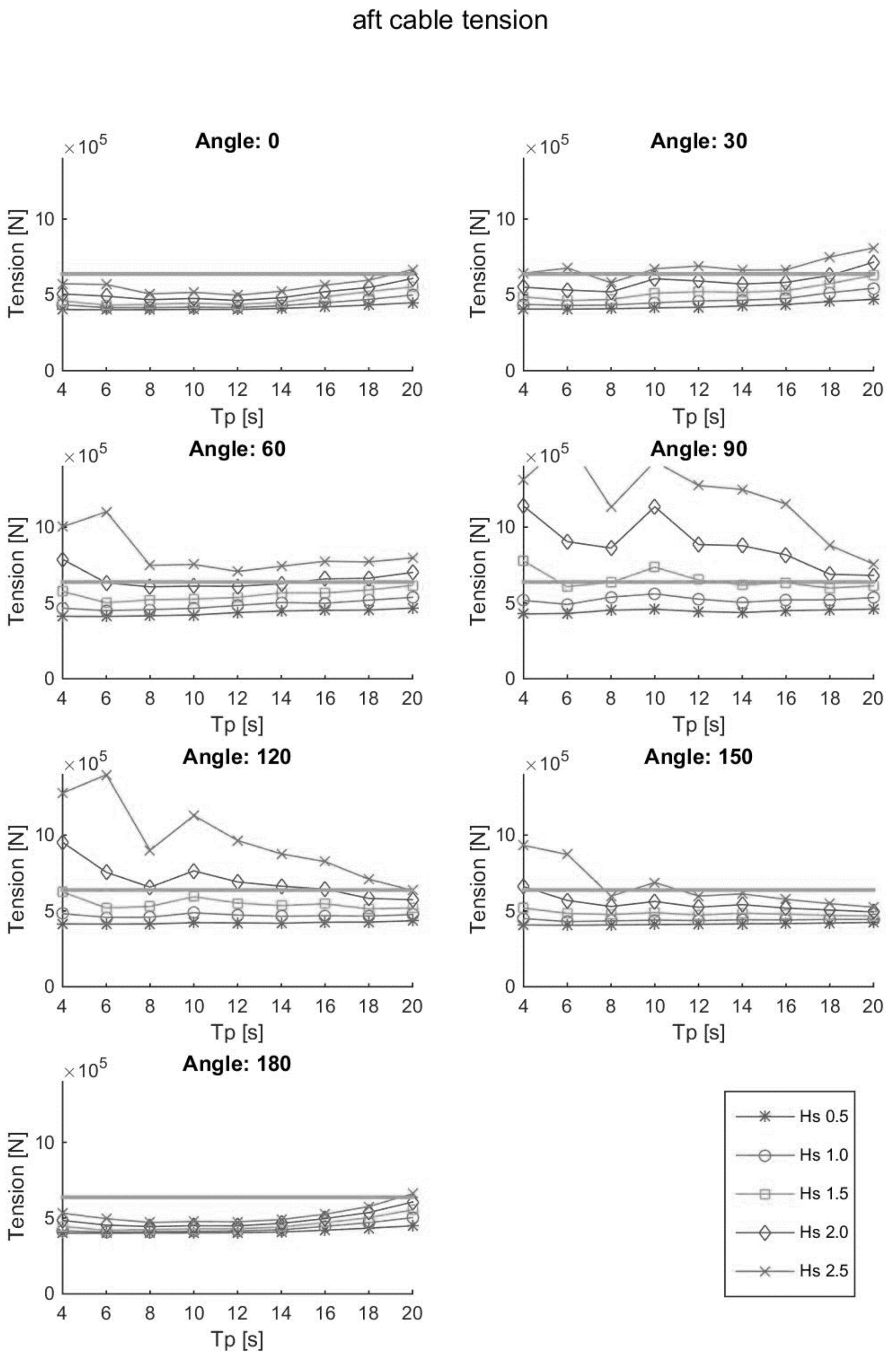

Figure 5.30: Aft mooring line with 1 m/s currents and 10 m/s wind.

6 Discussion

The results presented in Section 5 above give indications on phenomena that are discussed below. Individual phenomena are addressed first, then the connection and interaction effects of them along with the assumptions that are necessary for the analysis.

Motions

The wave angle will have a large impact on the ships rolling motions. When operating in shallow water, the waves are more likely to come from an angle perpendicular to shore, due to refraction (see *section 2.1.2*). This will be to the advantage of the cable laying operation since the roll will be much less when the waves are not hitting the side of the vessel. In cases where the waves are coming alongside the coast and hits the vessel directly from the side, the waves are less likely to have had the fetch needed to develop high waves comparable with that from the open ocean.

The waves are going to contribute more to the motions of the vessel than wind and current. For this reason, the focus has been to look at different H_s an T_p. If the winds are strong and onshore, they are likely to generate waves that will have a larger effect on the motions than the wind itself.

In order to focus on the wave motions, no wind or currents were added to the first set of simulations. When comparing these results with the simulation cases including wind and current, a very small difference can be observed. The motions have increased slightly but not to an extent that further investigation is necessary.

The Degrees of Freedom

The DOF were all extracted separately around the global axis of the vessel. In a normal ship response simulation, the purpose is not normally whether grounding occurs, but rather looking at forces on the ship, risk of sea sickness and cargo damage that is of interest. The total motion of the vessel is calculated in post processing. It is possible that the results would have looked a little different if the simulation was done taking all factors into consideration at the same time. Due to the small allowed motions and low keel clearance however, it is questionable if it would result in a large difference in the final results. The DOF that have been observed to get the vertical movements are heave, pitch and roll. The vessel is moored with a six-point mooring system that will absorb the forces from any potential sway, surge and yaw. Even though these are not movements in a vertical direction, they could cause it if the vessel was freely moving, due to shallow water effects. A horizontal movement of the vessel would cause a squat effect (see *section 2.5.2.*)

Roll damping

The roll damping is based on data provided by ABB seen in *Table 4.6*. This data could not be applied directly into the simulation. It was instead applied to the results of the roll motions retrieved from Aqwa. The method will give a total vessel motion where the roll damping has been included in the final vertical movement. It is not a completely accurate method since the reduced motions would also reduce the accelerations from the restoring forces. However, since this would be included in the roll reduction comparison, it will still give a solution with a reasonable accuracy.

The biggest reduction of movements with the roll damping system activated was around a wave period of 10 seconds. This is most likely close to the natural frequency of the vessel. Without the damping system around this wave period, the vessel is close to grounding even at low wave heights. With the damping system activated, the movements are almost the same for the different T_p at a H_s height of 0.5 meters. Even if the likeliness is small that the waves will hit the vessel at a 90° angle during operation, it should be seen as a possibility. If it would happen, the damping system will definitely contribute to a lesser likeliness of hitting the bottom.

Added mass

The added mass had to be validated in order to ensure that the added mass was taken into consideration. The added mass calculated by Aqwa shows an increase as the vessel gets closer to the bottom, which corresponds well with the aforementioned literature and DNV standards. The program calculates these properties for a set depth. For an even more realistic simulation, it would have to recalculate the added mass for each time step when the vessel has moved in a vertical direction. This would however not be practical in reality since the simulation times would be extremely long.

Lower depth

A simulation case was run with a keel clearance of 0.5 meters. In the initial phase, more simulations were made with regular waves and a keel clearance varying from 93.3 to 1 meters. A decreasing vertical movement could be observed with a depth reduction of keel clearance. When running the simulation with 0.5 meters however, the motions increased slightly. It could be due to other factors having a greater influence than added mass, such as the squat effect, explained in *section 2.5.2*. The first simulations were run in regular waves and it could be argued that the irregular waves also makes a difference in the outcome from the simulation.

Uncertainty

The difference in wave particle movements causing exaltation forces on the vessel is a factor that would likely affect the motions. It is very hard to say how much it would affect and if the program properly manages to take this into consideration.

The currents added to the simulation gave an increase in mooring line tension but not much in motions. When the keel clearance becomes this low the currents will have a larger effect as seen in *Figure 2.5* and explained in *section* Current Forces. The tested currents are relatively slow but it is possible that the program is not taking the depth into consideration properly when applying the forces, making them slightly lower.

Up-scale simulation

The simulation time was reduced to one hour instead of the three hours recommended in the DNV standards in order to run more simulations. To get the motions that were more likely to represent a full three hour simulation, the peaks were analysed and fitted to a Weibull distribution. When looking at a JONSWAP spectrum, approximately 15% of the waves would be analysed as an estimation of how many of the peaks that will have a higher value. A TMA spectrum however will have much fewer extreme peaks due to wave breaking explained in *section 2.1.2*. Looking at the top 15% would therefore give an over estimation of the predicted waves. Two full three hour simulations were run and compared to the final values to ensure a reasonable peak movement.

The results showed that there were very small differences in the total movement between the one hour simulation and the full three hour simulation. This is most likely due to the reduction of peak waves that occur in a TMA spectrum. The closest match was to look at the top 5% of the peaks and use these to give and estimation for a full simulation. This gave values close to the full simulation. Comparing the values from the full length simulation with the obtained values after fitting the data to a Weibull distribution and scaling for 3 hours showed that the values were very close but a bit on the conservative side. On average, the 1 hour simulation with the MLE gave approximately 5% larger values than the motions of the full length simulation.

Weather window

A longer operation would run a larger risk of heavy weather. There is always a risk of grounding with a very low keel clearance. The risk will however depend greatly on the area in which the operation is being conducted due to different weather conditions and bathymetry. With the damping system, the vessel is likely to hit the bottom when the waves are hitting from the side at a significant wave height of approximately 0.7 meters as seen in *Figure 5.18*. In an area where there is very low probability of the waves coming from that angle, an even higher significant wave height could be assumed as the limit for which to procced.

The limiting H_s cannot be universal. It will need to be decided depending on wind, current and most importantly direction of the waves in relation to the vessel. Looking at metocean data if available could be used as a tool to minimize the risk of having to abort a mission. The metocean data provided by ABB for a shallow area for example, showed that the probability of a significant wave height between 1.5 to 2 meters is only around 1% in August. 1 to 1.5 meters is only 5% (Hernon & Godwin, 2016). The most likely wave direction is almost straight towards the cost. The results show that the model does not exceed the limit of 1 meter with a significant wave height below 1 meter when the waves are towards the bow of the vessel. This implies that an operation during this time of the year has a very low probability of having to wait a long time for a weather window.

If operations are made in, for example February, the weather conditions are different. The percentage of significant wave heights which exceeds one meter are here 17.5% with significant wave heights reaching heights up to 2.5 - 3 meter. It is therefore quite obvious that the weather windows for operations during this time of year are smaller. If operations are necessary at this time, they should be performed with utmost caution and safety margins or a larger keel clearance could be used.

Keel Clearance of 1 meter

The safety margin of 1 meter for the keel clearance should be seen as a limit. Moving the vessel into more shallow water would increase the risk of bottom effects even more and the probability of grounding would increase. The keel clearance should be enough to give a very low probability of the critical significant wave height being exceeded during a reasonable time window. The results in this thesis shows critical parameters for a H_s and T_p. Based on these results, a 1 meter keel clearance could be considered a reasonable limit.

Cancelling an operation would result in very high costs. The amount would depend on in what stage the operation would have to be aborted. However, having the ship on standby is also very costly. These two factors will have to be analysed when considering the weather window. This is not something which is covered in this thesis but could be considered as a future work.

The possibility of cancelling a mission should also be considered. Reducing the keel clearance would reduce the limiting H_s and thus shorten the time needed to produce waves reaching this limit. Once the limit has been reached, the possibility of the vessel hitting the ocean bed is high. What actions that should be taken in this situation is considered future work.

Spectrum difference

The difference in movement between the TMA spectrum and the JONSWAP spectrum is rather large. On these depths however, such high peak values as the JONSWAP spectrum have is not possible due to all shallow water effects (see *section 20*) and the results are therefore hard to apply in any real case. The TMA spectrum is on the other hand only a JONSWAP spectrum with an extra parameter and might therefore not fully represent the reality in as good extent as the JONSWAP spectrum. It should be mentioned that the TMA spectrum is a method which has been used since 1984 with good results (Hughes, 1984; DNV, 2014).

Box shape assumption of hull bottom

The assumption that the bottom of the vessel is shaped like a box (see *section 3.2*) is not fully accurate. Some small verifications were made to see whether this method was feasible but it is still slightly conservative, especially regarding the combination of pitch and roll motions. Since the hull bottom is shaped more according to an irregular hexagon then a rectangle (see *Figure 3.1*) it would in reality take less time for the vessel to hit the bottom if it had a slight pitch. The roll motions on the other hand matches the real case quite well due to the cubic shape of the hull sides. Since the pitch motion effects are rather small compared to the roll motions, the assumption should not be too far from reality but could still be considered slightly conservative.

Cable forces

The limit shown in the result graphs is set to the hold point for the winches. It does not necessarily mean that the system will break or be useless afterwards. It is only in the cases when looking at higher significant wave heights with a very short period that the limit of the cable tension will be reached. The metocean data shows that this is very unlikely, even if it does occur. It can also be taken into consideration that the largest forces in low wave periods occur when the angle is around 90° which is where the roll is high. The roll damping system will therefore reduce the force peaks on the mooring system during these conditions. It is also less likely that such conditions would occur at that angle.

The results show that for angles which will give large roll motions, the forces are smaller when the wave periods are higher. This is most likely because the forces would be spread out over a longer period, reducing the peaks significantly. It can be seen that in most cases, the motions will be the limiting factor for the simulated conditions. Other factors for the mooring systems such as anchors have not been considered in this thesis.

7 Conclusions

This thesis addresses the motion response and keel clearance of a cable-laying vessel operating in shallow waters. The motions of the vessel are affected by several physical phenomena e.g. suction of water beneath the ship, wave spectrum in shallow waters and forces from wind and currents, which are studied individually along with interaction effects between them.

The data obtained from the simulations correspond well with what was expected from the literature study. The important factors for the movements have been included in the model, such as different wave spectra and shallow water effects with added mass and damping. This gives a realistic representation of the motions in shallow water.

The tested keel clearance should be enough to provide a reasonable weather window in areas with a long shallow coast and the possibility to align waves mostly towards the bow of the vessel. When waves are hitting the sides of the vessel, the roll will increase the total depth movement and thus reduce the wave height the ship can handle. The ship should therefore be aligned towards the waves whenever possible.

Some areas where the keel clearance should be increased should be taken into consideration. If the operation area usually has higher waves, standby cost could become higher than cost for keeping higher keel clearance. In cases where the operation is not carried out in a long shallow area, there is less reduction of ocean waves and the JONSWAP spectra should be applied instead. This is due to less reduction of the waves.

Setting a limit of one meter for the keel clearance would be sufficient for most cases to get a low probability of grounding, especially during summer time for the specific observed area. In winter time, the weather windows are substantially smaller and much more caution must be taken if operations during this time of year is necessary.

Reducing the limit would require further tests and research to provide a reliable result because of the shallow water effects.

The mooring system will not be the limiting factor in very shallow factors according to simulations. Their maximum values will occur either during very low time periods for high waves which is an unlikely scenario or during high waves hitting the side. This is also unlikely in most areas where the vessel will operate.

The results from this thesis are slightly conservative due to certain assumptions but should still be used with caution as no validation of the results has been made. The results should therefore only be considered as an initial investigation of the vessel motions.

8 Future Work

The outcome of this thesis was to see how much vertical motions and mooring line tensions that would occur for a cable laying vessel in very shallow water. Whether the keel clearance limit of one meter was sufficient or not was also of interest. In order to receive more accurate results, several areas would need further attention:

- More variation of parameters, such as wind and current: Wind and currents have only been tested for a common condition. To further test different parameters would give a better basis when looking at operations and when they can be conducted.
- Introduce a safety margin: The results in this thesis show at what depth the model will exceed the set keel clearance. Even if there is a small factor of conservative calculations it is still not enough to be used as the safety margin. A more thorough investigation should be made to establish a more proper safety margin.
- Other software with more possibility of adjustments: There are several softwares that allow for the user to freely input all the variables and how the program is going to calculate the motions. This could give a more precise simulation resulting in even more accurate results. Examples of such programs are OpenFOAM and ANSYS Fluent. It was considered to use such a program for this thesis but due to the complexity of the programs along with the longer simulation time it was decided against it for the priority of more results.
- Model testing: To test the validity of the simulations, a model test would be the best way. Model test are costly but it would provide a realistic result that hopefully would provide a realistic result which could be used to compare the results from the simulations.
- Cost vs risk analysis: When will the risks outweigh the cost? Could the vessel handle hitting the bottom and continue the operation? If so, would it be cheaper to risk it and repair later or would it be dangerous for the crew or cargo? When should an operation be cancelled? There are a lot of factors to be considered and having an analysis made would serve as an aid to those making decisions during an operation.
- If the vessel is to be moored for a longer period of time, there is a possibility that sediment transport will occur underneath the hull. This could affect the motions and should be analysed further.

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