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Writer: Ingvild Lodden	…………………………………………… (Writer's signature)
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Ingvild Lodden
Stavanger, June 2013

Abstract

Through the years in the oil and gas industry, the marine operations have been developing, and it continuous to develop. More production facilities offshore are under construction, and the activities offshore seem to increase rapidly. The operations done offshore are more advanced than ever and as a consequence of this, so does the marine operations, e.g. lifting operations.

In this thesis, we will present several considerations when it comes to planning and performing a lifting operation. There are several factors to include in the planning and performing phase of a lift operation. Among them are waves, winds and currents, i.e. weather conditions. The weather conditions are also different in different geographical areas you are operating in. Another important factor is the vessel performing the operation. What is the capability of the vessel`s crane? How is the vessel availability? These questions will be discussed in the introduction below.

This thesis will be concentrated on two specific areas, The North Sea and Offshore Angola. The reason for choosing these two areas is that they have two completely different sea states. The North Sea is mostly influenced by waves with higher significant heights and wave periods of around 8 to 10s, while offshore Angola has waves with shorter significant wave heights and periods of around 10s to 12s.

In this thesis different sea states - , stability - , lifting – and simplified risk analyses will be presented. There will also be presented a simulation with the use of the software OrcaFlex.

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Abbrivations

θ	Roll, or pitch, angle [rad]
COG	Centre of gravity
DAF	Dynamic amplification factor
DOF	Degree of freedom
DP	Dynamic Positioning
g	Gravitational acceleration [m/s^2]
H_{max}	Maximum wave height [m]
Hs	Significant wave height [m]
IWRC	Independent wire rope core
MPSV	Multi purpose service vessel
OCV	Offshore construction vessel
RAO	Response Amplitude Operator
ROV	Remotely Operative Vehicle
TBN	To be named
T_C	Contingency time
T_P	Peak period [s]
T_{POP}	Planned operation time
T_R	Roll, or pitch, period[s]
T_R	Reference period
Tz	Zero up – crossing period [s]
y	Horizontal distance from the centerline of the barge
z	Height above the center of rotation (assumed to be at the waterline)

1. Introduction

For the past 10 years the development of new technology in the offshore industry has increased rapidly. More and more often we see that heavy equipment is being used subsea. In this thesis we will look at installation of equipment having a weight of 340T which is a typical module used subsea. One of the reasons for choosing this exact weight is that many of the biggest multi-purpose service vessels (MPSV) today have a limited lifting capacity of 400T harbour lift. In this thesis we have used a safety factor of 1,15 for subsea lift which is a typical safety factor used in the industry when assessing the capability of large lifting equipment [1]

$$\frac{400T}{1,15} = 347,8T$$

To have some margin, the weight has been reduced to 340T.

World-wide, the most influential companies in the subsea industry are Subsea 7, Technip, Saipem and EMAS AMC. By taking a look into the vessel fleet of these companies, we see that quite a handful of the vessel have the capacity of lifting a 340T subsea module. Vessels like Skandi Acergy, Seven Seas, Lewek Crusader and Skandi Arctic are all vessels that are capable of lifting 340T. These vessels are typically owned by shipping companies and are in charter for the subsea construction companies for longer periods at a time.

The second quarter of 2014 a new vessel will be delivered for Eidesvik; Viking TBN. Viking TBN is a vessel of this size that is being considered in this thesis. The reason for choosing this particular vessel is because she is the newest in her size.

As the weight of subsea and topside equipment increase, so do the demands for lifting capacity. In the future we might see large MPSVs with a lifting capacity of 600T as the most common size, and during this last year we have seen that Subsea 7, Toisa and DOF have ordered vessels of this crane size. Viking TBN has the capacity of having a 600T crane on-board, but to upgrade from a 400T crane will increase the cost with approximately 16 mill NOK.

When choosing a weight of 340T we see, as mentioned above, that many of the subsea companies have a vessel in their chartered fleet that could do the lift. In the case of using an “internal” vessel for the lifting operation, they reduce the cost of hire an “external” heavy lift vessel. With the huge activity of heavy lift of topside and subsea modules, the risk of down time because no vessel is available should be taken into account. The risk of downtime is also present while using an “internal” vessel, as most of the vessels have specific projects they are committed to.

Another factor to take into consideration is how the vessels behave in different sea states, and it is therefore important to look into how the vessels behave in the specific area the operation is planned to take place. A vessel could be the best solution to be used in the North Sea, but it may not be the best for offshore Angola.

In this thesis we will therefore discuss and analyse the considerations around lifting a 340T subsea module in different environmental conditions.

2. Marine Operations

As mentioned previous, marine operations and the industry it belongs to have developed a lot through the years. The operations have been more extensive and advanced, and so has the vessels and equipment. Although the technology has evolved, there are always limitations regarding marine operations. One of the factors that have an impact when it comes to limitation for a marine operation is the weather. The weather conditions are different from every area in the world, and an operation has to be planned according to what area and what operation it is performing under. If a marine operation is delayed because of the weather is too harsh for the used vessel, the operation expenses increases rapidly.

As a result of the development in subsea technology, the equipment and structures that are being used increases in size, and the lack of vessels that are capable of lifting these structures increase. The industry needs vessels that are capable of lifting large modules in size and weight, as the use of a rig to do the lifting operation will not be economically suitable, [2].

2.1. Lifting Operations

The lifting operations done offshore are varying and can be difficult to compare to each other's. The items being lifted can be either topside or subsea, different shapes and geometry demanding unique lifting points and different weights, so the challenges when lifting offshore range over a large scale. Also the difference in vessel type performing the lifting has an impact on the operation. These considerations come in addition to those mentioned in the beginning, weather conditions.

Every lifting operation also includes risk. This could be risk of injury to people, dropped objects, damage to the wire in the crane, slamming load, etc.[3] Some lifting operations have larger risk than other, depending on the load being lifted, the geographical area the operation is being performed in, vessel type etc. Heerema Hermod is capable of a tandem lift of 8100 T. The vessel has an overall length of 154 meters and width of 86 meters. [4]

Figure 2-1 Heerema Hermod [5]

Stanislav Yudin is also a heavy lift vessel with two cranes, one that is capable of lifting 2500T and another with capability of lifting 500T. Stanislav Yudin is 183,2 m long and has a width of 36 m, she has also an eight point mooring type system and is [6]

Figure 2-2 Stanislav Yudin [7]

Viking TBN is a 145,6 meters long and 31 meters width subsea vessel under construction by Kleven Maritim. Viking TBN has a crane capability of 400T subsea lift. This vessel will be delivered in the third quarter of 2014.

Figure 2-3 Viking TBN [8]

2.2. Viking TBN; an Offshore Construction Vessel

Viking TBN is a subsea construction and installation vessel, Figure 2-4, with capability of doing ROV operations, pipe laying and cable/umbilical lay. The vessel is built by Kleven Verft and is owned by the vessel company Eidesvik Offshore ASA, that has it's headquarter located at Bømlo. Viking TBN will be built to enhance the operability, and this is done by installing 2 passive tanks above the ROV hangar, one passive tank below the 1st deck and a bilge keel. The roll motion is the most important motion concerning a lifting operation over the side, so a bilge keel will help to reduce this motion by providing larger added mass. A reduction in the roll motion will make the lifting operation capable of being performed in more harsh environmental conditions.

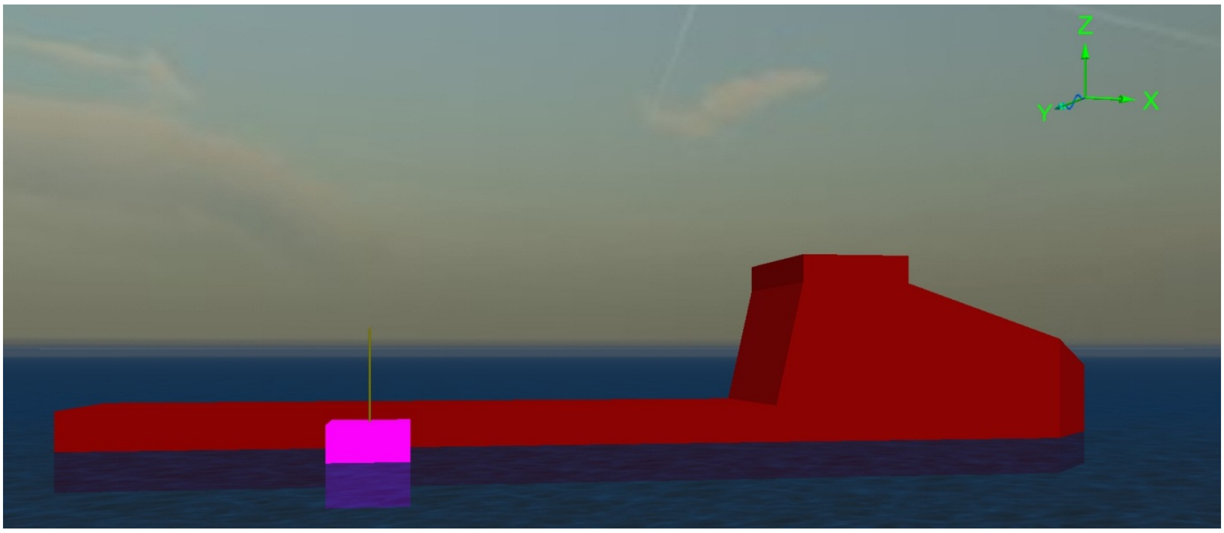

Figure 2-4 Model of Viking TBN made in OrcaFlex

Viking TBN also has a 400T active heave compensated main crane and an active heave compensated aux crane of 100T located on the 2600m^2 working deck. This vessel, designed by Salt, gives a stable platform for subsea operations, flexible deck – layout for wide range of deckspreads, high redundancy and robust solutions. [8]

This vessel`s characteristics will be used further for the analysis in the thesis.

2.3. Subsea Lift

All marine operation is unique and has to be planned each time they are executed. However, there are some similarities to every subsea lift, and that is the phases during a subsea lift operation. The main phases of a subsea lift are, [9]:

- Lift off from deck and maneuvering object clear of vessel
- Lowering through the splash zone
- Further lowering down to seabed
- Positioning and landing

Figure 2-5 to Figure 2-7 illustrates the phase of lowering through splash zone. All these phases must be evaluated and analyzed for each operation, as they could, and most likely have, different properties and thereby act differently. For example, the properties change when lifting in air, and when it is submerged, so this has to be taken into consideration.

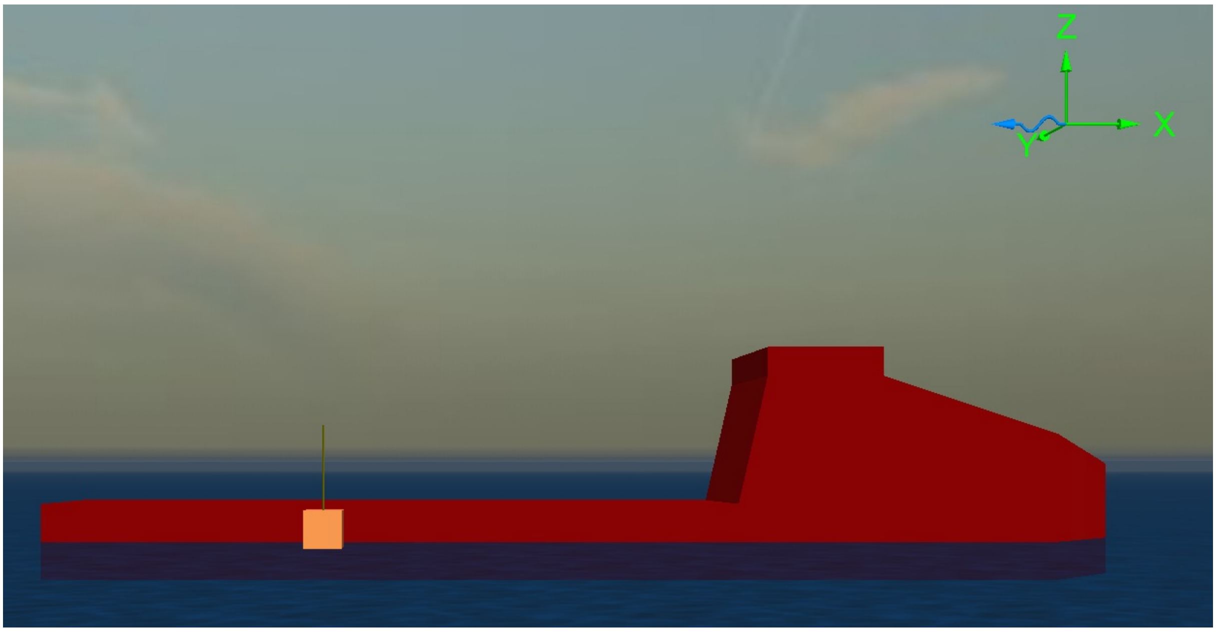

Figure 2-5 Module lift in air

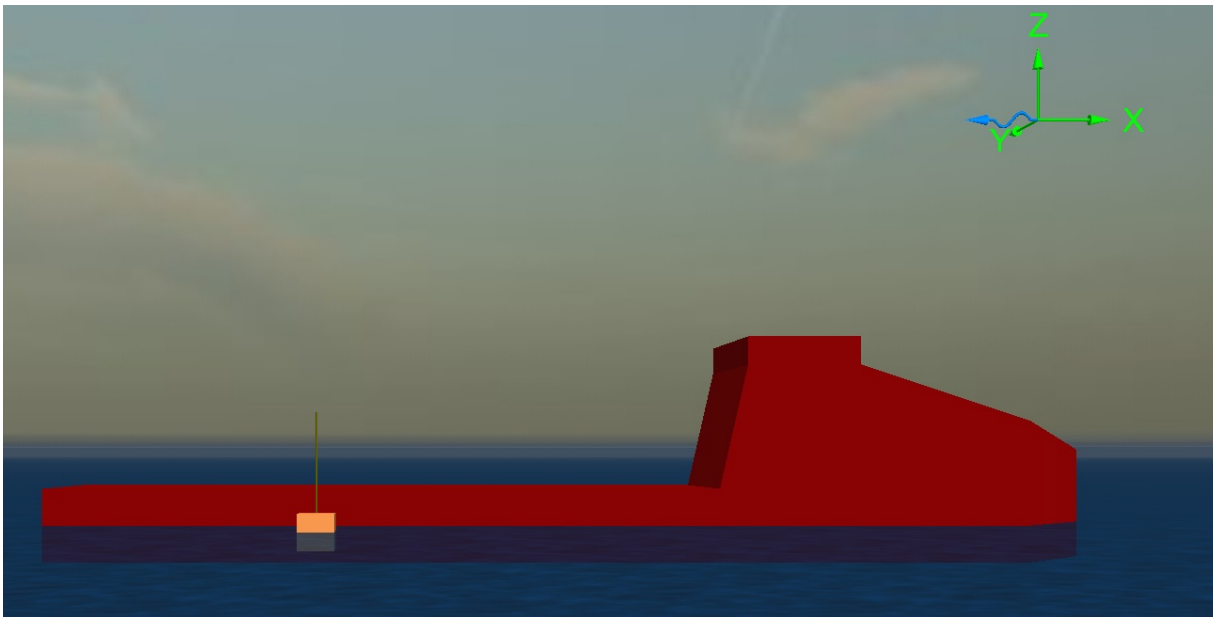

Figure 2-6 Module lift partly submerged

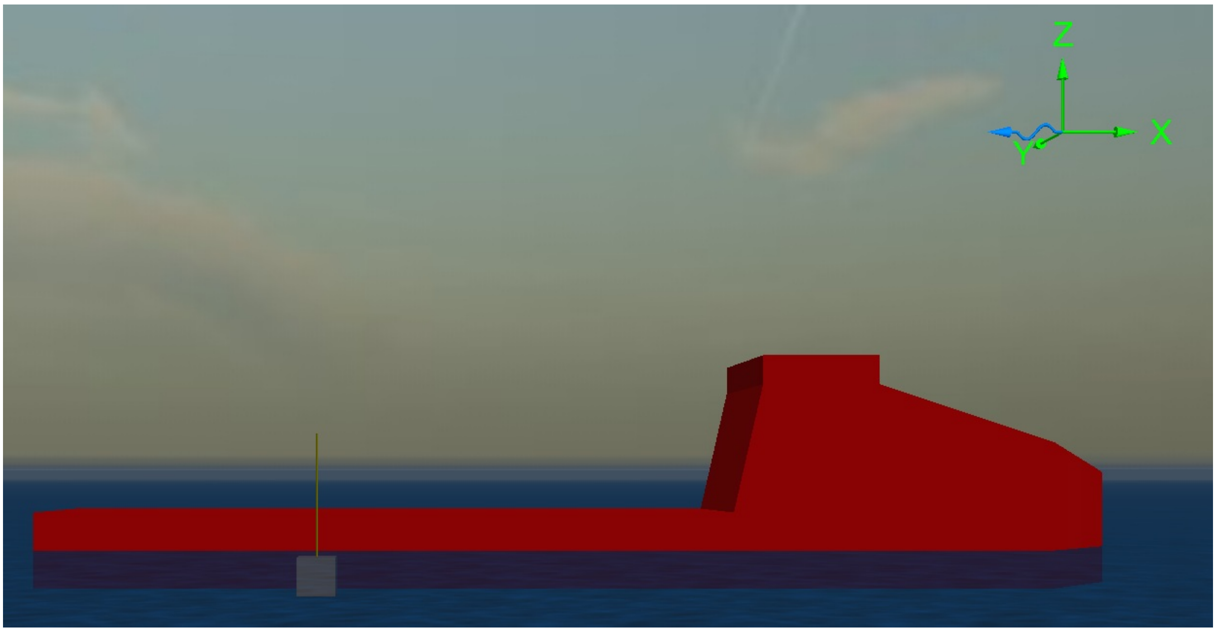

Figure 2-7 Module lift fully submerged

2.3.1. Module

The module being analysed in this thesis is a module like the one presented in Figure 2-8 with data given in Table 1. There are several forces acting on this module during the operation, from lifted on – board onshore until the main lifting operation takes place at the location offshore. Some of the forces are considered as the same as the one the vessel is experiencing, and some of them are just acting on the module. This chapter will consider some of the forces and motions the module can experience. Some of the calculations are done with help from Microsoft Excel and some of them are calculated with help from OrcaFlex. The formulas being used for the calculations are presented in DNV – RP – H103 chapter 3 and 4. These two chapters are concerned about lifting through the wave zone.

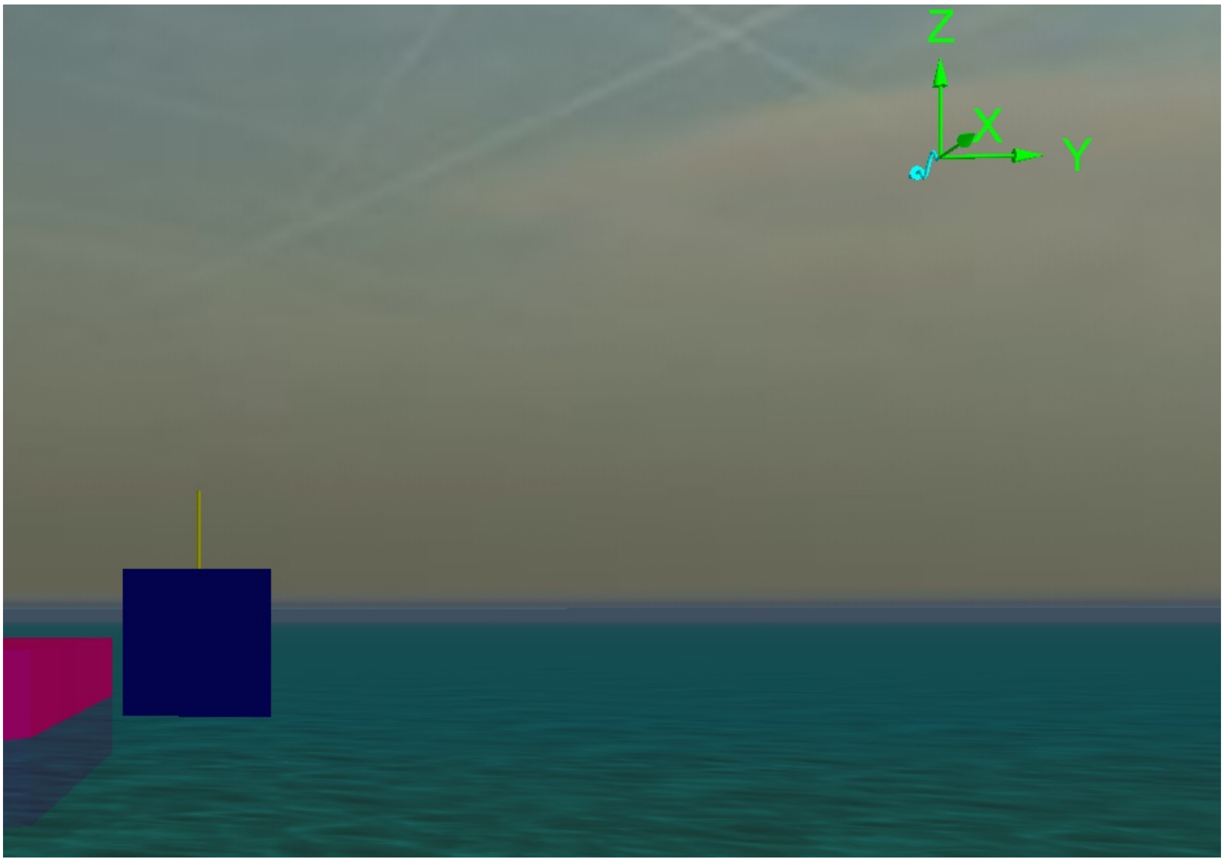

Figure 2-8 Lifted module

The module in Figure 2-8 above is modelled in OrcaFlex.

Table 1 Input data module

Mass[kg]	340000
Length[m]	6
Width[m]	6
Height[m]	6
Gravity g	9,81
Density of sea water	1025
Displaced Area of water[m^2]	36
Added Mass A_{33} [kg]	231200

The added mass of the module, A_{33}, is calculated according to DNV – RP – H103 *"Appendix A",* with an added mass coefficient C_a of 0,68.

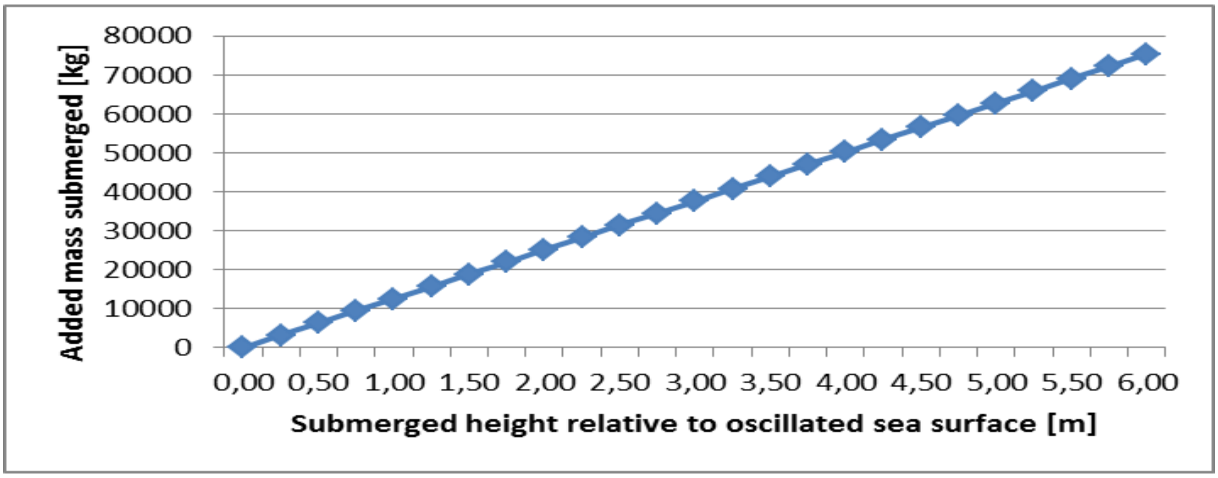

Figure 2-9 Added mass relative to submerged height

In Figure 2-9 we see how the added mass changing relative to the submerged height. This figure is based on the data given in Table 17 appendix A.
During the lifting operation we have a critical period in the subsea lift, and that is when we launch the subject. The forces the subject is exposed to could be slamming, drag and buoyancy. The subject is first exposed to slamming when it is in contact with the water surface, like in Figure 2-6, [10]. A subsea lift, e.g. an object lifted into or out of the water surface, must consider several forces affecting on the object. These forces are:

- Force in hoisting line/cable, F_{line}
- Weight of object in air, W_0
- Buoyancy force, F_B
- Steady horizontal force due to current, F_c
- Inertia force, F_I
- Wave damping force, F_{wd}
- Wave excitation force, F_W
- Slamming force, F_s
- Water exit force, F_e

All these forces are defined in DNV – RP – H103

The slamming load does normally not transmit globally and is therefore to be considered to act on the area of the subject that is in contact with the sea surface. The drag and the buoyancy forces result from the submergence of the structure in the water. The duration of these forces is of the same magnitude as the vessel motions and wave periods, [9].

2.3.1.1. Morison equation

When we look into the loads that affect a structure, we distinguish between static loads and dynamic loads. Under the category static load we have gravity load, deck load, hydrostatic load and current load. The dynamic loads are affected by the following terms,[11]:

- Environmental conditions
- Rigging arrangement
- Type of crane vessel
- Crane boom stiffness and lifting appliances
- Type of cargo vessel
- Weight of lifted object
- Weather the object is lifted in air or in water

The dynamic amplification factor can be used to estimate the effect of the dynamic loads. The DAF values are given in Table 2.

Table 2 DAF for different loads [11]

Static load	DAF onshore	DAF inshore	DAF offshore
50 – 100T	1,10	1,15	1,30
100 – 1000T	1,05	1,10	1,20
1000 – 2500T	1,05	1,05	1,15
>2500T	1,05	1,05	1,10

This chapter will contain a discussion around how these forces will act on the object that are presented above.
One way of explain the dynamic load on small structures is by using Morison equation, that is given by the following formula

$$F = \frac{\rho C_M \pi D^2 \dot{u}}{4} + \frac{1}{2}\rho C_D |u|u \qquad 2\text{-}1$$

The slamming force is defined by the DNV RP – H103, April 2011, *Modelling and analysis of marine operations,* as the force on an object lowered trough the free surface with a constant velocity v_s . The slamming force can be written in terms of a slamming coefficient C_s as

$$\boldsymbol{F_s(t) = \frac{1}{2}\rho C_s A_p v_s^2}\ [\boldsymbol{N}] \qquad 2\text{-}2$$

Where the slamming coefficient is defined by, [9]:

$$\boldsymbol{C_s = \frac{2}{\rho A_p v_s} * \frac{dA_{33}^{\infty}}{dt} = \frac{2}{\rho A_p} * \frac{dA_{33}^{\infty}}{dh}}\ [\textbf{No unit}-] \qquad 2\text{-}3$$

And

ρ = mass density of water [kg/m^3]
A_p = Horizontal projected area of object [m^2]
h = Submergence relative to surface elevation [m]
$\frac{dA_{33}^{\infty}}{dh}$ = rate of change of added mass with submergence [kg/m]

After a discussion with Arunjyoty Sarkar,[12], and studying DNV – RP – H103 a slamming factor of

$$C_s = 5{,}0$$

Is chosen and this is according to DNV – RP – 103 chapter 3.4.2.20 page 47.

When lifting an object into the sea, the object will be exposed to several loads. Two of these forces are called inertia load and drag load. These loads are obtained due to friction between the object and the fluid, which will cause eddy currents around the structure,[13].

These loads are given by the equations for the drag force and the inertia force, respectively;

First we investigate the drag force:

$$F_D = \frac{1}{2} * \rho * C_d * u * |u| \qquad \text{2-4}$$

Where the parameters are
F_D= drag force [N]
ρ=density of the fluid the object is submerged into [kg/m^3]
C_D = the drag coefficient
u= relative velocity between the module velocity during lowering and the wave water particle velocity.

A selection of the hydrodynamic coefficients may be challenging, as most of the structures today used in subsea lift has complex geometries. For lifting operations through splash zone, see DNV – RP – H103 *"Modelling and Analysis of Marine Operations"* regarding the different hydrodynamic coefficients.

If the object that is under consideration has a complex geometry design, it is recommended by DNV to divide the structure into several less complex structures to define the hydrodynamic coefficients. For this thesis the object has a geometry formed as a cube, with dimensions 6x6x6 m, so it will not be necessary to divide the structure into multiple structures. DNV has introduced the drag coefficient in *"Modelling and Analysis of Marine Operations"* Appendix B.

The inertia force on the object is the force caused by the weight of the water that is "forced away" when lowering through the water surface, given by the following equation from DNV;

$$F_I = \rho * V * C_m * \dot{v}$$ 2-5

Where
V= displaced volume [m^3]
$\dot{v}$ = fluid particle acceleration [m/s^2]
$C_m = 1 + C_a$ is the inertia or mass coefficient

From this we see that the inertia force is dependent of the submerged height, and will increase with increasing height of submergence. In Table 3 below it's an overview of the hydrodynamic coefficient used, all determined by using DNV – RP – H103, *"Modelling and Analysis of Marine Operations".*

From tables in appendix F of DNV – RP – H103 we obtain the following coefficients for the object considered in this thesis as follows:

C_A = 0,68
C_D = 1,15
$C_I = C_m = C_A + 1$

Table 3 Overview of hydrodynamic coefficients

Hydrodynamic Coefficient	Value
C_D	2,30*
C_A	0,68
C_S	5,00
C_m	1,68

*To determine the drag coefficient for the lift it is understood from the DNVs recommendation that the drag coefficient given in the appendix F should be multiplied by 2, as the coefficient given in the appendix is for steady flow, and lowering an object through splash zone is not considered steady flow.

2.4. Motion Analysis

Vessel motion is a 6 degree of freedom motion, like shown in Figure 2-10 below. This is motion that a vessel will be exposed to in different headings, and is dependent on the shape of the surface and vessel, the position of the COG and similar parameters that contribute to the behaviour of a vessel. The 6 degrees of freedom can be divided into two main categories;

Linear Motions

- Surge
- Heave
- Sway

Rotational Motions

- Roll
- Yaw
- Pitch

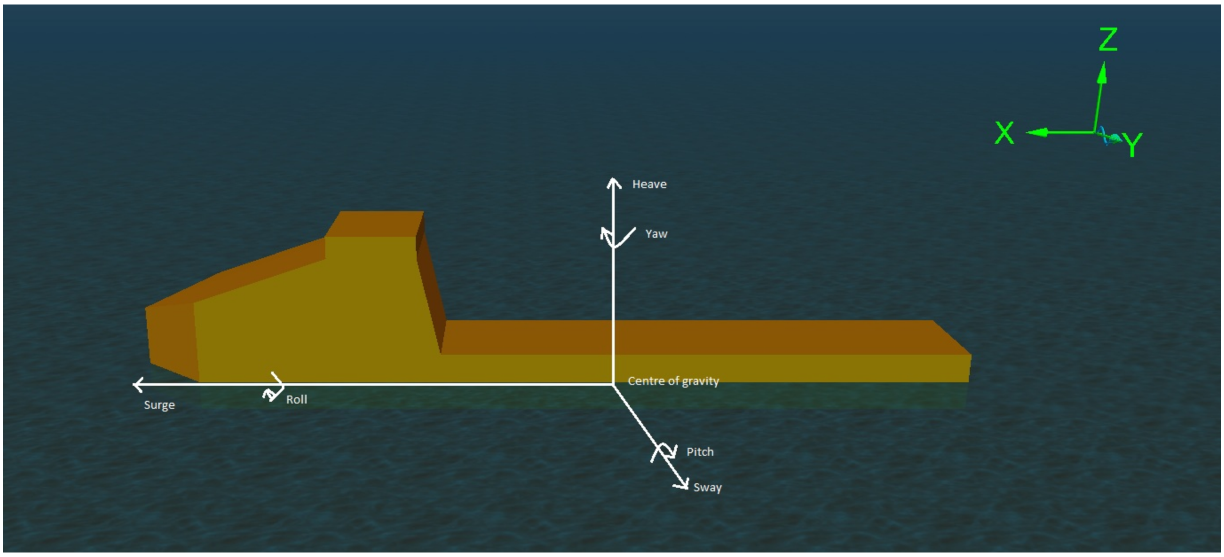

Figure 2-10 6 degree of freedom

Here the surge is the motion along the longitudinal axis, heave is the motion along the vessels vertical axis and sway is the motion along the vessels transverse axis. Roll is movement from side to side of the vessels longitudinal axis, and is, as already mentioned, a very important motion when considering lifting operations. Pitch and yaw are the movement of a vessel around its transverse axis and vertical axis respectively, [14].

To be able to do an analysis of the vessel motion, we need to determine the following factors;

- Significant wave height
- Wind speed
- Vessel heading relative to waves

In this thesis we will look at the motions for the vessel, and also how the module behaves in the different stages of the lifting operation. An assumption made is that the vertical motion of the module is following the crane tip motion, which again is following the vessel`s motion, when the module is lifted in air and we neglect the spring motion of the lifting wire and dynamics of the crane tip relatively to the vessel. The motions of the module will change when it is in contact with the sea. The peak period, T_p, can be obtained from the following equation, where H_s is the design wave height, expressed as significant wave height, [9];

$$\sqrt{13 * H_s} \leq T_p \leq \sqrt{30 * H_s} \qquad 2\text{-}6$$

3. Environmental theory

In this thesis we will look into two different geographical areas, the North Sea and Offshore Angola. These two areas represent two very different types of sea states, and the limitations in the respective areas are also different. In the following chapters both these areas will be discussed and the most characterizing factors will be presented.

3.1. Wave theory

Today we have multiple wave theories, such as,[15],:

- Linear Airy wave theory
- Stokes finite amplitude wave theory
- Stream function wave theory
- Standing wave theory
- Cnoidal wave theory

Linear wave theory is the simplest and most useful wave theory, [15]. The wave theories mentioned above are all used when describing regular waves, or like in Figure 3-1 below, formed as sinus waves.

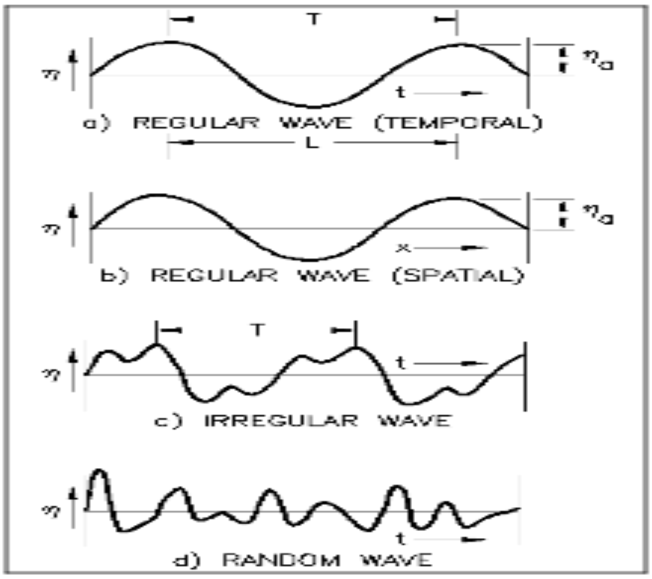

Figure 3-1 Representation of various types of wave profiles [16]

A regular wave almost never occurs in the real ocean. In reality we have irregular waves, also shown in Figure 3-1. Figure 3-2 shows wave profiles of linear wave with Hs=2,5m and period T=12s. Figure 3-3 shows a wave profile based on JONSWAP wave spectra with Hs=2,5s and peak period T_p=12s. Both Figure 3-2 and Figure 3-3 is made with results obtained from OrcaFlex.

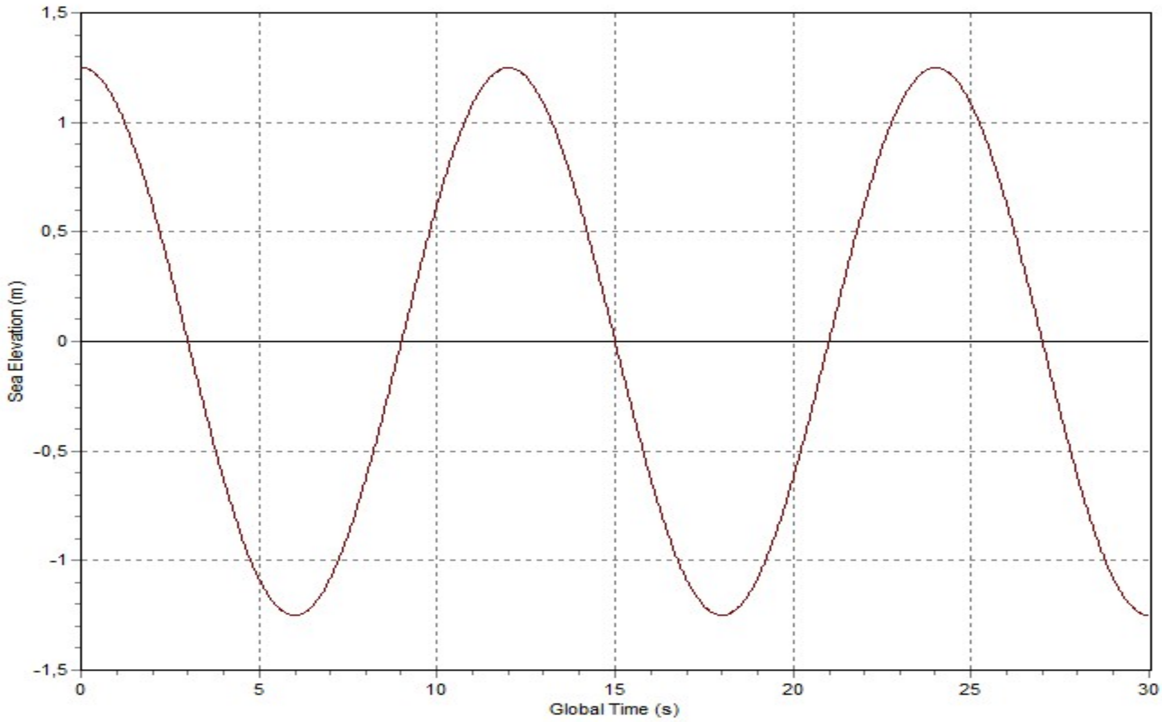

Figure 3-2 Single Airy wave profile H_s =2,5m T=12s

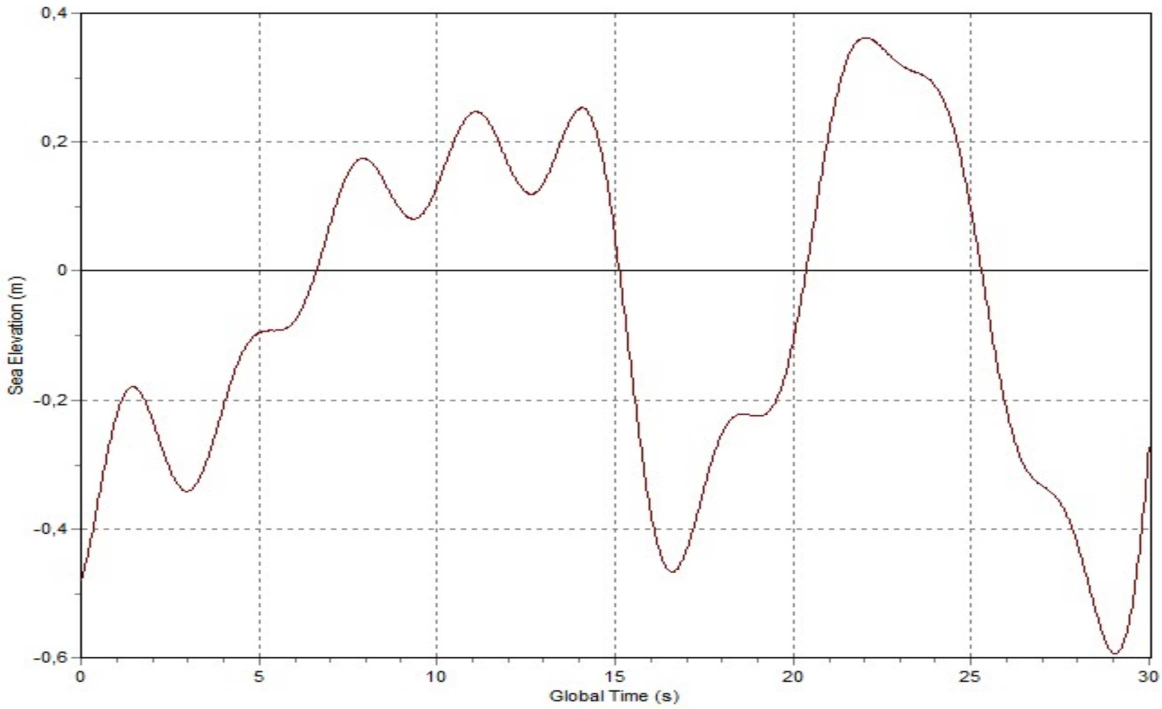

Figure 3-3 JONSWAP wave profile H_s=2,5m Tp=12s

If we compare Figure 3-2 and Figure 3-3 with Figure 3-1 we see that the single Airy wave profile is similar to a regular wave profile, and that JONSWAP wave profile is similar to an irregular wave profile. From this we understand that irregular waves must be described by a wave spectrum, which is according to DNV standard.

3.2. North Sea

One of the busiest seas in the world is the North Sea. The North Sea is located on the northwest continental shelf of Europe, and is bounded by England and Scotland in the west, Sweden and Norway in the east, and Denmark, Germany, the Netherlands, Belgium and France in the south, [17]. Figure 3-4 and Figure 3-5 shows an overview of the North Sea with water depth.

Figure 3-4 North Sea, [17]

3.2.1. Overview of the North Sea climate

The North Sea can experience both Arctic and temperate conditions. The weather condition depends on the location in the North Sea.
The storm surge that is experienced in the South – East area could also effects areas that have large tidal range, like we know occur in the coast lines and channels of Great Britain.

The water depths in the north – west Europe region are shown in Figure 3-5. As it shows, much of the water depths in this area are less than 200 m. However, there are some areas with water depths deeper than 1000m, [19].

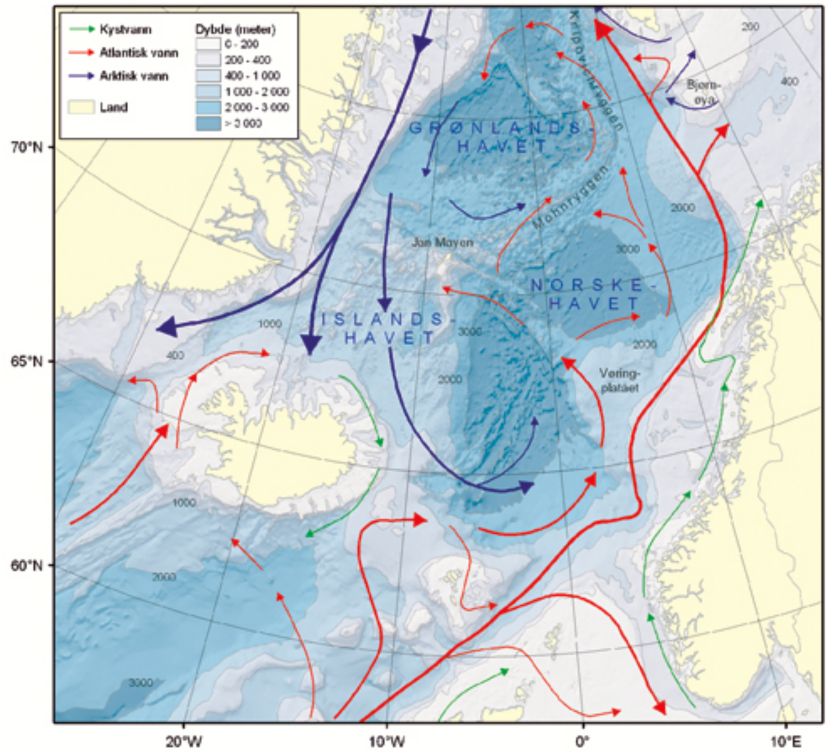

Figure 3-5 Map of the North Sea [18]

3.2.2. Winds and waves

The North Sea is influenced by the Atlantic Ocean water, the Gulf Stream and large air circulation from the west. The influence from these environmental conditions is essential for the North Sea climate, because without them the North Sea would most likely be covered with ice. As a result of the frequently depression in the airflow from the west, the North Sea experience a high level of variation in wind direction and wind velocity, [17]. When the Gulf Stream, with higher temperature in the ocean, meets the North Sea with lower temperature of air, this can result in an unstable atmospheric condition that can contribute to bad weather and turbulent flow, [19].

The waves are dependent of the water depth and the fetch length, and as mentioned in chapter *3.2.1* the water depths in the North Sea vary from 200m up to 1000m. This results in a variation of the wave height. If the fetch length is limited, storm waves will be shorter, steeper and less high than in deeper water depths. The North Sea is also affected by swell way. The swell can be present without any wind, and travels over large distances, with periods up to 20 seconds, [19].

In Appendix D one can see an overview of significant wave height and different peak periods, also known as a scatter diagram, for the North Sea. This scatter diagram shows an overview from the Northern North Sea in the period 1973 to 2001. From the diagram we see that the most common sea state is significant wave height from 1,5 to 2,5 m with a peak period of around 9 seconds. In Figure 8-9 in appendix D the wave heights and peak periods are combined and presented in a diagram, to easier see what type of period the specific wave heights has.

3.2.3. Wave spectra

There are several ways of defining a wave spectrum. In Figure 3-6 below, one wave spectra is shown to the left, with the corresponding equation (3-1), [20]. In Figure 3-6 to the right, the wave spectrum is defined according to DNV – RP – C205, *Environmental Conditions and Environmental Loads,* with the corresponding equations (3-2) and (3-3). The wave spectra in Figure 3-6 are presented with a peak shape parameter of 1 and a peak shape parameter of 3,3. By using a peak shape parameter of 1, we have what is called a Pierson – Moskowitz spectrum, which is most commonly used offshore Angola, in the Gulf of Mexico and off the west coast of Brazil, [10].

$$S_\eta(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp^{-1{,}25\left(\frac{f}{f_m}\right)^{-4}} \times \gamma^{\exp^{-\frac{(f-f_m)^2}{2\sigma^2 f_m^2}}} \quad (3\text{-}1)$$

$$S_{PM}(\omega) = \frac{5}{16} H_s^2 \omega_p^4 \omega^{-5} \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \quad (3\text{-}2)$$

$$S_J(\omega) = A_\gamma S_{PM} \gamma^{\exp\left(-0{,}5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)} \quad (3\text{-}3)$$

$$\omega_p = \frac{2\pi}{T_p} \quad (3\text{-}4)$$

According to Isherwood

σ = spectral width parameter

$\sigma = \sigma_a$ for $f \le f_m$

$\sigma = \sigma_b$ for $f > f_m$

$S_\eta(f)$= Spectral density

g= acceleration due to gravity

f= Frequency in Hz

According to DNV

σ = spectral width parameter

$\sigma = \sigma_a$ for $\omega \le \omega_p$

$\sigma = \sigma_b$ for $\omega > \omega_p$

$S_{PM}(\omega)$ = Pierson – Moskowitz spectrum

γ = non – dimensional peak shape parameter

$A_\gamma = 1 - 0{,}287 * \ln(\gamma)$ is a normalizing factor

According to Table 7 the JONSWAP wave spectrum is the most common wave spectra used for the North Sea. The JONSWAP wave spectrum is a modification of the Pierson – Moskowitz spectrum for a developing sea state in a fetch limited situation.

Table 4 Input data for JONSWAP wave spectra based on DNV

γ	3,3
σ_a	0,07
σ_b	0,09
ω_p	0,698
H_S	3,5
T_p	9,0
Aγ	0,657

Table 5 Input data for JONSWAP wave spectra based on OrcaFlex

γ	3,3
σ_a	0,07
σ_b	0,09
α	0,0062
f_m	0,1111
T_p	9,0
H_s	3,5

Average values for the JOSNWAP experimental data are given in the Table 4 and Table 5 above, [21].

Figure 3-6 below shows a JONSWAP spectrum for the wave statistics in the North Sea, by taking the most common H_s and peak period T_P from Table 26 in appendix C and combining formula **3-1** and **3-2**.

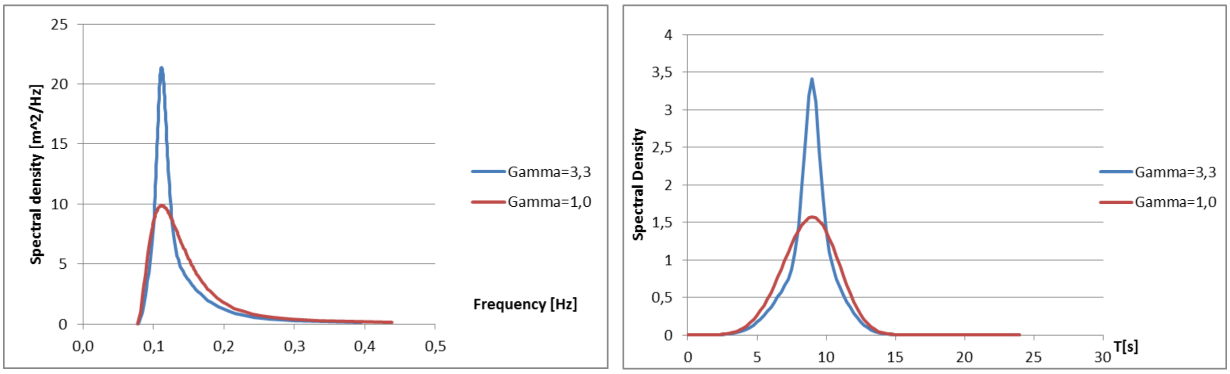

Figure 3-6 Wave Spectra for the North Sea

3.3. Offshore Angola

On the west coast of Africa, one of the most resources – rich country, Angola, is located, shown in Figure 3-7. In 1975 Angola became independent from Portugal, and 27 years of almost continuous civil war followed. Due to this, Angola is also one of the economically and socially less developed countries. Despite the major problems caused by two long periods of civil war, Angola has a great potential for economic development. Angola is by nature one of Africa's richest, with large deposits of diamonds and oil, and good conditions for both agriculture and industry. Revenues from diamonds and oil are the mainstay of the Angolan economy, but due to economic mismanagement, with widespread corruption as one of the biggest social problem, the population of Angola does not get the benefit of it, [22].

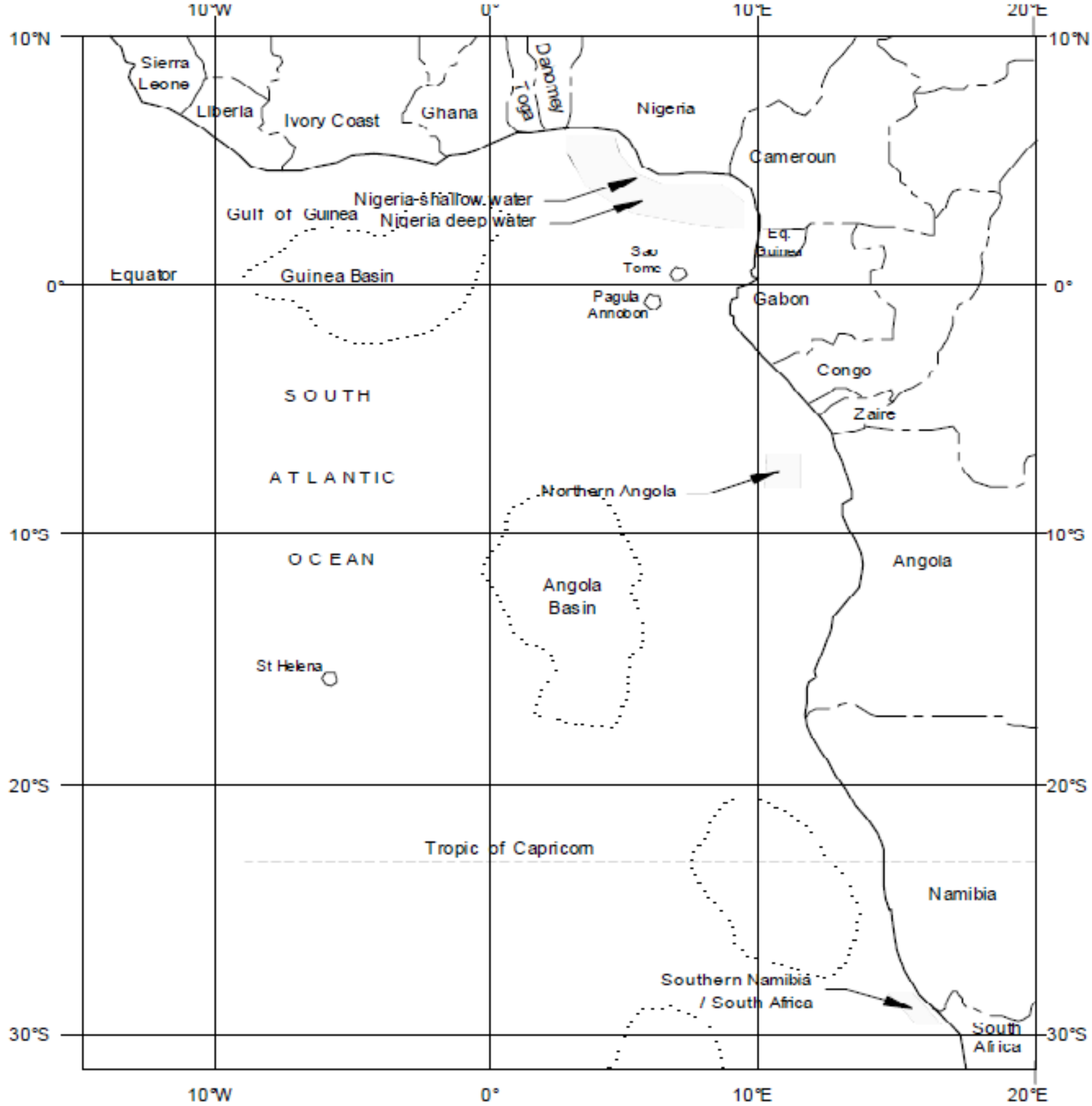

Figure 3-7 Map of region showing locations of example metocean parameters [19]

Angola had a relative diversified industrial sector in the colonial period, but as Angola became independent, the Portuguese population fled the country, taking competence and means of production, as well as capital, with them. With huge natural resources from the agriculture and mining, as well as significant energy reserves, Angola has good prospects for increased industrial production. This is today significant concentrated in and around the big cities close to the coastline as Luanda, Benguela, Lobito and Namibe. This includes petroleum refining, textile manufacturing, iron – , steel – and cement industry, finished goods production and processing of agricultural products. Angola has a large energy potential in hydropower, with opportunities to produce for export, [18].

3.3.1. Overview of the regional climatology

The environmental climate offshore of West Africa can be considered gentle compared to areas like the Gulf of Mexico and West of Shetland. Offshore Angola the normal wind condition is dominated by the airflow from South – East, while the extreme wind that occurs from time to time is a result of brief local storm events.

When the West Coast of Africa considered, one can see that the differences compared to the North Sea are distinct. The water depths offshore Angola is around 1000 meters and deeper. The distance the waves travels (from the Antarctica) are also longer, which makes the periods of the waves long. The wave height is lower than for the North Sea. Offshore operations done in this area are also affected by a second order waves, called swells. This is a factor that has to be taken into consideration when designing for an operation in this area, [19].

As a summary, one can see that in the North Sea we have larger wave heights with wave period around 9 to 11 seconds, while for offshore Angola a lower wave height with corresponding higher wave period of around 16 seconds is more common. This is shown in the scatter diagram tables in Appendix D. In Figure 8-10 in appendix D we see the percentage of occurrence of wave heights with different peak period for the location offshore Angola. Figure 8-10 and the scatter diagram, Table 27, in Appendix D are based on the scatter diagram, Table 26, for the North Sea found in *“Handbook of offshore engineering”* by Chakrabarti, S, combined with Table 27 in appendix E.

3.3.2. Water depths, tides and storm surges

There are three major deep ocean basins in the region, all considered deep water area; The Guinea basin, the Angola basin and the Cape basin. The Guinea and Angola basins are separated by a gently sloping ridge along which exist numerous seamounts and further inshore an island chain. The much steeper Walvis Ridge separates the Angola and Cape basins. Between these ridges the continental slope (from the 200m to 5000m depth contours) varies in width from approximately 100km offshore Ghana to over 600 km offshore Angola.

Equatorial and South – West Africa experiences a semi – diurnal tidal regime. Tidal ranges are relatively small at the coast with spring tidal ranges around 3 m and neap tidal rages about 2,4 m. the tidal range decreases rapidly further away from the shore, with a spring tidal range usually less than 1,5 m in deep water. Storm surges are small throughout the region, [19].

3.3.3. Winds and Waves

As explained in chapter *3.3.1* above, the airflow from South – West has a huge impact on the normal wind that is obtained at the West Coast of Africa and offshore Angola. This airflow is again affected by the atmospheric pressure systems in the area.
Because of a suddenly increase in wind velocity associated with the leading edge of multi – cell thunderstorms, extreme winds may occur in the West coast of Africa. These types of thunderstorms and brief storm events occurs more frequently equatorial West Africa.

At this point we understand that in this area a rapidly varying wind velocity both in the normal wind and the brief storms occurs, from different directions. From vessel motion and vessel response we understand that large variations between the characteristics of a storm, can make it challenging to calculate the actual environmental loads a vessel or structure can be exposed to. We will refer to ISO 19901 -1: "…*Further measurements are required to better define squall characteristics, including spatial variations in the wind field, rates on increase and decay, variations in wind direction, and improved extreme value estimates. These are likely to be considered as part of a future joint industry project…*"

The wave climate offshore West Africa is dominated by swell from two distinct sources:

- High latitude extra tropical storms in the South Atlantic generate swell from the south – west
- Episodic increases in the trade winds offshore South Africa generates swell from the south – east

The swell is greatest in southern parts of the region, where extreme significant wave heights can be about 9m. Wave heights decrease further north due to dissipation, where extreme values of about 4 m are more typical.

Swell waves from distant storms can be associated with long peak periods, sometimes in excess of 20 s. Such long period waves can be critical for the operability of some vessels. Longer period swells are generally encountered in northern parts of the region, due to the longer propagation distance from the source, [19].

In addition to swell, the wave spectrum usually also contains a locally wind driven sea wave component with significant wave heights of about 1 m. Due to the presence of both storm waves and swell it is not appropriate to represent the sea state offshore West Africa using a spectral model with just one peak. In Figure 3-8 we see an example of a 2 peaked wave spectra based on Table 6 and Table 27.

Table 6 Input data for wave spectra

$H_{s\ storm\ wave}$	T_p	ω_p	$H_{s\ swell}$	$T_{p\ swell}$	$\omega_{p\ swell}$
1,5	12	0,523598776	2	22	0,285599332

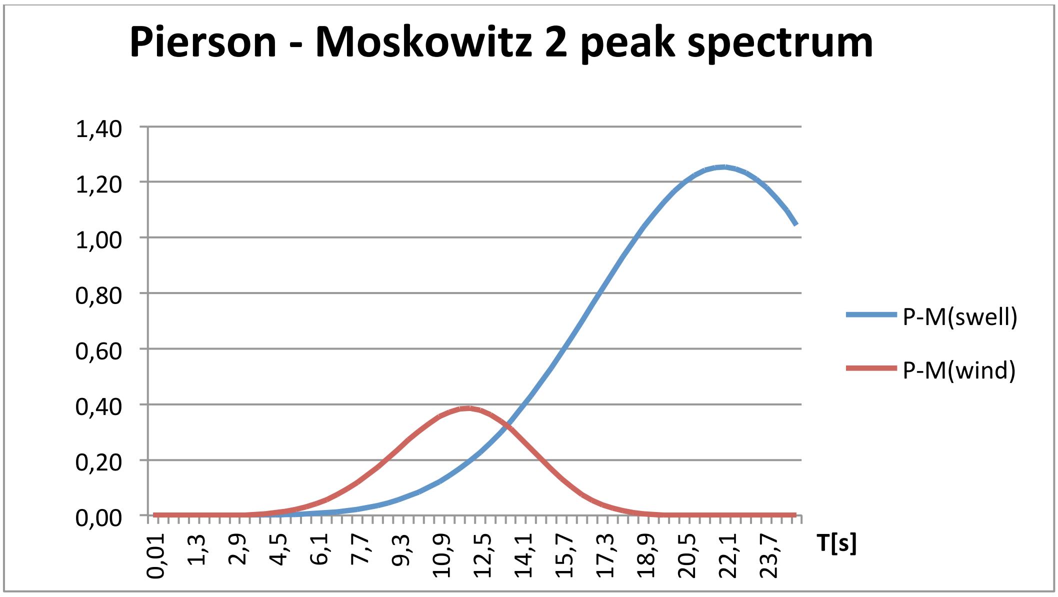

Figure 3-8 Pierson - Moskowitz spectra

The P – M spectra above in Figure 3-8 is based on equation **3-2** with input data given in Table 6 above.

$$S_{PM}(\omega) = \frac{5}{16} H_S^2 \omega_p^4 \omega^{-5} \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \quad 3\text{-}2$$

Where

There are several other wave spectra that can be used for waves in the west coast of Africa, such as the Orchi Hubble wave spectra and Torsethaugen wave spectra, [23].

As swell approaches the coast in some parts of the region, particularly along the coast of South – West Africa, it can be transformed into phenomena called “rollers”. These large steep waves are likely to affect vessels in near – shore regions and coastal infrastructure, [19]

3.4. Summary

Through this thesis we have looked at the sea state of North Sea and offshore Angola. By studying these two areas we have found that the differentials are severe, and there are different limitations to both of these two sea states.

The most distinctive difference is the long period of the waves. In offshore Angola area around it makes the wave have a long travelling route before hitting shallower water and shore. This makes the wave build up with a longer period. With the long period it also comes a smaller significant wave height. With the long periods and small significant wave height the vessel motions are different compared to the North Sea. This will be discussed further in chapter 5.

4. Environmental conditions

The weather conditions have a huge impact on how the marine operations are executed. It is therefore very important to plan everything, and to take the weather forecast into consideration. Some areas have very limited information about the weather forecast, e.g. Barents Sea, where the weather is very challenging and changing. When I talk about weather conditions I mean waves, wind, currents etc. It is also important to take into account if there has been a storm somewhere else closed to the area that the operation is planned to take place. This is because of the wave velocity versus the wind velocity. The swells travel much faster than the wind, so if there have been a storm somewhere close to the area that you are working in, it might have an influence on the area for the current operation.

According to "Handbook of Offshore Engineering" by Subrata Chakrabarti, the standard approach to the statistical modelling of ocean waves in engineering applications is to assume that the ocean surface constitutes a stochastic wave field that can be assumed stationary in time and homogeneous in space.

Table 7 below is showing what type of wave spectra is common for the different geographical areas. In this thesis two areas are considered, the North Sea and Offshore Angola, and used JONSWAP for the North Sea and Pierson – Moskowitz wave spectra for offshore Angola**.** Figure 3-6 and Figure 3-8, respectively, shows this and is discussed further in chapter 4.1. and chapter 5.3.

Table 7 Common form of spectral models applied to different regions [10]

Location	Operational	Survival
Gulf of Mexico	P – M	P – M or JONSWAP
North Sea	JONSWAP	JONSWAP
Northern North Sea	JONSWAP	JONSWAP
Offshore Brazil	P – M	P – M or JONSWAP
Western Australia	P – M	P – M
Offshore Newfoundland	P – M	P – M or JONSWAP
West Africa	P – M	P - M

JONSWAP and P – M is two of the most used spectral models, where P – M spectrum is a special case of JONSWAP with the peakedness parameter value being one.

4.1. Current

In open sea, current is a common occurrence. The current at the sea surface is mainly introduced by the wind effect on the water, variations of atmospheric pressure and tidal effects. But current is also present in the subsurface and seafloor region. The most common categories of current are:

- Wind generated currents
- Tidal currents (associated with astronomical tides)
- Circulational currents (associated with oceanic circulation patterns)
- Loop and eddy currents
- Soliton currents

The vector sum of these currents is the total current, and the speed and direction of the current at specified depths are represented by a current profile. [21]

4.2. Alpha factor

When a marine operation is planned to be executed, the operator companies must identify probable forces, by use of industrial guidelines. Critical elements for a marine operations and offshore operations in general are the time duration of the operation and the expected weather during the operation, [24]. In DNV they have introduced two types of marine operations, characterized as weather restricted or as unrestricted. An operation reference period, T_R, is used to tell us the duration of a marine operation and is based on the formula

$$\boldsymbol{T_R = T_{POP} + T_C} \quad (4\text{-}1)$$

Where

T_{POP} = Planned operation time
T_C = Estimated maximum contingency time

4.2.1. Weather restricted and unrestricted operations

A weather restricted operations is a marine operation with a reference period T_R of less than 96 hours and operation time planned T_{POP} for less than 72 hours, this requires what we can call, a reliable weather forecast.

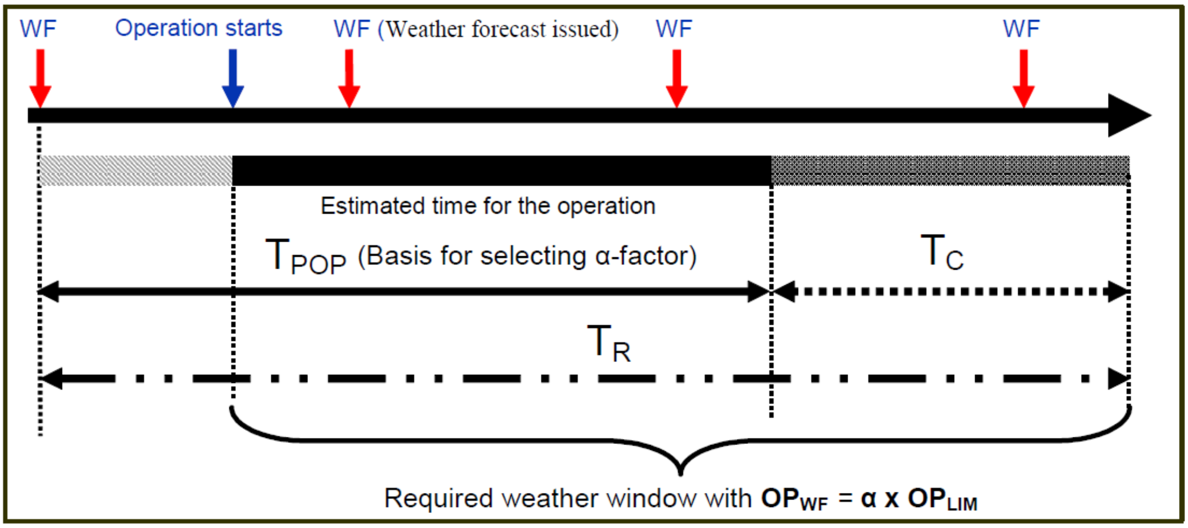

Figure 4-1 Operation Periods [25]

Figure 4-1 above shows how long the duration of an operation lasts from start to end, with the unexpected period, T_C, caused by delay, included. We select an “alpha factor” for the period the operation was planned to take place. The alpha factor is the relationship between the operational criterion and the design criterion. The variations of the alpha factor also take into account the fact that it is harder to estimate the wave height for small sea conditions than for larger sea conditions, [24].

According to DNV, operations of longer duration than 72 hours are characterized as unrestricted operation. The environmental conditions should be based on extreme values.

One of the limiting factors in a marine operation is the weather and weather forecast. A marine operation uses the weather forecast to estimate the operation`s duration. The weather forecast is given by the meteorologist that has analysed and calculated the weather development over a period. Even though they have done these analysis and calculations, the weather forecast will not be 100% certain. For this reason a forecasted operational criterion OP_{WF} is used:

$$OP_{WF} = \alpha * OP_{LIM} \quad \textbf{4-2}$$

OP_{LIM} is the operational limit criterion, and is affected by the alpha factor. From this we understand that the alpha factor is used to represent the uncertainty in the weather and the weather forecast, [26].

There has not been published a lot of literature about the alpha factor, but DNV has published one way of selecting the alpha factor for different weather conditions. They are given in the tables Table 21 to Table 25 in appendix C,[25].

5. Analysis

In this chapter we will present the results obtained by OrcaFlex, for different H_S, T_p and water depths, as these factors are different for the locations offshore Angola and the North Sea, and also important for the analysis. For the North Sea a water depth of 300m is chosen, and for offshore Angola a water depth of 1500 m is chosen.

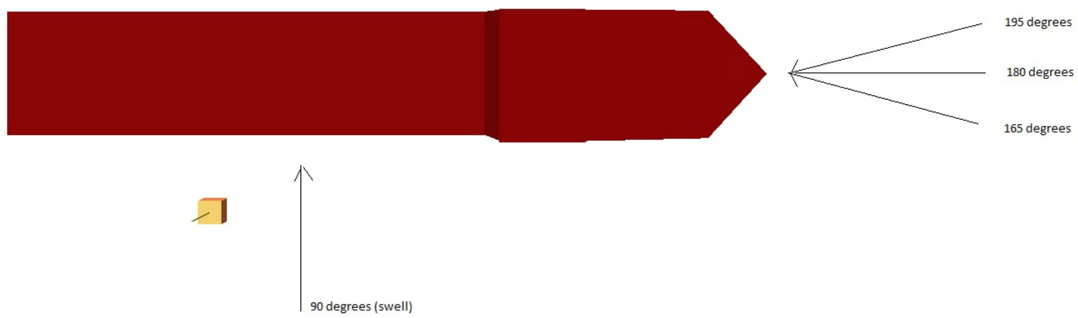

Figure 5-1 Wave direction relative to vessel

Using regular wave theory, the wave period T is assumed to be the same as the zero up – crossing period T_z, and that the period should be within the following interval, [9];

$$8{,}9 * \sqrt{\frac{H_S}{9{,}81}} \leq T_z \leq 13 \qquad \text{5-1}$$

With the lowest H_s considered for the North Sea and Offshore Angola to be H_s = 1,5m and H_s = 1,0 m respectively, the following results are obtained by using linear wave theory;

Table 8 Deep sea situations the North Sea

North Sea			
T	L	d/L	Deep Water
4,01	25,11	11,95	OK
5	39,03	7,69	OK
6	56,21	5,34	OK
7	76,50	3,92	OK
8	99,92	3,00	OK
9	126,47	2,37	OK
10	156,13	1,92	OK
11	188,92	1,59	OK
12	224,83	1,33	OK
13	263,86	1,14	OK

Table 9 Deep sea situations offshore Angola

Offshore Angola			
T	L	d/L	Deep water
2,84	12,59	119,11	OK
3	14,05	106,75	OK
4	24,98	60,05	OK
5	39,03	38,43	OK
6	56,21	26,69	OK
7	76,50	19,61	OK
8	99,92	15,01	OK
9	126,47	11,86	OK
10	156,13	9,61	OK
11	188,92	7,94	OK
12	224,83	6,67	OK
13	263,86	5,68	OK

From Table 8 and Table 9, we see that both the North Sea and offshore Angola can be considered as deep water for these waves, when using linear wave theory.

The formulas used to obtain the results are as follows:

$$\mathbf{L} = \frac{\mathbf{g}}{\mathbf{2\pi}}\mathbf{T^2} \quad (5\text{-}2)$$

$$\frac{d}{L} > \frac{1}{2}\ for\ deep\ water\ situations \quad (5\text{-}3)$$

Where

L= wave length [m]

d= water depth [m]

T=wave period [s]

For a comparison between T_z and T_p, see equation **5-4**.

5.1. Acceptance criteria

Lower limit criteria:

One of the criteria that the lifting operation must be checked for before a lift can be performed is to ensure that we avoid slack wire. The requirement is, [9]

$$F_{hyd} \leq 0,9 * F_{static\ min}$$

This is called the slack sling criterion.

Upper limit criteria:

The upper limit criteria is

$$DAF_{conv} \leq DAF_{static}$$

DAF_{static} is given in Table 2 and is according to DNV 1,2 for this case.

With these criteria shown, we have that we are only allowed to perform the lifting operation if

- $DAF_{conv} \leq 1,2$
- Slack factor (see tables in appendix G) ≥0,1

5.2. Assumptions made for the analysis

To be able to perform the analysis, some assumptions have been made, they are explained as follows:

- The crane tip is fixed and follows the vessels motion; this makes the vertical motions the same for the vessel and the crane, furthermore the active heave compensation in the crane is neglected.
- To be able to perform a simplified analysis according to DNV, the waves have been considered as regular waves.
- The hydrodynamic coefficients given in DNV is for a square rod parallel to the flow, and the module in this thesis is a cube, so with L/D=1 we have the coefficients given above in Table 3.
- It is assumed according to DNV that $C_m=1+C_A$
- Loads that have an impact on the vessel during transport, as well as sea fastening and dropped objects that can have an impact on the vessel and the module after being launched are not covered.
- The stiffness of the crane system is assumed to be the same as for the crane wire, i.e. the stiffness of the crane is neglected.

5.3. Wire

To be able to perform an analysis of the forces and motions the module are exposed to, one needs to know some details about the wire. DNV present two methods for calculating the forces acting on the module during lifting through splash zone, [9]. These methods are:

- Lifting through splash zone – general
- Lifting through splash zone – simplified method

OrcaFlex analyses are based on the first method, while chapter 5.5 is containing the calculations based on the simplified method. According to DNV the most commonly used wire type is a 6x37 IWRC wire with the following characteristics, [9],

$E = 85*10^9 N/m^2$
$C_F = 0,58$

Where
E is the elasticity modulus
C_F is the filling factor.

From documentation for the crane type planned to be installed on Viking TBN the wire is given an outer diameter of 126mm. From this there it is assumed that the wire is of type 6x37 IWRC with the above data. By using the formulas given in chapters 4 and 5 of in DNV – RP – H103, we find:

$$A_{wire} = \frac{\pi * D^2}{4} * C_F = \frac{\pi * (0,126m)^2}{4} * 0,58 = 0,0574m^2$$

$$K = \frac{E * A_{wire}}{L} = \frac{85 * \frac{10^9 N}{m^2} * 0,0574m^2}{L} = \frac{4,8788 * 10^9}{L} N/m$$

This stiffness of the wire is also used to compute the results in OrcaFlex.

5.4. North Sea

In the previous chapters, the most characteristic environmental conditions for the North Sea have been discussed. In this chapter we will get to know how all these factors are contributing to the forces and motions acting on the vessel and structures lifted over the side of the vessel.

By now, together with the results found in chapter 2.3.1.1 *"Morison Equation"*, we have the values that are needed for the analysis.

5.4.1. Forces at end B

We are now looking at the forces acting at end B of the lifting wire. In appendix G graphs with maximum and minimum forces at end B are presented for different significant wave heights and wave directions. End B is the end position where the wire that is connected to the module and where the forces in the wire represent the vertical loads on the object. In this thesis three cases have been looked into;

- Case 1, where the module is located with bottom at z=1,0m
- Case 2, where the module is partly submerged, z=-3,0m
- Case 3, where the module is fully submerged, z=-6,0m

By performing multiple simulations in OrcaFlex, with zero up – crossing period ranging from 4,5 seconds to 13 seconds and varying significant wave height from 1,5m to 3,0m, the maximum force at end B are as follows for the three cases presented in Figure 5-2:

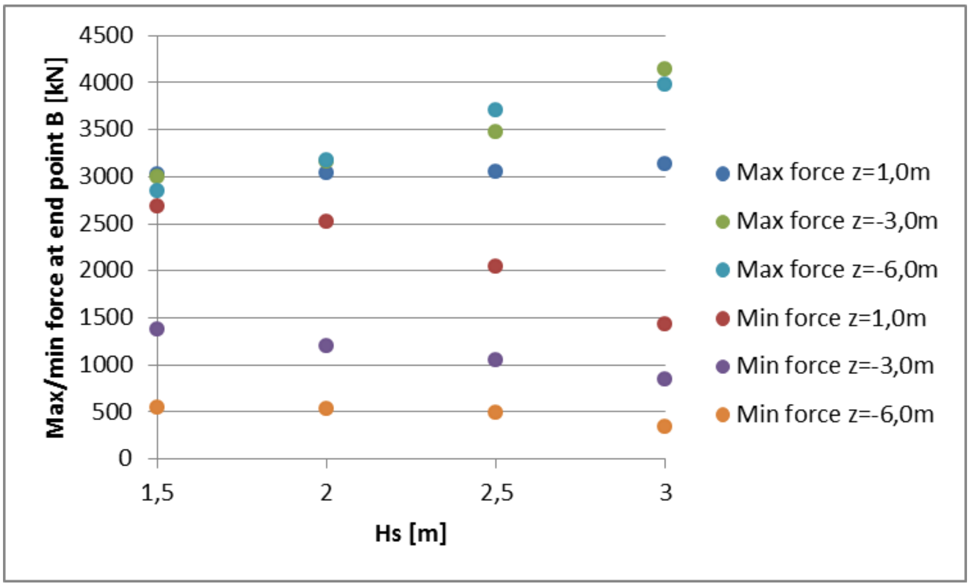

Figure 5-2 Forces at end B for different levels of submergence

The maximum forces at end B are obtained for a wave direction of 165 degrees, and the minimum forces at end B are obtained with a wave direction of 180 degrees. If we look at Figure 5-1 we see the different wave directions relative to the vessel. We see from Figure 5-2 and Figure 8-17 to Figure 8-19 in appendix G that the maximum forces at end B are as presented in Table 10. Generally the maximum forces are obtained with a wave heading of 165 degrees. However, in the results presented in Table 10, there are some deviations where we see that some of the maximum forces at end B are obtained from a wave heading equal to 180 degrees. Since the difference between the maximum forces from headings of 165 and 180 degrees at the respective cases are small, the wave heading of 165 degrees is considered as the worst case heading in the rest of the analysis.

Table 10 Results of forces at end point B for the North Sea with different levels of submergence and H_s

Z=1,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	3019	3025	2993	2670	2689	2784
2,0	3043	3057	3006	2486	2524	2636
2,5	3056	3063	3023	2114	2047	2499
3,0	3132	3196	3035	1459	1431	2248
Z=-3,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	3001	2843	2848	1392	1374	1320
2,0	3163	3217	2889	1262	1194	1304
2,5	3476	3733	3157	1106	1045	1179
3,0	4146	4367	3590	818	842	961
Z=-6,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	2841	2085	1475	605	543	612
2,0	3174	2767	2809	520	526	504
2,5	3708	2924	4494	466	494	481
3,0	3978	4047	2173	271	344	444

From these results we conduct the vessel motion with the respective H_s and T_z for each case, to see how the vessel behaves in the actual sea state. The results of the analysis of these cases are also compared with the simplified method in DNV.

5.5. Offshore Angola

Through this thesis, one of the factors that have been discussed is the characteristic long period of the waves offshore West Africa. Further in this chapter the results from the lift analysis for offshore Angola will be discussed and compared to the results obtained for North Sea lifting. For the calculations and analysis done, a swell with constant significant wave height H_s = 1,0m and T_z=13s is chosen, with heading 90 degrees relative to the vessel, see Figure 5-1. Further we have analyzed different significant wave heights with varying zero up – crossing periods in the range of T_z=3s – T_z=13s (equation **5-1**). These results are to be found in appendix G Table 40 to Table 51.

5.5.1. Force at end B

The wave situation offshore Angola is as we have discussed in chapter 3 and 4 different compared to the environment in the North Sea. We can see from Table 26 and Table 27 that the waves are calmer offshore Angola. There is also another important factor at this location that influence the marine operations, and that is the swells. Even though these are considered small in height, they have long periods that can influence the motions of the vessel. We see from Table 11 that the largest force that end point B experience offshore Angola is 3781 kN from a wave heading of 165 degrees and significant wave height 2,5m.

Table 11 Results of forces at end point B for offshore Angola with different levels of submergence and H_s

Z=1,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	3009	3012	3135	2738	2749	2798
1,5	3024	3044	3136	2560	2583	2760
2,0	3049	3105	3134	2410	2385	2639
2,5	3134	3292	3125	1800	2149	2497
Z=-3,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	2856	2927	2470	1293	1347	1517
1,5	2981	3209	2616	1158	1268	1373
2,0	3555	3596	2828	1097	1096	1281
2,5	3781	3436	3094	1010	973	1303
Z=-6,0m						
H_s	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	2338	2632	1565	575	595	576
1,5	2865	2836	1919	564	492	528
2,0	3719	3476	2412	525	468	615
2,5	3246	3701	3043	440	419	506

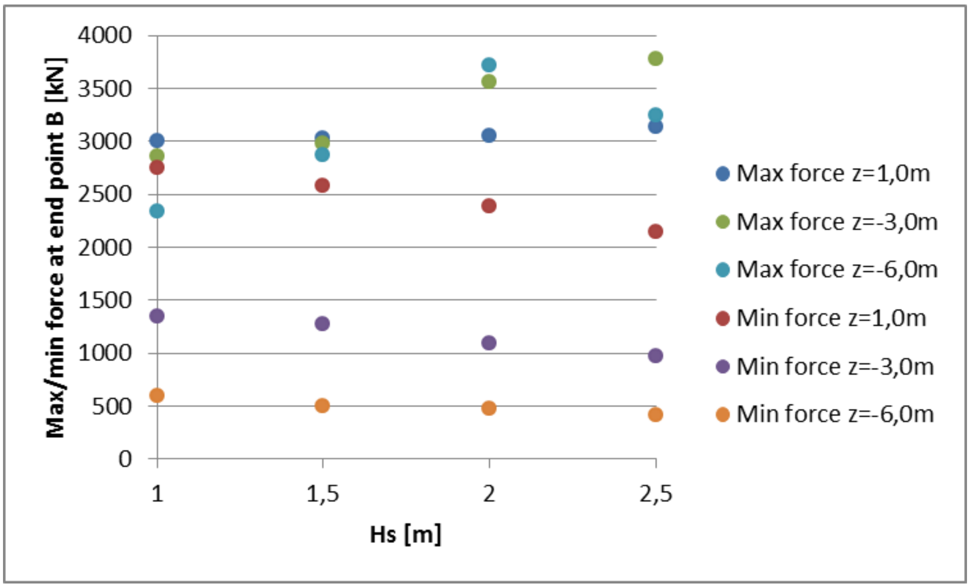

Figure 5-3 Forces at end B with different H_s

5.6. Simplified Method according to DNV – RP – H103

DNV has suggested a simplified method for calculating the loads that affect the structure through wave zone. In this chapter an overview for some selected H_s and T_p values will be presented. As we already have calculated, offshore Angola and the North Sea are both characterized as deep water. Table 12 and Table 13 are representing the most common peak periods based on the scatter diagram given in appendix 0. The peak period T_p can be related to the zero up – crossing period T_z by the following approximate relation, [21]:

$$\frac{T_z}{T_p} = 0{,}6673 + 0{,}05037\gamma - 0{,}006230\gamma^2 + 0{,}0003341\gamma^3 \quad (5\text{-}4)$$

For γ=3,3 (The North Sea) $T_p = 1{,}2859T_z$
For γ= 1,0 (offshore Angola) $T_p = 1{,}4049T_z$

From this the values for T are as presented in tables 12 and 13.

Table 12 Period T for the North Sea

The North Sea		
H_s	Tp	Tz=T
1,50	9	7,00
2,00	9	7,00
2,50	9	7,00
3,00	10	7,78

Table 13 Period T for offshore Angola

Offshore Angola		
H_s	Tp	Tz=T
1,0	10	7,12
1,5	10	7,12
2,0	10	7,12
2,5	11	7,83

We can now calculate the total force acting on the module by using the equations described by DNV – RP – H103 chapter 4, *"Lifting through wave zone – simplified method":*

$$F_{static} = Mg - \rho V g \quad (5\text{-}5)$$

$$F_{slam} = 0{,}5\rho C_s A_s v_s^2 \quad (5\text{-}6)$$

$$v_s = v_c + \sqrt{v_{ct}^2 + v_w^2} \quad (5\text{-}7)$$

$$F_{pi} = \rho\delta V g \quad (5\text{-}8)$$

$$F_M = \sqrt{[(M + A_{33})a_{ct}]^{\,2} + ([(\rho V + A_{33})a_w])^2} \quad (5\text{-}9)$$

$$F_{drag} = 0{,}5\rho C_D A_{pi} v_r^2 \quad (5\text{-}10)$$

$$v_r = v_c + \sqrt{v_{ct}^2 + v_w^2} \quad (5\text{-}11)$$

$$F_{hyd} = \sqrt{\left(F_{drag} + F_{slam}\right)^2 + \left(F_M - F_{buoyancy}\right)^2} \quad (5\text{-}12)$$

$$F_{total} = F_{static} + F_{hyd} \quad (5\text{-}13)$$

Where

M	Mass of object in air	[kg]
g	gravitational acceleration	[m/s^2]
ρ	Density of sea water	[kg/m^3]
V	volume of displaced water during different stages when passing through the water surface	[m^3]
F_{Static}	Static weight of the submerged object	[N]
F_{slam}	The characteristic slamming impact force on the parts of object that penetrate the water surface	[N]
C_s	Slamming coefficient	[No unit-]
A_s	Slamming area	[m^2]
v_s	Slamming impact velocity	[m/s]
v_c	Hook lowering velocity, typically 0,50	[m/s]
v_w	Characteristic vertical water particle velocity	[m/s]
v_{ct}	Characteristic single amplitude vertical velocity	[m/s]
F_p	The change in buoyancy force due to the wave surface elevation	[N]
δV	Change in volume of displaced water from still water surface to wave crest or wave through	[m^3]
A_{33}	Heave added mass of object	[kg]
a_{ct}	Characteristic single amplitude vertical acceleration of crane tip	[m/s^2]
a_w	Characteristic vertical water particle acceleration	[m/s^2]
F_{drag}	Characteristic drag force on an object	[N]
C_D	Drag coefficient	[No unit-]
A_{pi}	Area of submerged part of object projected on a horizontal plane	[m^2]
v_r	Characteristic vertical relative velocity between object and water particles	[m/s]
F_{hyd}	Hydrodynamic force	[N]
F_{total}	Total force on an object lowered through water surface	[N]

5.6.1. The North Sea

First we look at the North Sea area, with a selected water depth of 300m. It has already been stated that this area is deep water for the waves we consider, and we can now use the linear wave theory equations to calculate the wave amplitude velocity and acceleration for vertical direction. These results are shown in appendix A.

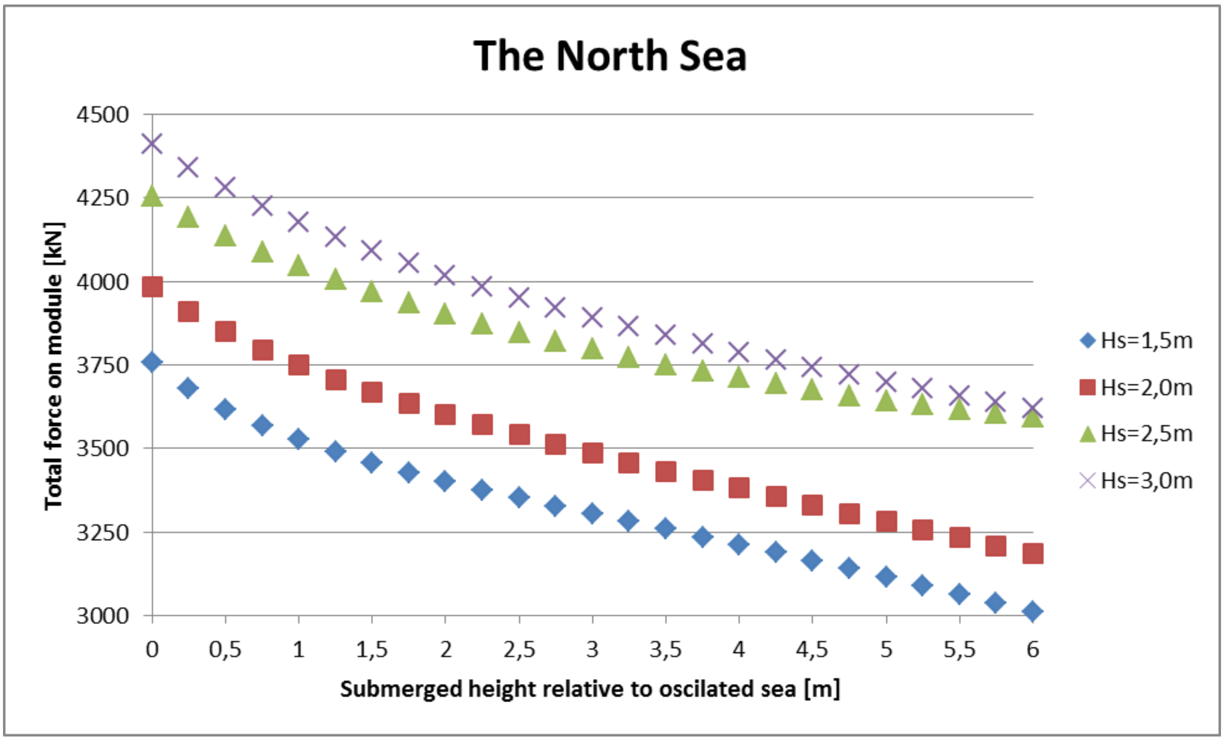

Figure 5-4 Total force acting on module in the North Sea with different Hs

In Figure 5-4 we see how the forces acting on the module change due to level of submergence and significant wave height according to the simplified method described by DNV. We see from Figure 5-4 that the forces the module are exposed to is at its highest at sea level, and then decline proportional with the level of submergence. DAF_{conv} is calculated with the following equation, [9]:

$$DAF_{conv} = \frac{F_{total\,max}}{Mg} \qquad 5\text{-}14$$

By comparing the forces obtained for the module in Figure 5-4 and the forces obtained at end point B in Table 10 we see that the forces in Figure 5-4 have a higher value. We can also observe that the limiting H_s is 2m for the simplified method, while the H_s for the analysis in chapter 5.4 is 2,5m. The simplified method is a conservative method, and is more appropriate to use to get a brief overview of what forces the module can be exposed to, and it would not be recommended to use the simplified method to decide whether an operation should be performed or not. In Table 14 and Figure 5-5 below the results are presented with respect to the significant wave height. In Table 14 we see that DAF_{conv} exceeds DAF_{static} =1,2 with a H_s =2,5m, and it is therefore not allowed to perform the lifting operation according to the acceptance criteria stated in chapter 5.1.

Table 14 Max/min force [kN] and DAF_{conv} North Sea

North Sea			
H_s	$F_{total\ max}$	$F_{total\ min}$	DAF_{conv}
1,50	3758	3011	1,13
2,00	3983	3184	1,19
2,50	4256	3594	1,28
3,00	4410	3621	1,32

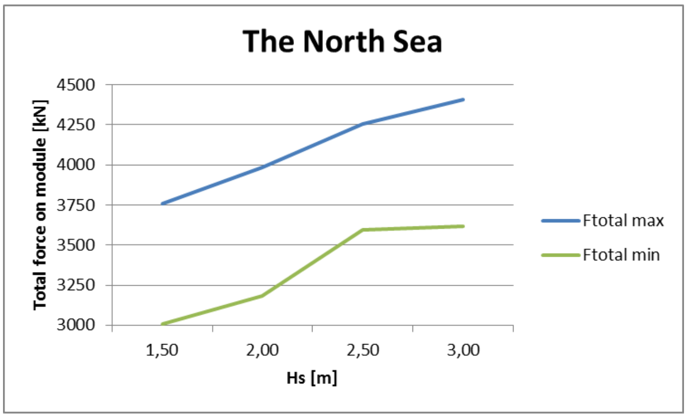

Figure 5-5 Max and Min force at module with different Hs

If we look at Table 26 in appendix D, we see that in the North Sea a $H_s \leq 2{,}0$m is not unusual, and with the periods in Table 12 we see that the most common Hs at a $H_s \leq 2{,}0$m. If we were going to base the lifting operation on the simplified method, we would have a lot of down time with waiting on weather, especially if the operation takes place in the fall – or winter months, when the weather can be considered as worst.

5.6.2. Offshore Angola

Off the coast of Angola, the water depth is decided to be 1500 m. This is stated to be deep water according to Table 9. In figure 6-6 we see how the forces on the module act in different significant wave heights. The total force is calculated according to equation 5-13 given in DNV.

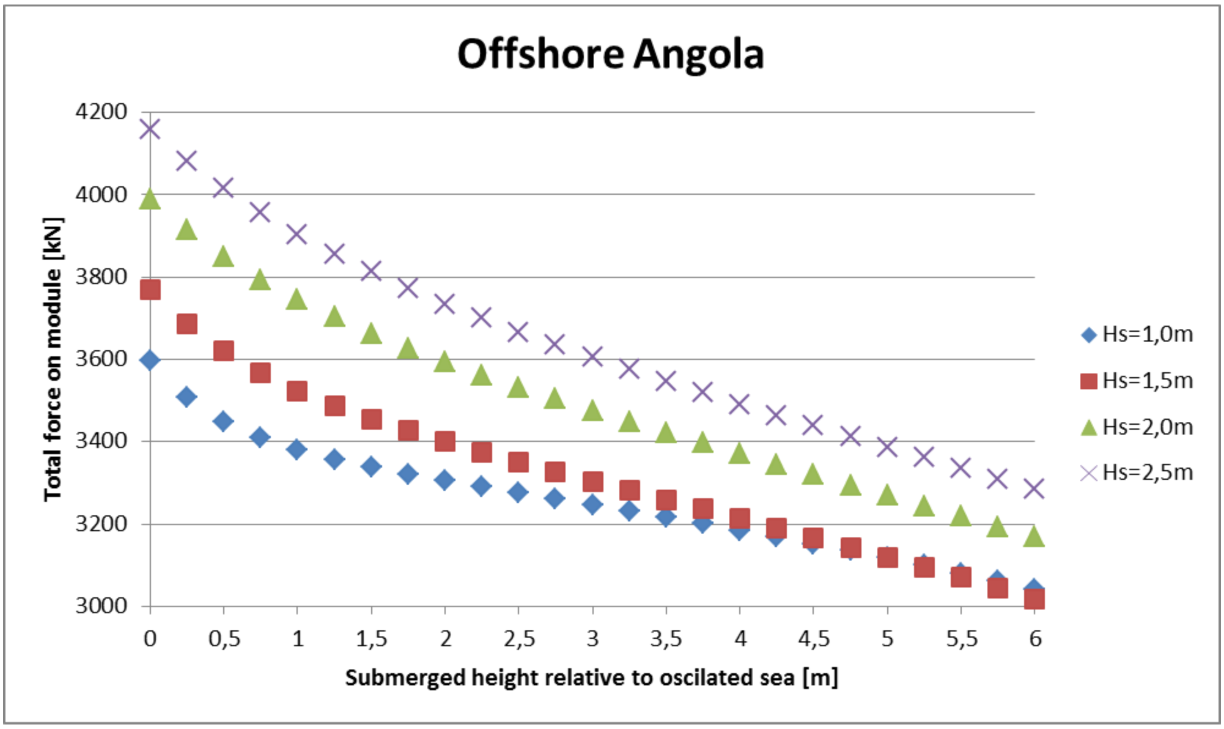

Figure 5-6 Total force acting on module offshore Angola with different Hs

Figure 5-7 shows the maximum and minimum forces acting on the module for the different Hs. The forces in Table 15 are taken as the maximum and minimum points from figure 6-6 with respect to the significant wave height, and DAF_{conv} is calculated according to equation 5-14.

Table 15 Max/min force and DAF_{conv} offshore Angola

Offshore Angola			
H_s	$F_{total\ max}$	$F_{total\ min}$	DAF_{conv}
1,0	3597	3042	1,08
1,5	3769	3018	1,13
2,0	3989	3169	1,19
2,5	4159	3285	1,25

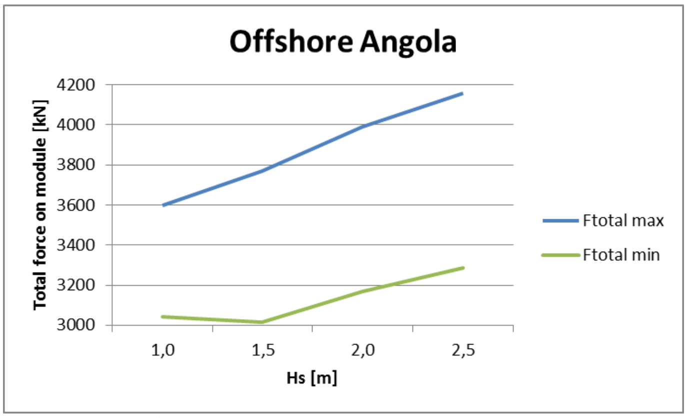

Figure 5-7 Max/min total force offshore Angola

If we compare the DAF_{conv} value in Table 15 with the DAF given in Table 2, we see that for $H_s \leq 2,5$ m the DAF_{conv} > DAF. This is a critical situations, and according to DNV we are not allowed to install the module if DAF_{conv} > DAF, so the limiting H_s for offshore Angola according to the simplified method becomes 2,0 m. By looking at Table 27 we see that the most common H_s is between 1,50 – 1,99m, meaning that there will not be many wave situations delaying the operation, but exceptions may occur.

5.6.3. Summary

We have now looked at how the forces at the module are obtained based on the simplified method suggested by DNV. From this analysis we see that the forces have a higher value in general compared to the analysis done in chapters 6.4 and 6.5. The limiting H_s for the lifting operation is lower when we use the simplified method. The simplified method is used to give a simple, but conservative, estimate of the forces acting on the module when lifting through splash zone, and the limiting H_s found in this chapter (6.6) will not be considered as the final limiting H_s. Even though we see that the forces found by using the simplified method for offshore Angola has a higher value than the analysis in chapter 5.5, the waves offshore Angola have a lower frequency compared to the North Sea. By this we can conclude that the simplified method is more accurate offshore Angola compared to the North Sea.

5.7. Extreme values

Through this analysis, we have looked into the forces that have an impact on the lifting wire and module being lifted. We have seen that the maximum forces that are most critical during this lifting operation, based on the assumptions made. In this chapter we will therefor investigate further on the extreme statistics and the upper limits.

In wave reports and statistics there have been seen that larger and/or steeper waves occur, even though the forecast says the significant wave height is for example 2,0 m. From Figure 5-8 we see that over a given time period, here 1800 seconds, there will be values that distinguish from the more frequent observed data. This analysis is based upon the maximum wave height, and we have looked into the possibility of the return of these “extreme” values for a given H_s.

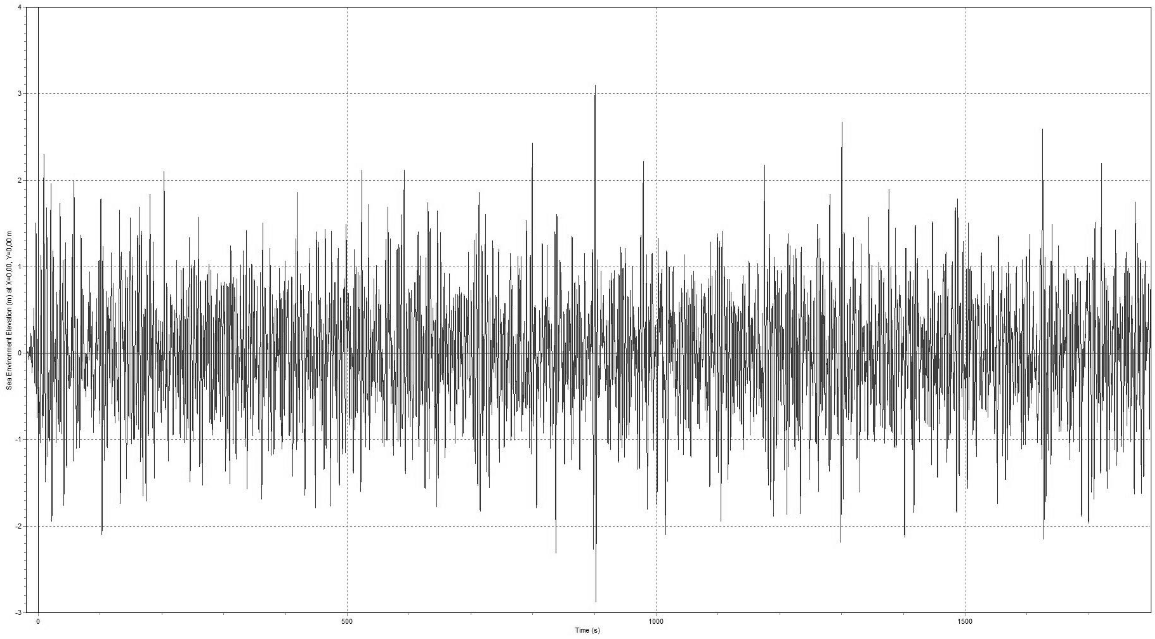

Figure 5-8 Time vs elevation H_s =2,5m

From Figure 5-8 we see that at around 900s we have a higher wave than observed for the rest of the period. It is therefore important to take the maximum wave height in the time period for the analysis into account, to get a more accurate result for the extreme values.

The analysis in this chapter has considered a 30 minutes interval containing the maximum wave height. In Figure 8-23 to Figure 8-28 in appendix G. we see how the different distributions behave with respect to significant wave height and level of submergence. In Figure 5-9 and Figure 5-10 we see how a Generalised Pareto distribution and a Weibull distribution fit a given sea state. In both figures a wave heading of 165 degrees is used, as this is assumed to give the maximum force at end B for this thesis, though with some deviations explained above in *chapter 5.4.1.*

Through chapter 5, when OrcaFlex is used, a 1800 seconds duration period have been used for the simulation to get the result presented in this chapter. A 1800 seconds duration have also been used to obtain the result presented in Figure 5-9 to Figure 5-12 below. These figures present the extreme values of the forces at end point B over a storm duration of 0,5 hours. The maximum significant wave height used for the North Sea and offshore Angola are also used in the extreme value statistics result below, H_s =3,0m and H_s=2,5m respectively. The zero up – crossing periods used are $T_{z\ North\ Sea}$= 7,5 s and $T_{z\ offshore\ Angola}$ =7,0 seconds.

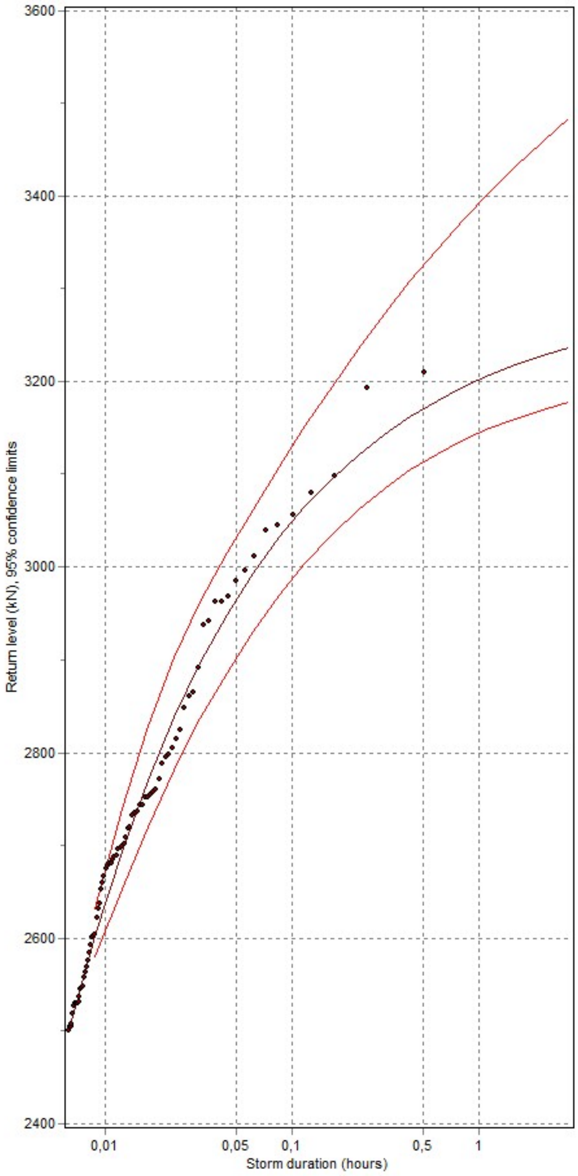

Figure 5-9 Generalised Pareto distribution for the North Sea Hs=3,0m z=-3,0m

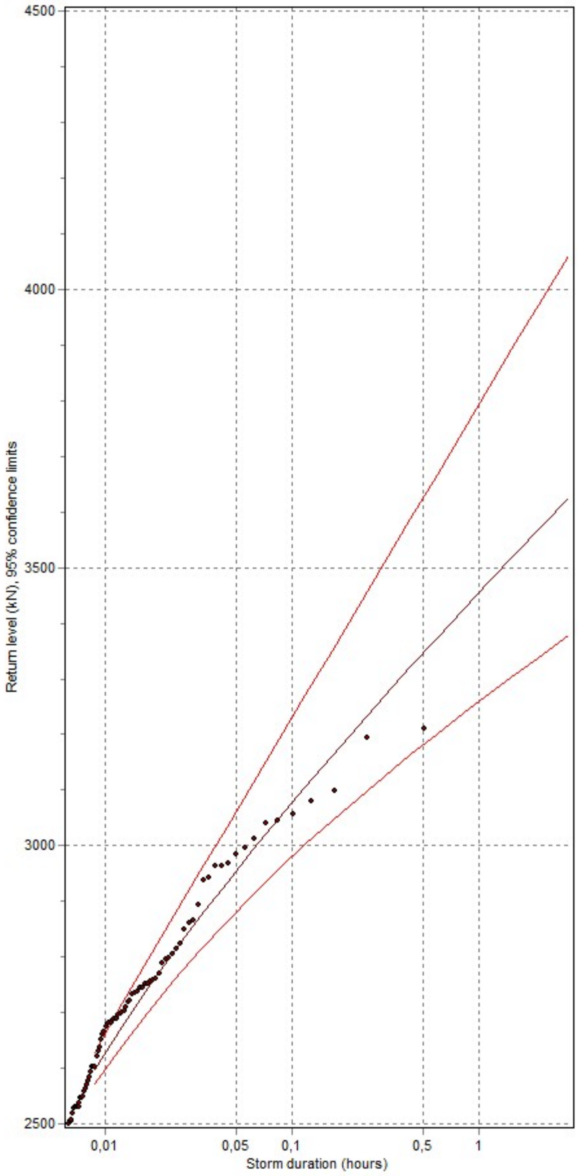

Figure 5-10 Weibull distribution for the North Sea Hs=3,0m z=-3,0m

Figure 5-9 and Figure 5-10 indicate the level of force against the return period, represented on a logarithmic scale. The black line in the middle illustrates the return level, and the red lines at the top and bottom illustrates the upper and lower 95 confidence limits respectively. Figure 5-9 and Figure 5-10 shows how the Generalised Pareto distribution and the Weibull distribution fits the maximum force obtained at end B for the North Sea. We see from the figures that Weibull distribution is a better choice for this particular location with the given significant wave height. Almost every force obtain are within the Weibull distribution range, and we can therefor say that 95% of every force that end B is exposed to can be predicted by a Weibull distribution.

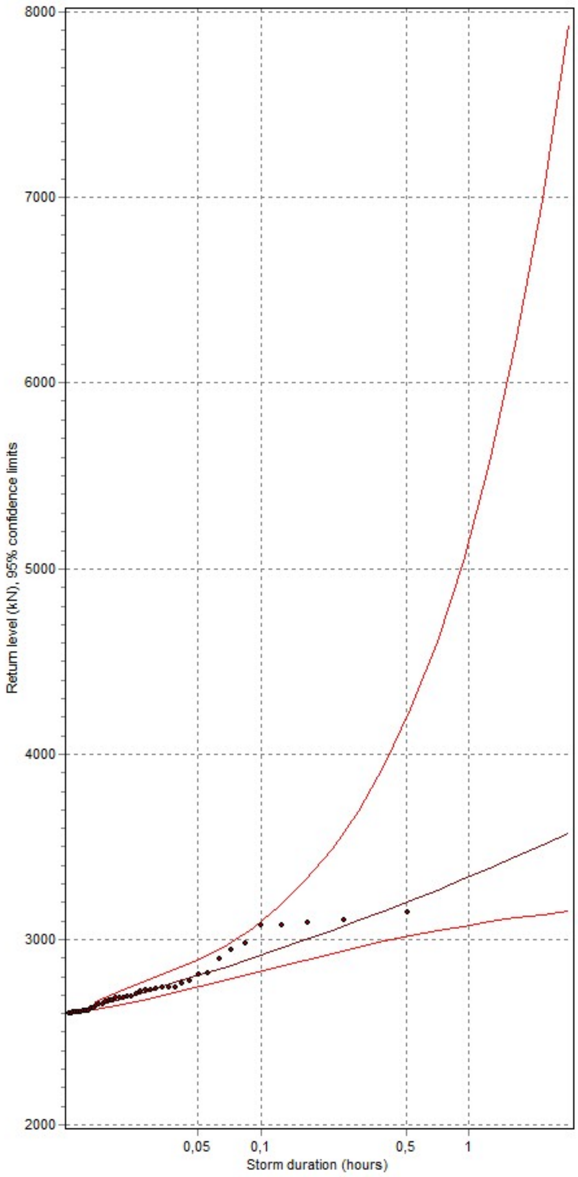

Figure 5-11 Generalized Pareto distribution Offshore Angola Hs=2,5m z=-3,0m

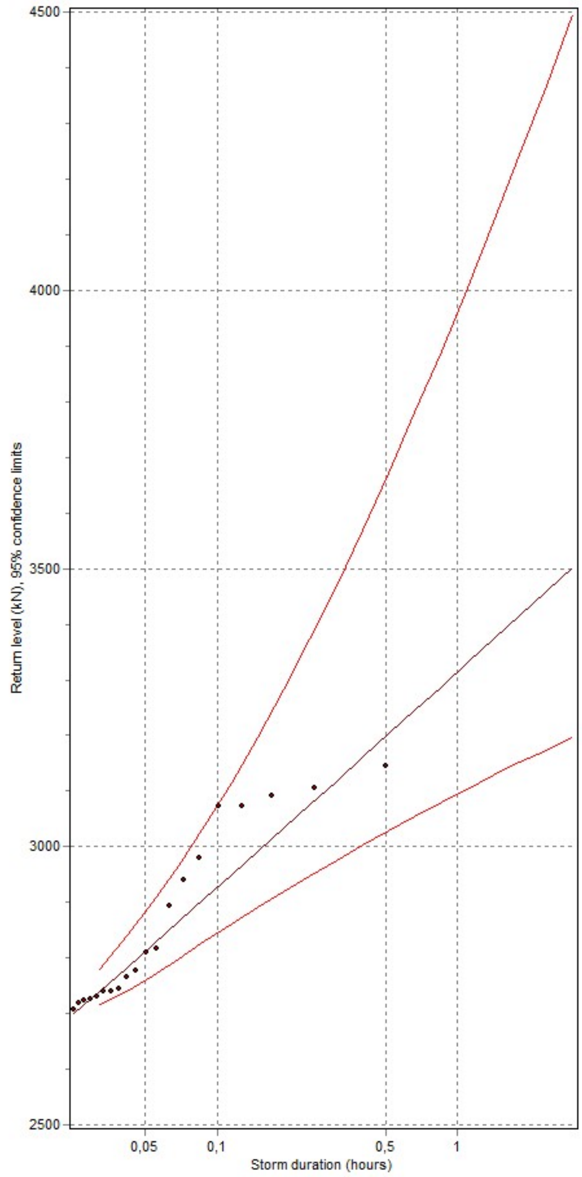

Figure 5-12 Weibull distribution Offshore Angola Hs=2,5m z=-3,0m

As for the North Sea, this applies for Offshore Angola as well. We see from Figure 5-11 and Figure 5-12 that a Weibull distribution fits the data better than a Generalised Pareto distribution. Weibull and Generalised Pareto distributions are both fitted using the maximum likelihood method. This is a standard – purpose statistical technique for fitting a given parametric distribution to a random set of data. The only difference for Weibull and Generalised Pareto distributions is the actual statistical distribution that is fitted and then used to predict the extreme values, [27]

5.8. Vessel motions

As we now have found these results for the module and crane wire, we are going to take a look into the vessel motion of Viking TBN. The vessel motions are obtained from OrcaFlex, by looking at the largest force acting on the wire and module. We see from Figure 5-2 and Figure 5-3 that for the North Sea we have the largest forces at end B when H_s= 3,0m and for offshore Angola we have the largest forces when H_s=2,5m. This is the H_s we are going to investigate for vessel motion at this location. The wave direction used is 165 degrees, this is shown in Figure 5-1. Further we are going to compare how the vessel motion differentiates when Viking TBN is localized in the North Sea compared to offshore Angola.

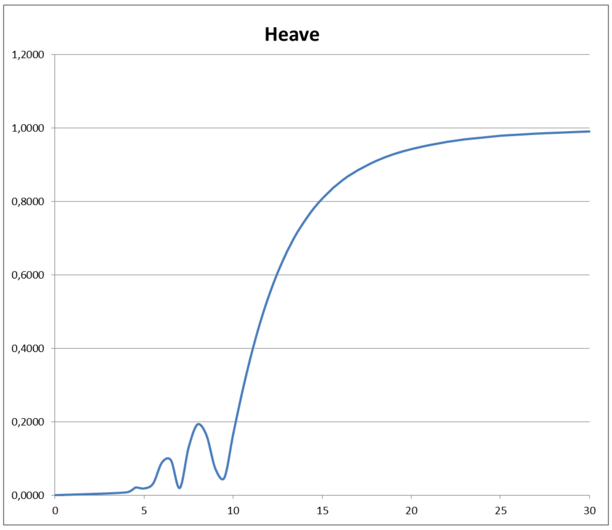

Figure 5-13 RAO Heave

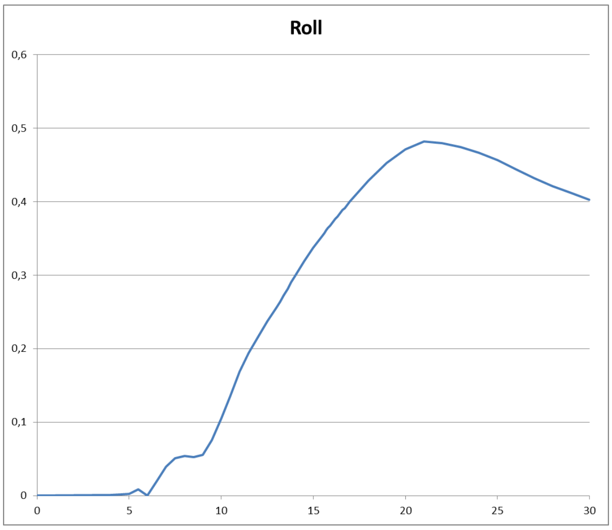

Figure 5-14 RAO Roll

Figure 5-13 and Figure 5-14 shows Viking TBN`s roll and heave motion at a random heading. Due to confidentiality of the RAO information the actual heading will not be given in the text. From these figures and comparison with the forces acting at end point B, it is observed that the forces in general have the same peaks as for the RAO.

From Table 10 and Table 11 we see which H_s have the biggest influence on the forces acting at different wave directions. From this table we find the results for Viking TBN`s vessel motion with the H_s giving the maximum forces at end B and the corresponding zero up – crossing period given in appendix G. For the North sea T_z = 8,5 seconds, while for offshore Angola T_z=7,0 seconds, based on the average zero up – crossing period giving maximum force at end point B. The module have the same level of submergence, z=-3,0m, in both cases. As we see from Figure 5-15 to Figure 5-18 we see that the values for the North Sea have a lower frequency than for offshore Angola. This is because of the long periods offshore Angola. The values obtained for heave and roll offshore Angola are resulting from H_s=2,5m, while for the North Sea the values for heave and roll are resulting from H_s=3,0m. It is understood from this that it is more than just the wave height that has an influence on the motion of a vessel, also wave period and water depth has a role when looking at these motions.

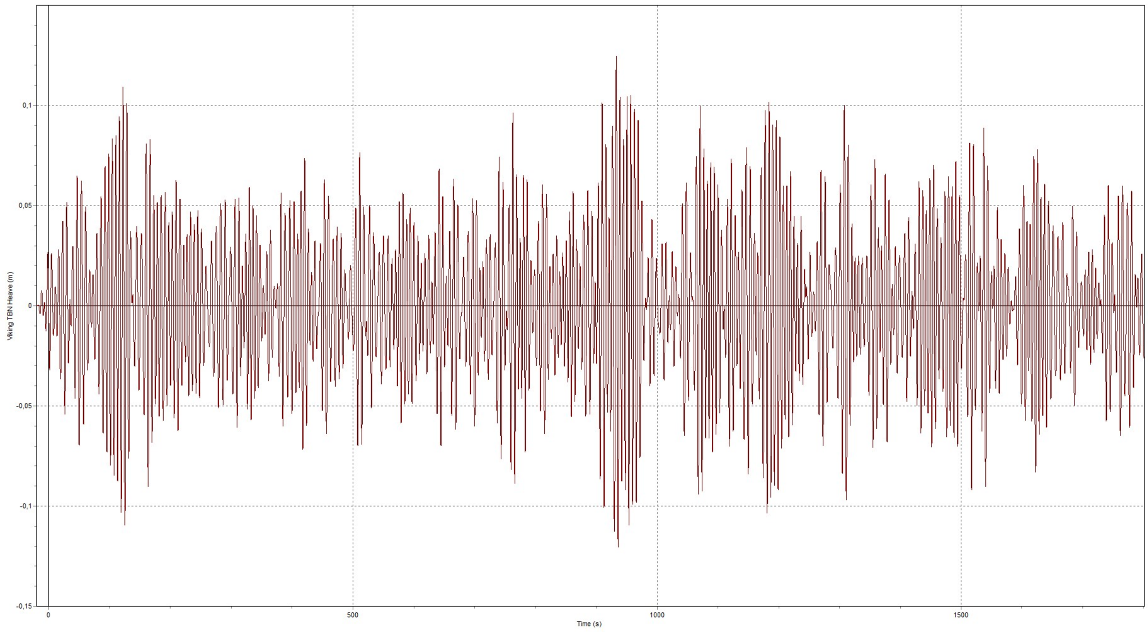

Figure 5-15 Heave for Viking TBN obtained in the North Sea

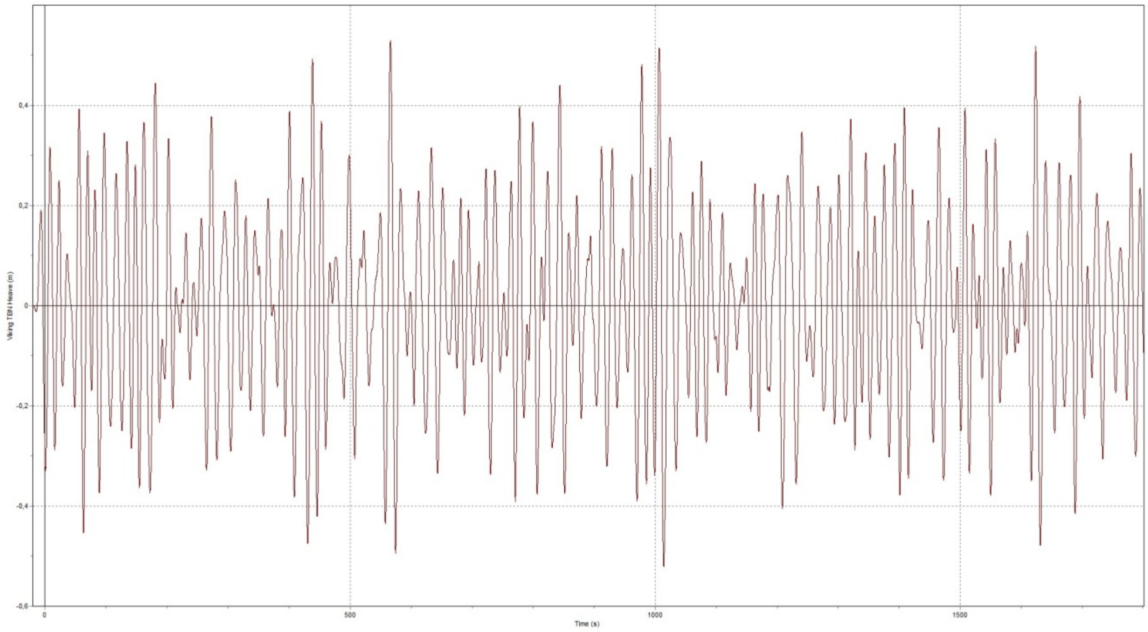

Figure 5-16 Heave for Viking TBN obtained offshore Angola

From Figure 5-15 to Figure 5-18 the heave and roll obtained for Viking TBN in the North Sea and offshore Angola are presented. From these figures it is observed that the heave and roll motions have a higher frequency offshore Angola compared to the location in the North Sea. This is one of the characteristics for the location offshore Angola due to lower waves with longer periods discussed in chapter 3 and 4. It is also known that the water depth offshore Angola is large compared to the North Sea location, which contribute to smaller waves with longer periods.

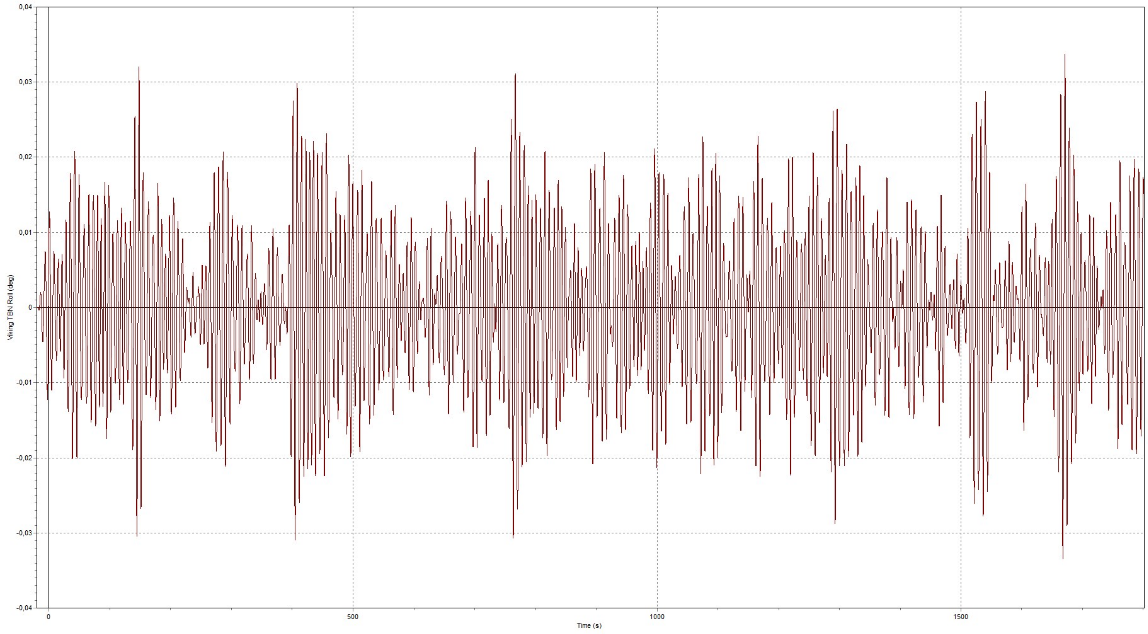

Figure 5-17 Roll for Viking TBN obtained in the North Sea

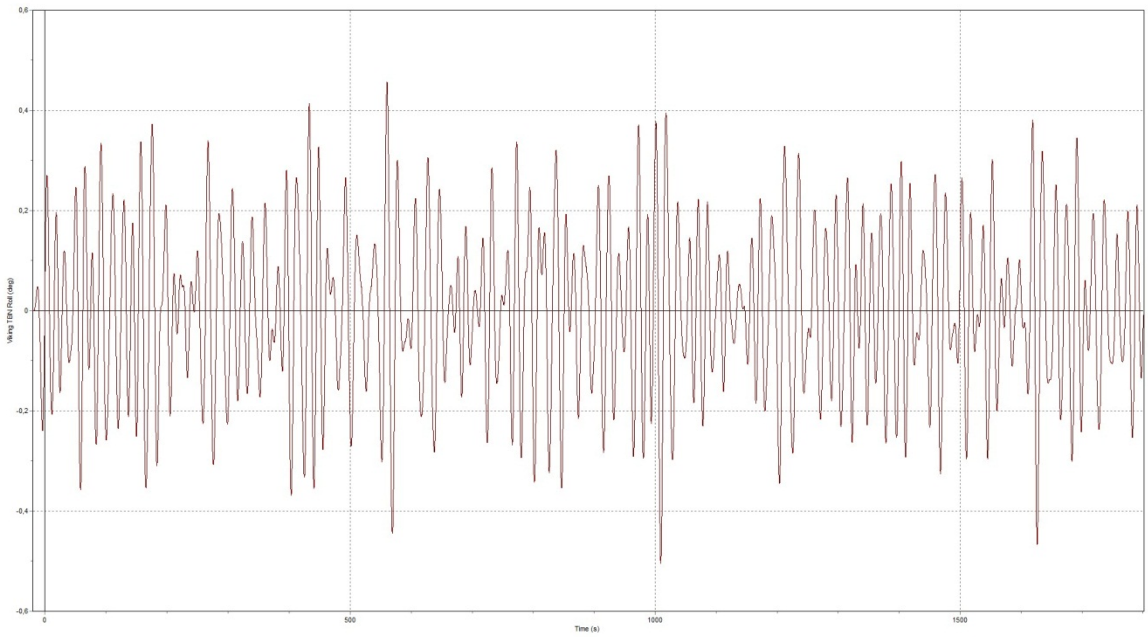

Figure 5-18 Roll for Viking TBN obtained offshore Angola

5.9. Summary

The objective of this thesis was to compare two different geographical locations with respect to offshore lifting operations and the considerations around this. Hydrodynamics, alpha factor, environmental conditions, vessel motion and forces acting on the module and crane wire have been discussed.

The North Sea and offshore Angola are the two locations that have been considered throughout this thesis. The environment in the North Sea can be seen as more harsh compared to offshore Angola. Off the coast of Angola, and West Africa in general, it has been shown that the waves are calmer, they are lower in height but longer in period compared to the waves obtained in the North Sea. This is also supported by the scatter diagrams in appendix D. In Table 26 and Table 27 we see that the periods are longer and the significant wave height are lower for offshore Angola compared to the North Sea, as already stated.

The force acting at end point B and the module can also be considered lower for offshore Angola compared to the North Sea, where we have a limitation for the lifting operation a a Hs=2,5m before DAF_{conv} is exceeding 1,2. Offshore Angola we can lift at Hs=3,0m before DAF_{conv} exceeds 1,2, and as it is shown in Table 27 a $H_s \leq 2,5$m most likely will not occur. In the North Sea there is a higher risk for obtaining a $H_s \leq 2,5$m. The reason for a lower significant wave height and longer wave periods offshore Angola is a result of the long travel distance and deep water depths in this area, (for this analysis water depths of 1500m and 300m are used for Offshore Angola and the North Sea, respectively).

With the differences in the wave conditions for these two locations we see that the motion of the vessel is also different for these locations. In offshore Angola Viking TBN obtains a higher frequency of heave and roll than obtained for the North Sea. This is a result of the differences in the wave conditions explained above and it shall be noted that for offshore Angola we have a second wave with heading 90 degrees relative to the vessel, Figure 5-1, called swell. The forces at these two locations are also following the same pattern as the vessel`s heave and roll. By comparing Figure 5-13 and Figure 5-14 with the forces acting at end point B of the wire, we see that they have peaks around the same period for both locations. This will be expected because of the importance of the vessel`s RAO.

6. Conclusion

Through this thesis several topics related to marine operations have been discussed. Environmental conditions are one of the topics that have been mostly focused on, and these are among the most critical factors that influence a marine operation, including offshore lift.

Lifting through the splash zone is a sensitive stage during subsea lift. In this thesis three different levels of submergence during subsea lift through splash zone have been evaluated and analyzed; when the module is in air, when the module is partly submerged and when the module is fully submerged. We have seen that the forces on the module and crane wire changes through the lifting operation through the splash zone, and that the DAF_{conv} at a given H_s exceeds the DAF_{static} for the given sea state, resulting in a critical phase of the operation. We have discussed that when DAF_{conv} exceeds DAF_{static} we are not allowed to continue the operation, and have to wait on the weather. Waiting on weather is something that every company wants to avoid, due to the cost of this.

Table 16 below gives an overview over the maximum forces at end point B. We see here that the forces for the North Sea are higher compared to offshore Angola. We have discussed that the wave are calmer offshore Angola compared to the North Sea, and it is therefore natural that the forces in the North Sea have a higher value.

Table 16 Results of forces in crane wire

North Sea		
Hs	Level of Submergence, Z	Max force [kN]
1,5	1,0m	3019
2,0	-6,0m	3174
2,5	-6,0m	3708
3,0	-3,0m	4146
Offshore Angola		
Hs	Level of Submergence, Z	Max force
1,0	1,0m	3009
1,5	1,0m	3024
2,0	-6,0m	3719
2,5	-3,0m	3781

In chapter 5.8 we discussed vessel motions. Even though the forces are higher in the North Sea, we see that the heave and roll motions are higher in offshore Angola compared to the North Sea,Figure 5-15 to Figure 5-18,and this also influence the lifting operation, and marine operations in general.

The alpha factor described in chapter 4.1 is not taken into account in these results, and needs to be calculated before a lifting operation takes place.

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All links verified 24.06.13

8. APPENDIX

A. Simplified method according to DNV – RP – H103

In this appendix we have an overview over the results computed using the simplified method described in DNV – RP – H103. The forces that are calculated and presented in Table 17 are calculated using the equations described in chapter 5.6. In Table 17 we see how the forces change due to submergence of the module. The height of the module is 6,0m and weight in air is 340T, given in Table 1.

Table 17 Data for module

Submerged height relative to oscillated sea surface [m]	Displaced Volume of water [m^3]	Buoyancy force $\mathbf{F_b(t)}$ [kN]	Weight of Module in air $\mathbf{W_0}$ [kN]	Submerged weight of module **W(t)** [kN]	Submerged weight [T]	Added Mass Submerged [T]
0,00	0	0	3335	3335	340	0
0,25	9	90	3335	3245	331	3
0,50	18	181	3335	3154	322	6
0,75	27	271	3335	3064	312	9
1,00	36	362	3335	2973	303	13
1,25	45	452	3335	2883	294	16
1,50	54	543	3335	2792	285	19
1,75	63	633	3335	2702	275	22
2,00	72	724	3335	2611	266	25
2,25	81	814	3335	2521	257	28
2,50	90	905	3335	2430	248	31
2,75	99	995	3335	2340	239	35
3,00	108	1086	3335	2249	229	38
3,25	117	1176	3335	2159	220	41
3,50	126	1267	3335	2068	211	44
3,75	135	1357	3335	1978	202	47
4,00	144	1448	3335	1887	192	50
4,25	153	1538	3335	1797	183	53
4,50	162	1629	3335	1706	174	56
4,75	171	1719	3335	1616	165	60
5,00	180	1810	3335	1525	156	63
5,25	189	1900	3335	1435	146	66
5,50	198	1991	3335	1344	137	69
5,75	207	2081	3335	1254	128	72
6,00	216	2172	3335	1163	119	75

In Table 18 below the input data for velocities and acceleration are given. They are calculated by the formulas given in chapter 5.6. A lowering velocity of 0,5m/s is used, recommended by DNV – RP – H103, chapter 4. Further in Table 19 and Table 20 some results and input data are presented. In Table 20 we have used the linear wave theory for deep – water situations to calculate the horizontal velocity and acceleration.

Table 18 Input data for simplified method

The North Sea				
Hs	**1,5m**	**2,0m**	**2,5m**	**3,0m**
v_{ct}	0,1871	0,2494	0,3117	0,5406
v_c	0,5	0,5	0,5	0,5
a_{ct}	0,1319	0,1759	0,22	0,3345
C_D	2,3	2,3	2,3	2,3
C_A	0,68	0,68	0,68	0,68
C_S	5	5	5	5
C_M	1,68	1,68	1,68	1,68
Offshore Angola				
Hs	**1,0m**	**1,5m**	**2,0m**	**2,5m**
v_{ct}	0,3114	0,3655	0,428	0,6148
v_c	0,5	0,5	0,5	0,5
a_{ct}	0,1558	0,1855	0,2157	0,2761
C_D	2,3	2,3	2,3	2,3
C_A	0,68	0,68	0,68	0,68
C_S	5	5	5	5
C_M	1,68	1,68	1,68	1,68

Table 19 Result max/min force at module simplified method

North Sea			Offshore Angola		
H_s	$F_{total\ max}$	$F_{total\ min}$	H_s	$F_{total\ max}$	$F_{total\ max}$
1,50	3758	3011	1,0	3597	3042
2,00	3983	3184	1,5	3769	3018
2,50	4256	3594	2,0	3989	3169
3,00	4410	3621	2,5	4159	3285

Table 20 Linear Wave Theory input data and some results

North Sea							
H_s	H_{max}	$d_{water\ depth}$	ω	$T=T_z$	ξ0=Hmax/2	L	k=2π/L
1,5	2,79	300	0,8976	7,00	1,40	76,5	0,0821
2,0	3,72		0,8976	7,00	1,86	76,5	0,0821
2,5	4,65		0,8976	7,00	2,33	76,5	0,0821
3,0	5,58		0,8076	7,78	2,79	94,5	0,0665
Offshore Angola							
H_s	H_{max}	$d_{water\ depth}$	ω	$T=T_z$	ξ0=Hmax/2	L	k=2π/L
1,0	1,86	1500	0,8825	7,12	0,93	79,1	0,0794
1,5	2,79		0,8825	7,12	1,395	79,1	0,0794
2,0	3,72		0,8825	7,12	1,86	79,1	0,0794
2,5	4,65		0,8025	7,83	2,325	95,7	0,0656

Figure 8-1 to Figure 8-8 shows how the inertia, slam and drag force changes due to submergence level according to DNV `s recommendation "Simplified Method".

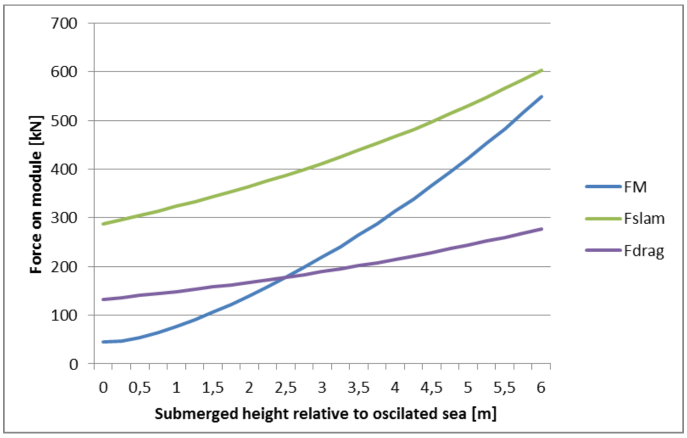


Figure 8-1 Hs = 1,5m North Sea

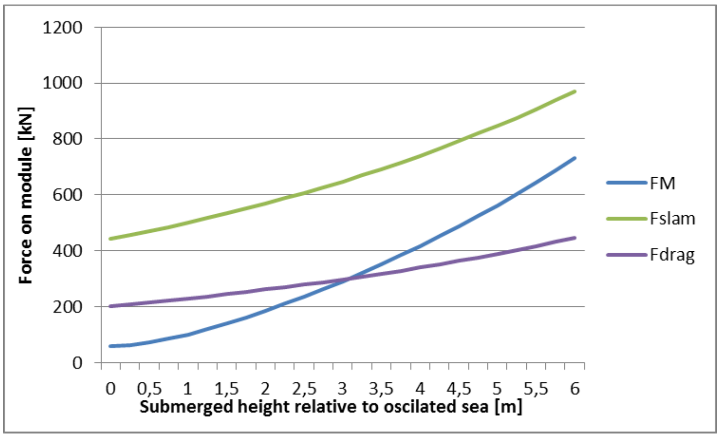


Figure 8-2 Hs=2,0m North Sea

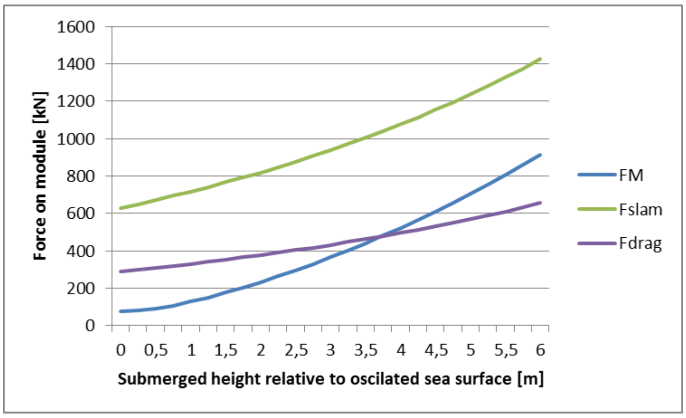


Figure 8-3 Hs=2,5m North Sea

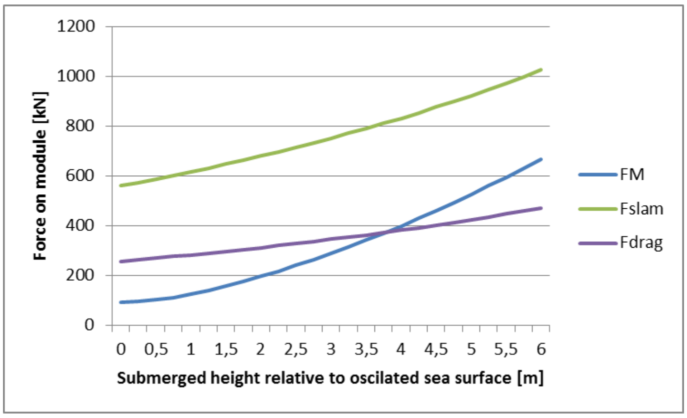


Figure 8-4 Hs=3,0m North Sea

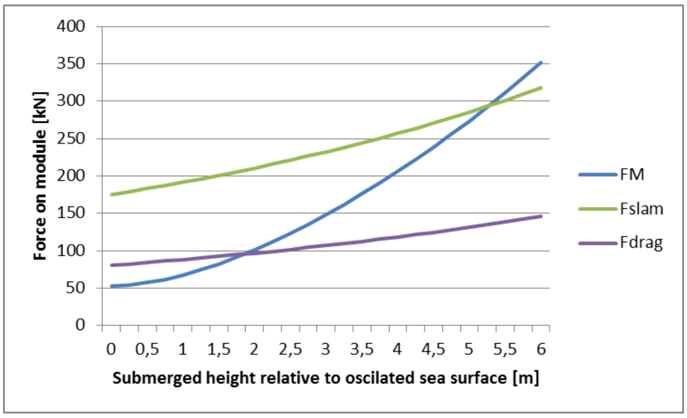


Figure 8-5 Hs=1,0m Offshore Angola

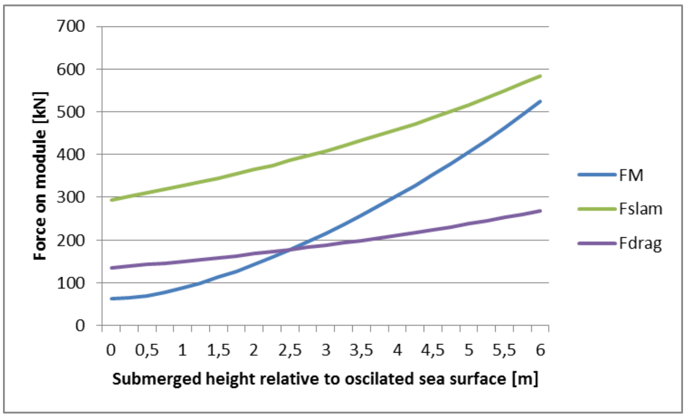


Figure 8-6 Hs=1,5m Offshore Angola

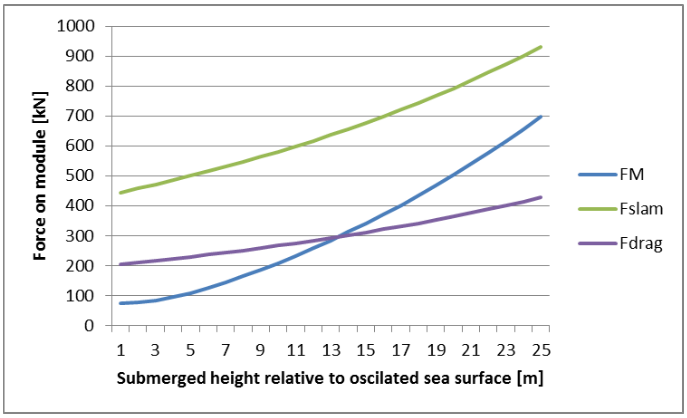


Figure 8-7 Hs=2,0m Offshore Angola

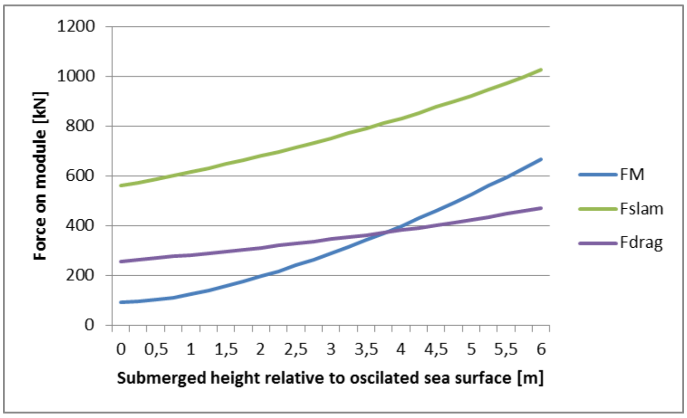


Figure 8-8 Hs=2,5m Offshore Angola

B. DATA SHEET

Appendix B contains the data sheet for Stanislav Yudin and Heerema Hermod. They are found at www.subsea7.com and http://www.theoffshorepartners.com/references.html#!prettyPhoto respectively.

*Stanislav Yudin**

The HLV *Stanislav Yudin* is a state-of-the-art crane vessel operated by a dedicated and experienced crew.

Type:
Heavy Lift

Classification:
DNV 1A1 crane vessel

The vessel has a 2,500mt revolving crane, over 2,500m² of free deck space and 20m of headroom between the crane boom in its boom rest and the vessel's deck. Lift heights of 78.3m for the 2,500mt main hook and approximately 100.7m for the 500mt auxiliary hook enable the vessel to undertake an impressive range of projects. The crane's ability to revolve adds to the workability of the vessel and provides full control of the heavy-lift operation, which reduces the offshore risks significantly and therefore safeguards the project investment.

The vessel has an 8.9m working draft. Its minimum draft of only 5.5m enables it to gain access to most fabrication yards. The vessel is self-propelled with a high sailing speed, which provides rapid availability for our clients.

* Operated by Seaway Heavy Lifting under JV.

seabed-to-surface

Stanislav Yudin

January 2012

General Description

Type	Heavy Lift
Operator	Seaway Heavy Lifting
Flag	Cyprus
Built	1985, Wartsila, Finland
Classification	DNV 1A1 crane vessel

Principal Dimensions

Length overall	183.2m
Length of vessel	173.1m
Breadth	36.0m
Depth from deck	13.0m
Draft	5.5 – 8.9m
Gross tonnage	24,822t
Deck load	>5,000t
Deck space	2,560m²
Free deck height	20m (to boom in rest)

Power and Propulsion

Main engines (three)	4,095kW
Generators (three)	4,860kVA; 600V; 50Hz
Main thrusters (two)	2,800kW, fixed pitch, 360°
Bow thrusters (two)	880kW, tunnelled
Emergency power	200kW; 380V; 50Hz
Maximum transit speed	12 knots

Ballast System

Ballasting tanks	24,100m³
Anti-heeling tanks	11,800m³
Ballast pumps (six)	2,850m³/h
Anti-heeling pumps (two)	12,800m³/h

Mooring System

Eight-point system

Anchors	10t Delta Flipper
Maximum pull	1,800kN
Maximum braking capacity	2,590kN

Accommodation

143 people

Helideck

Equipped for S-61

Cranes

Make	Gusto
Main hoist	
Maximum revolving capacity	2,500mt
Maximum lift height above water level	78.3m
Auxiliary hoist	
Maximum capacity	500mt
Maximum lift height above water level	100.3m

www.subsea7.com

subsea 7

PDS-08067

Client / Operator	:	Heerema Marine Contractors
Project name	:	Semi Submersible Construction Vessel HERMOD
Construction yard	:	N/A
Country	:	The Netherlands
Period	:	Aug 2008
Category	:	Engineering and consultancy

PROJECT DESCRIPTION

Heerema Marine Contractors requested engineering services from The Offshore Partners, for the preparation and execution of a Light Ship Weight survey, onboard the Semi Submersible Construction Vessel HERMOD.

TECHNICAL DATA

Principal Particulars

Length over all	:	154.00	m
Breadth moulded	:	86.00	m
Displacement	:	100,000	t
Operating draft	:	11.50 – 28.20	m
Total installed power	:	19,400	kW
DP system	:	N/A	-
SB crane	:	5,000	st
PS crane	:	4,000	st
Speed	:	6.0	kts
Accommodation	:	336	pers.

OUR SERVICES

The Offshore Partners provided the following services:

- Preparation, survey, execution and calculation of Light Ship Weight survey, with the following deliverables:
  - Procedure for class and authorities
  - Weight survey list
  - Calculations
  - Report

The Offshore Partners BV | Sluisjesdijk 155 | 3087AG Rotterdam | The Netherlands | Tel.: +31 (0)10 491 41 31 | www.theoffshorepartners.com

C. Alpha Factor

In appendix C tables of how and when the given alpha factor should be used, recommended by DNV. The alpha factor should be used as a factor for uncertainty in the weather forecast. This is explained in chapter 4.2. The alpha factor has not been calculated in chapter 5, but needs to be taken into account before a marine operation is performed.

Table 21 Alpha factor for waves in the North Sea and the Norwegian Sea, base case, [25].

Operational Period [h]	Design Wave Height [m]						
	H_s=1	1<H_s<2	H_s=2	2<H_s<4	H_s=4	4<H_s<6	H_s≥6
T_{POP}≤12	0,65	Linear interpolation	0,76	Linear interpolation	0,79	Linear interpolation	0,80
T_{POP}≤24	0,63		0,73		0,76		0,78
T_{POP}≤36	0,62		0,71		0,73		0,76
T_{POP}≤48	0,60		0,68		0,71		0,74
T_{POP}≤72	0,55		0,63		0,68		0,72

Table 22 Alpha factor for waves in the North Sea and the Norwegian sea, no meteorologist on site, highest forecasted wave height from at least two independent sources is considered,[25].

Operational Period [h]	Design Wave Height [m]						
	H_s=1	1<H_s<2	H_s=2	2<H_s<4	H_s=4	4<H_s<6	H_s≥6
T_{POP}≤12	0,68	Linear interpolation	0,80	Linear interpolation	0,83	Linear interpolation	0,84
T_{POP}≤24	0,66		0,77		0,80		0,82
T_{POP}≤36	0,65		0,75		0,77		0,80
T_{POP}≤48	0,63		0,71		0,75		0,78
T_{POP}≤72	0,58		0,66		0,71		0,76

Table 23 Alpha factor for waves in the North Sea and Norwegian Sea, meteorologist on site, several forecast sources are considered by meteorologist,[25].

Operational Period [h]	Design Wave Height [m]						
	H_s=1	1<H_s<2	H_s=2	2<H_s<4	H_s=4	4<H_s<6	H_s≥6
T_{POP}≤12	0,72	Linear interpolation	0,84	Linear interpolation	0,87	Linear interpolation	0,88
T_{POP}≤24	0,69		0,80		0,84		0,86
T_{POP}≤36	0,68		0,78		0,80		0,84
T_{POP}≤48	0,66		0,75		0,78		0,81
T_{POP}≤72	0,61		0,69		0,75		0,79

Table 24 Alpha factor for waves in the North Sea and Norwegian Sea, weather forecast calibrated based on monitoring of the weather, [25]

Operational Period [h]	Design Wave Height [m]						
	$H_s=1$	$1<H_s<2$	$H_s=2$	$2<H_s<4$	$H_s=4$	$4<H_s<6$	$H_s\geq6$
$T_{POP}\leq4$	0,90	Linear interpolation	0,95	Linear interpolation	1,0	Linear interpolation	1,0
$T_{POP}\leq12$	0,72		0,84		0,87		0,88
$T_{POP}\leq24$	0,66		0,77		0,80		0,82
$T_{POP}>24$	According to Table 21 and Table 22 as applicable						

Table 25 Alpha factor for waves in the North Sea and Norwegian Sea, meteorologist on site, monitoring of weather, [25].

Operational Period [h]	Design Wave Height [m]						
	$H_s=1$	$1<H_s<2$	$H_s=2$	$2<H_s<4$	$H_s=4$	$4<H_s<6$	$H_s\geq6$
$T_{POP}\leq4$	0,90	Linear interpolation	0,95	Linear interpolation	1,00	Linear interpolation	1,00
$T_{POP}\leq12$	0,78		0,91		0,95		0,96
$T_{POP}\leq24$	0,72		0,84		0,87		0,90
$T_{POP}>24$	According to table Table 23						

D. Scatter Diagrams

A scatter diagram is used to analyse the relationship between two variables. In this appendix the relationship between significant wave height and peak periods for the North Sea and offshore Angola is presented in Table 26 and Table 27 below respectively. They are used to further analyse the differences in these two geographical areas, discussed in chapter 5.

Table 26 Scatter Diagram Northern North Sea [10]

H_s[m]	T_P[s]																		
	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	>20
0,5	18	15	123	113	110	390	260	91	38	42	32	3	19	13	9	1	3	2	7
1,0	16	49	675	433	589	1442	1802	959	273	344	125	33	64	29	13	1	7	1	6
1,5	5	32	417	893	1107	1486	2757	1786	636	731	299	121	92	43	18	10	5	2	13
2,0	1	0	102	741	1290	1496	2575	1968	780	868	492	200	116	51	31	8	4	4	8
2,5	0	0	9	256	969	1303	2045	1892	803	941	484	181	157	58	23	19	5	1	8
3,0	0	0	1	45	438	1029	1702	1898	705	957	560	218	196	92	40	11	4	2	5
3,5	0	0	1	4	124	650	1169	1701	647	865	465	237	162	100	36	12	6	1	5
4,0	0	0	2	0	33	270	780	1369	573	868	427	193	157	91	51	13	3	0	1
4,5	0	0	0	0	3	90	459	1017	466	761	380	127	137	86	31	23	6	5	0
5,0	0	0	0	0	0	15	228	647	408	737	354	119	96	50	32	18	2	4	1
5,5	0	0	0	0	0	2	68	337	363	580	283	94	92	31	24	10	6	2	0
6,0	0	0	0	0	0	1	20	166	221	418	307	63	76	24	13	9	4	0	0
6,5	0	0	0	0	0	0	5	50	140	260	257	59	49	20	12	4	2	2	2
7,0	0	0	0	0	0	0	0	23	90	180	193	41	53	20	5	3	3	0	0
7,5	0	0	0	0	0	0	0	6	25	93	121	45	46	17	5	5	0	1	0
8,0	0	0	0	0	0	0	0	3	14	50	84	26	47	11	6	0	1	0	0
8,5	0	0	0	0	0	0	0	0	7	25	45	23	25	20	8	0	0	0	0
9,0	0	0	0	0	0	0	0	1	2	12	30	22	20	19	0	0	0	0	0
9,5	0	0	0	0	0	0	0	0	1	2	20	21	14	7	1	1	0	1	0
10,0	0	0	0	0	0	0	0	0	0	2	5	4	21	6	2	0	0	0	0
10,5	0	0	0	0	0	0	0	0	0	3	4	8	9	12	2	0	0	0	0
11,0	0	0	0	0	0	0	0	0	0	0	2	0	4	3	1	0	1	0	0
11,5	0	0	0	0	0	0	0	0	0	0	2	1	2	3	0	0	0	0	0
12,0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	1	0	0	0	0
12,5	0	0	0	0	0	0	0	0		0	0	0	0	1	0	0	0	0	0
13,0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

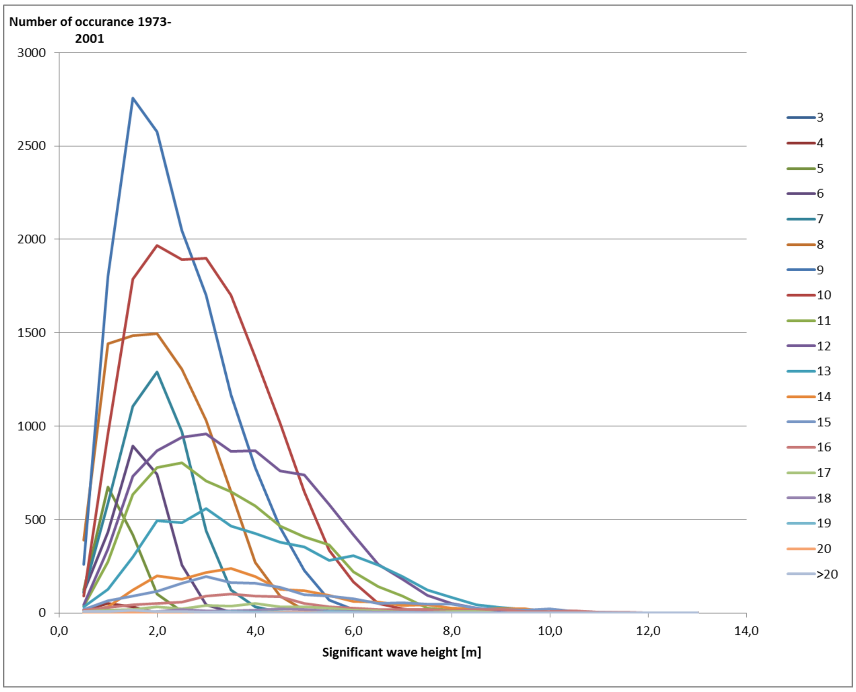


Figure 8-9 Wave Heights with different peak periods

Table 27 Scatter diagram offshore Angola [19]

Significant wave height (m)	Peak period Tp											
	0	2	4	6	8	10	12	14	16	18	20	22	>24
0,00-0,49	0	0	0	7	21	28	42	42	0	0	0	0	0
0,50-0,99	0	7	694	2764	1264	3590	3833	2569	812	236	90	7	0
1,00-1,49	0	0	417	4361	7277	7978	7902	6381	1993	576	132	42	0
1,50-1,99	0	0	7	42	1986	4013	3305	2444	1048	375	83	7	0
2,00-2,49	0	0	0	0	49	653	923	729	236	69	7	0	0
2,50-2,99	0	0	0	0	0	28	97	160	69	21	0	0	0
3,00-3,49	0	0	0	0	0	0	0	14	7	0	0	0	0
>3,50	0	0	0	0	0	0	0	0	0	0	0	0	0

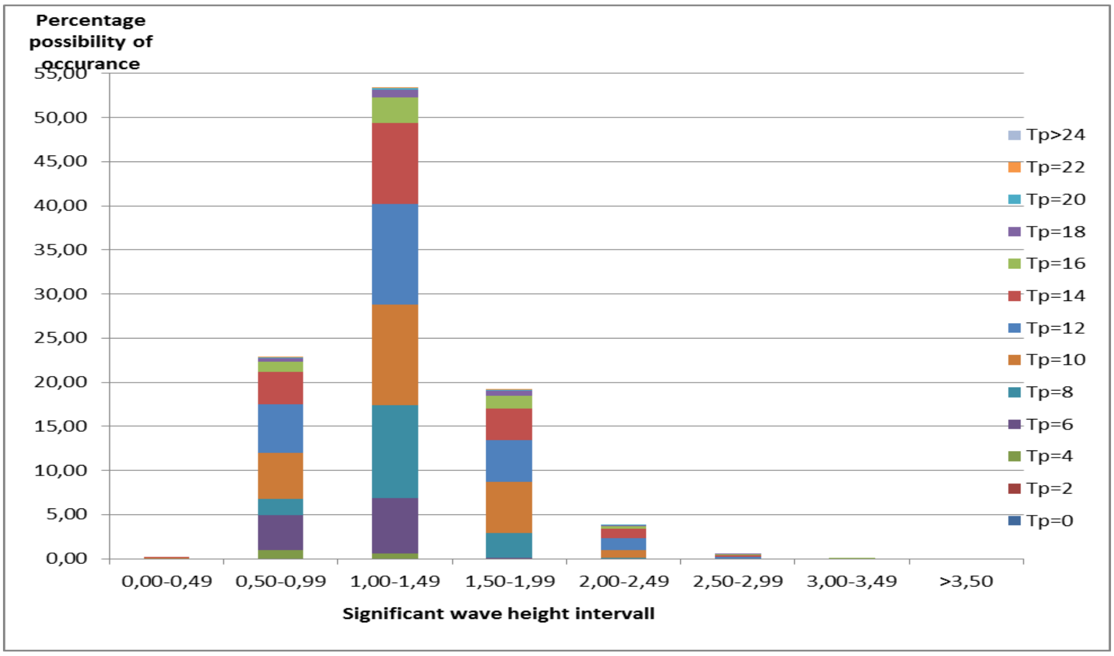


Figure 8-10 Wave Height vs. Peak Period offshore Angola

E. JONSWAP Wave Spectra

As we have described in chapter 3.1, the real ocean can not be considered as linear waves, or sinus waves. In reality we have irregular waves, and these can be considered using JONSWAP wave spectra. In Figure 8-11 to Figure 8-16 we see how the spectral dencity changes due to peak period and significant wave height. The equations used in these figures are described in chapter 3.1.

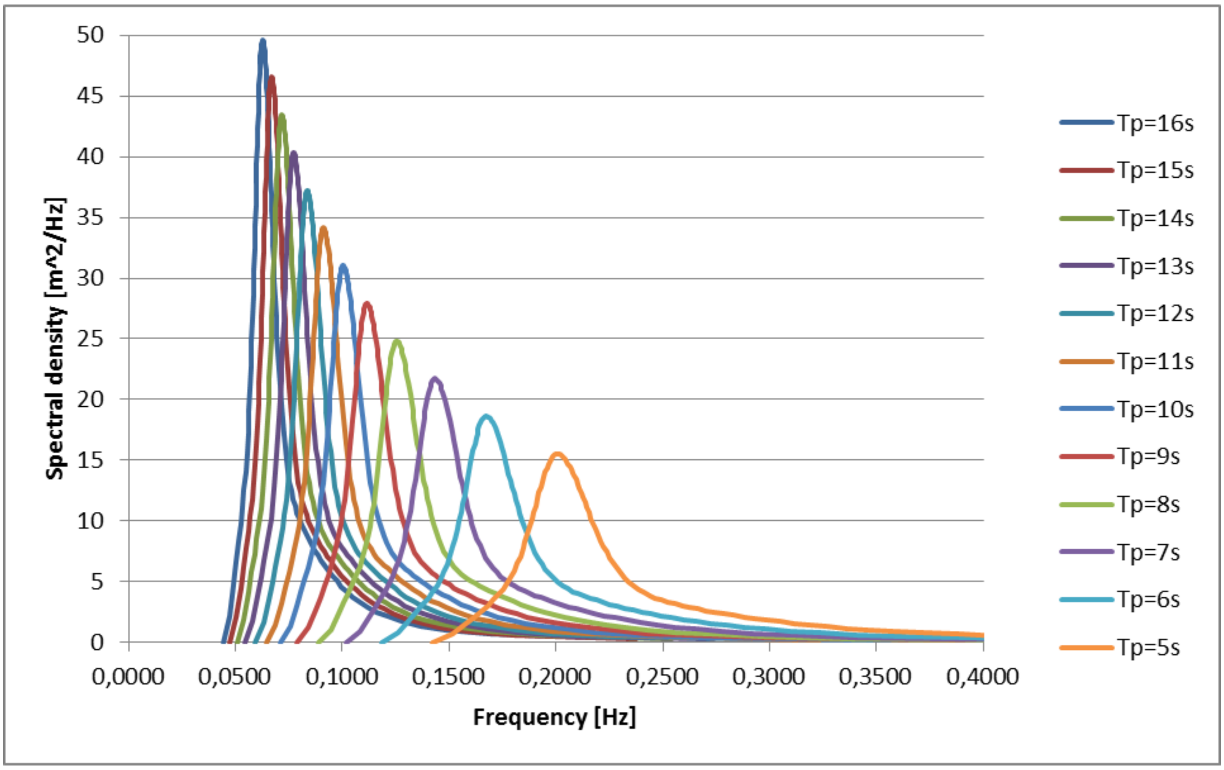


Figure 8-11 JONSWAP wave spectra for The North Sea Hs=4m

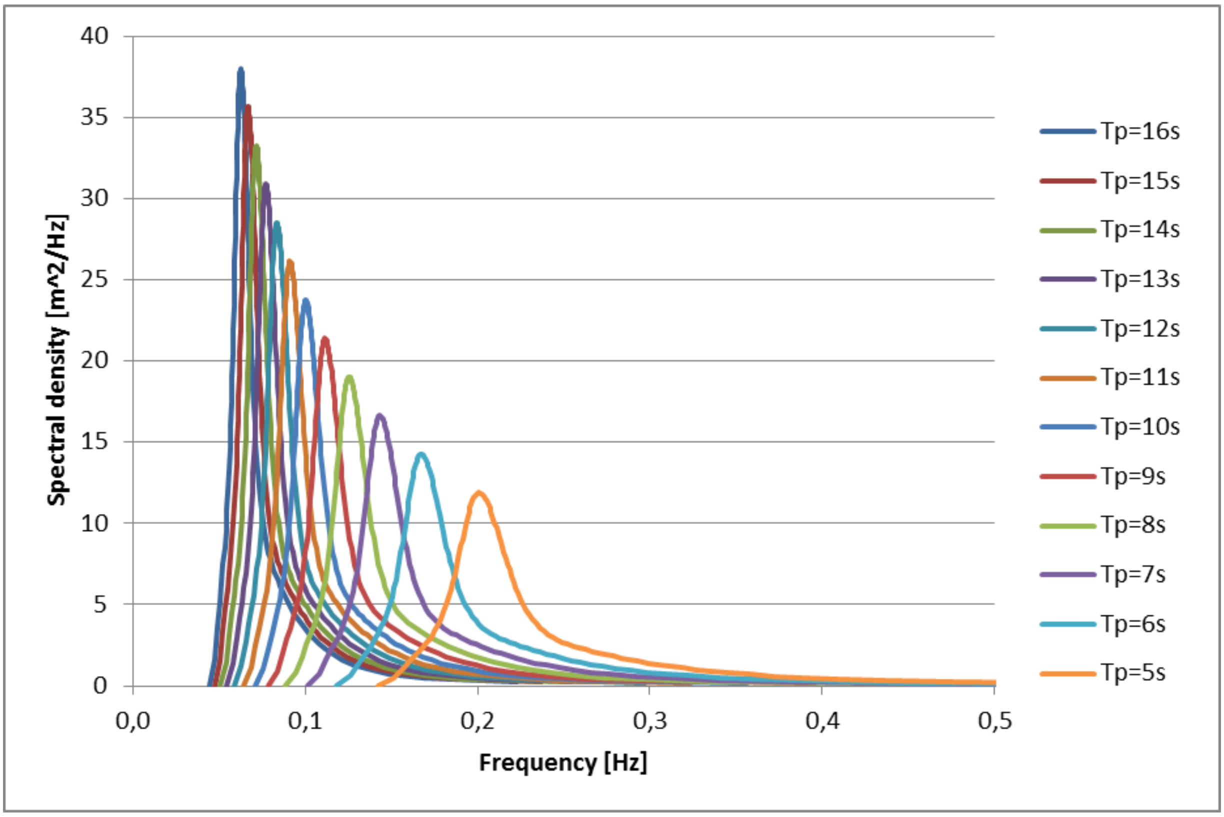


Figure 8-12 JONSWAP wave spectra for the North Sea Hs=3,5m

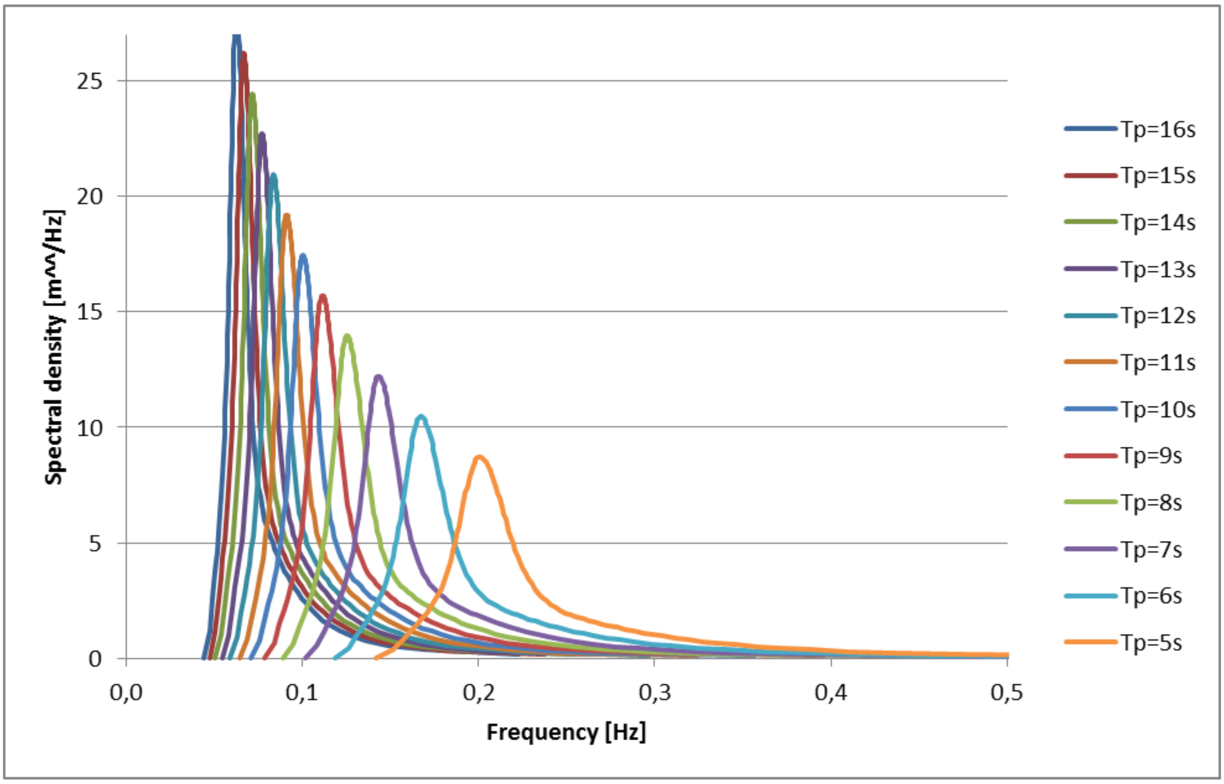


Figure 8-13 JONSWAP wave spectra for the North Sea Hs=3,0m

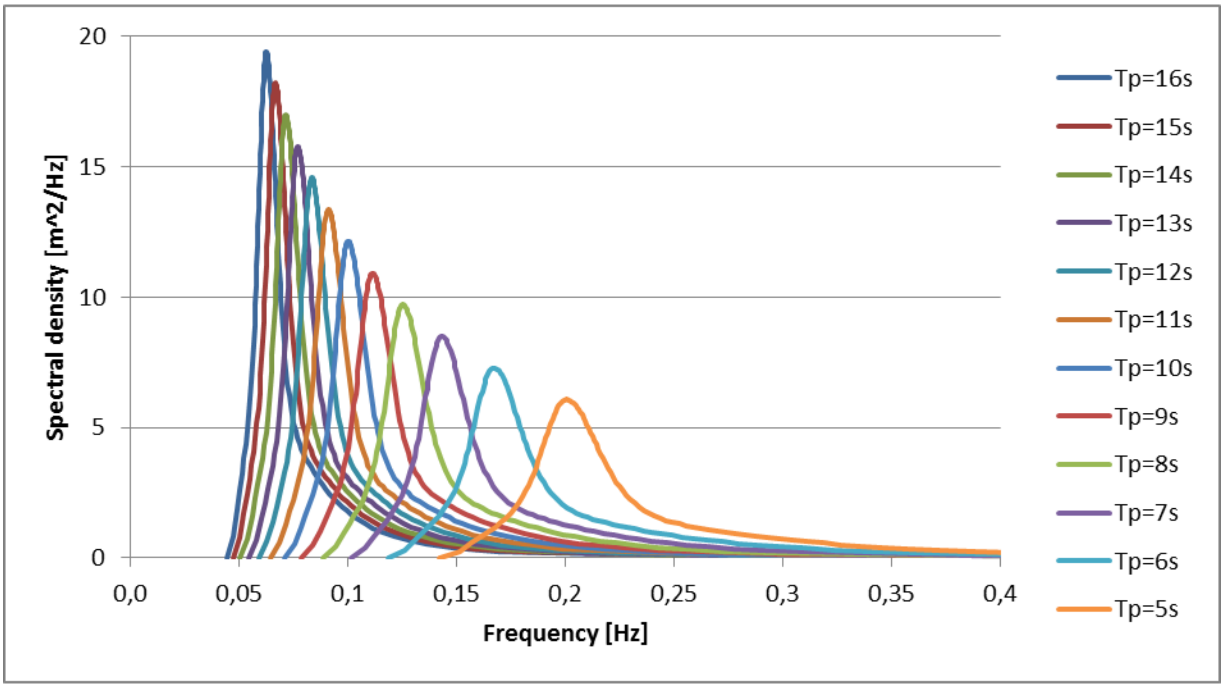


Figure 8-14 JONSWAP for the North Sea Hs=2,5m

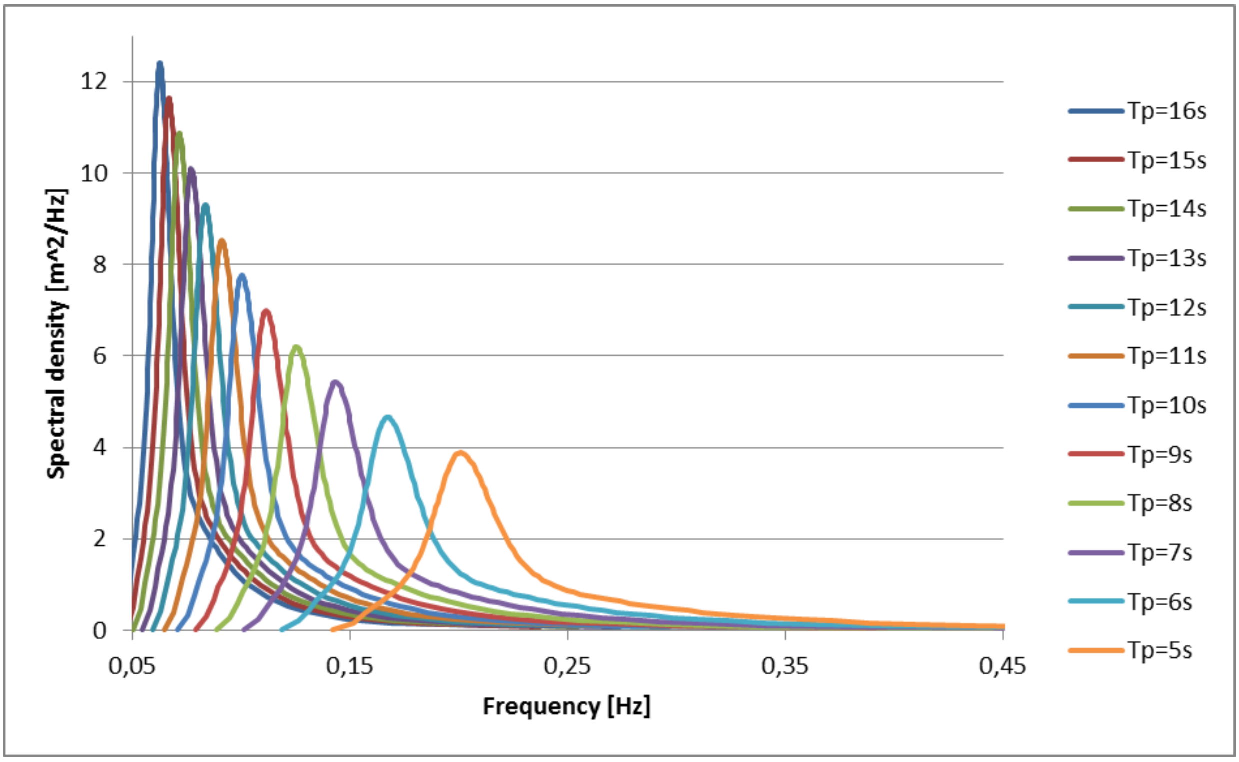


Figure 8-15 JONSWAP wave spectra for the North Sea Hs=2,0m

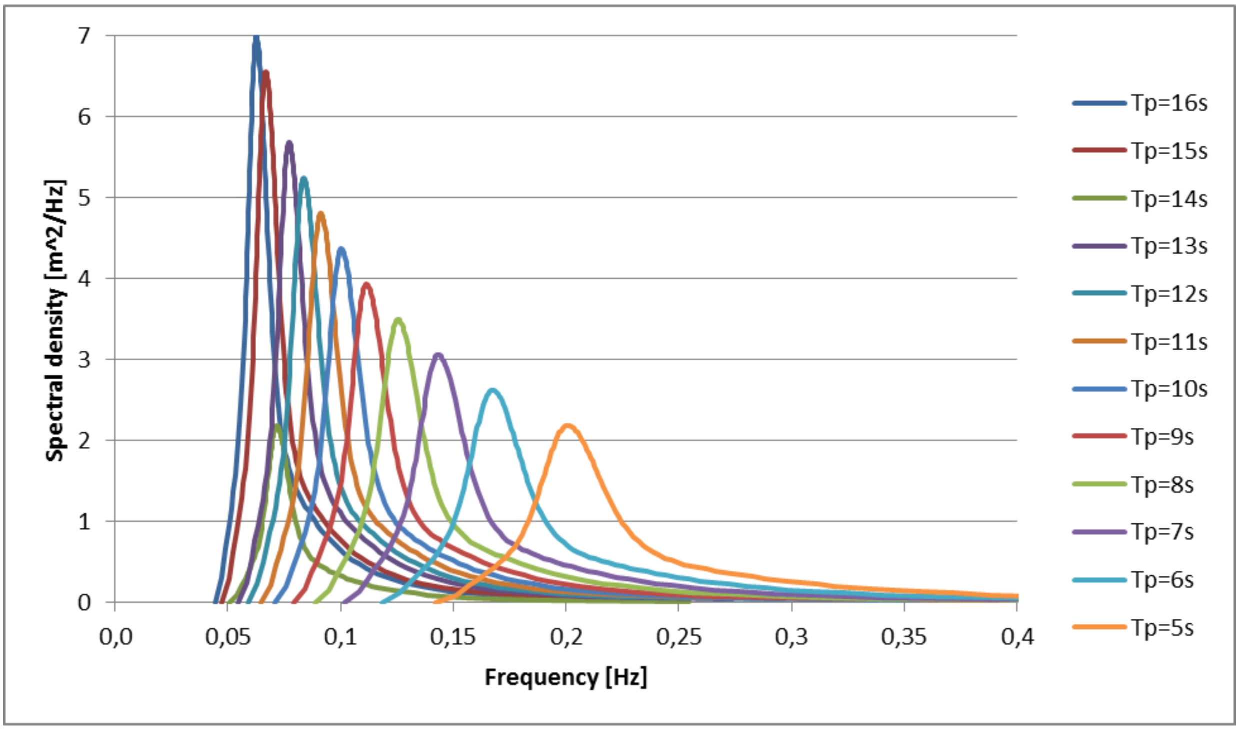


Figure 8-16 JONSWAP wave spectra for the North Sea Hs=1,5m

F. Hydrodynamic Coefficients

In this appendix tables explaining the added mass coefficients and drag coefficients are given, taken from DNV – RP – H103.

Table A-2 Analytical added mass coefficient for three-dimensional bodies in infinite fluid (far from boundaries). Added mass is $A_{ij}=\rho C_A V_R$ [kg] where V_R [m^3] is reference volume

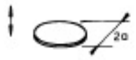
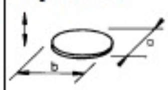
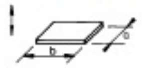
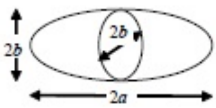
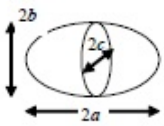
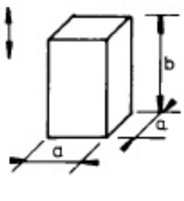
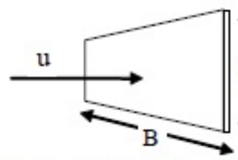
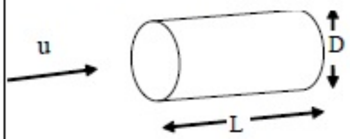
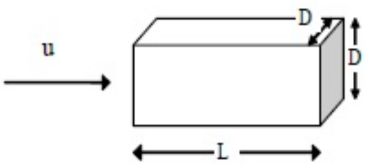
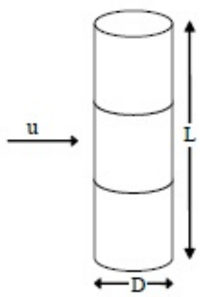
Body shape		*Direction of motion*	C_A	V_R
Flat plates	Circular disc 	Vertical	$2/\pi$	$\frac{4}{3}\pi a^3$
	Elliptical disc 	Vertical	*b/a*, C_A, *b/a*, C_A ∞, 1.000, 5.0, 0.952 14.3, 0.991, 4.0, 0.933 12.8, 0.989, 3.0, 0.900 10.0, 0.984, 2.0, 0.826 7.0, 0.972, 1.5, 0.758 6.0, 0.964, 1.0, 0.637	$\frac{\pi}{6} a^2 b$
	Rectangular plates 	Vertical	*b/a*, C_A, *b/a*, C_A 1.00, 0.579, 3.17, 0.840 1.25, 0.642, 4.00, 0.872 1.50, 0.690, 5.00, 0.897 1.59, 0.704, 6.25, 0.917 2.00, 0.757, 8.00, 0.934 2.50, 0.801, 10.00, 0.947 3.00, 0.830, ∞, 1.000	$\frac{\pi}{4} a^2 b$
	Triangular plates 	Vertical	$\frac{1}{\pi}(\tan\theta)^{3/2}$	$\frac{a^3}{3}$
Bodies of revolution	Spheres 	Any direction	½	$\frac{4}{3}\pi a^3$
	Spheroids 	Lateral or axial	*a/b*, C_A Axial, C_A Lateral 1.0, 0.500, 0.500 1.5, 0.304, 0.622 2.0, 0.210, 0.704 2.5, 0.156, 0.762 4.0, 0.082, 0.860 5.0, 0.059, 0.894 6.0, 0.045, 0.917 7.0, 0.036, 0.933 8.0, 0.029, 0.945	$\frac{4}{3}\pi b^2 a$
Ellipsoid	 Axis *a* > *b* > *c*	Axial	$C_A=\frac{\alpha_0}{2-\alpha_0}$ where $\alpha_0=\varepsilon\delta\int_0^\infty (1+u)^{-3/2}(\varepsilon^2+u)^{-1/2}(\delta^2+u)^{-1/2}du$ $\varepsilon=b/a \quad \delta=c/a$	$\frac{4}{3}\pi abc$
Square prisms		Vertical	*b/a*, C_A 1.0, 0.68 2.0, 0.36 3.0, 0.24 4.0, 0.19 5.0, 0.15 6.0, 0.13 7.0, 0.11 10.0, 0.08	$a^2 b$

Table B-2
Drag coefficient on three-dimensional objects for steady flow C_{DS}.
Drag force is defined as $F_D = ½\rho C_{DS} S u^2$.

S = projected area normal to flow direction [m^2].
R_e = uD/ν = Reynolds number where D = characteristic dimension.

Geometry	*Dimensions*	C_{DS}	
Rectangular plate normal to flow direction 	B/H 1 5 10 ∞	1.16 1.20 1.50 1.90 $R_e > 10^3$	
Circular cylinder. Axis parallel to flow. 	L/D 0 1 2 4 7	1.12 0.91 0.85 0.87 0.99 $R_e > 10^3$	
Square rod parallel to flow 	L/D 1.0 1.5 2.0 2.5 3.0 4.0 5.0	1.15 0.97 0.87 0.90 0.93 0.95 0.95 $R_e = 1.7 \cdot 10^5$	
Circular cylinder normal to flow. 	L/D	Sub critical flow $R_e < 10^5$	Supercritical flow $R_e > 5 \cdot 10^5$
		κ	κ
	2	0.58	0.80
	5	0.62	0.80
	10	0.68	0.82
	20	0.74	0.90
	40	0.82	0.98
	50	0.87	0.99
	100	0.98	1.00
	$C_{DS} = \kappa C_{DS}^{\infty}$ κ is the reduction factor due to finite length. C_{DS}^{∞} is the 2D steady drag coefficient.		

G. Results From OrcaFlex analysis

"OrcaFlex provides fast and accurate analysis of catenary systems such as flexible risers and umbilical cables under wave and current loads and externally imposed motions. OrcaFlex makes extensive use of graphics to assist understanding. The program can be operated in batch mode for routine analysis work and there are also special facilities for post-processing your results including fully integrated fatigue analysis capabilities.

OrcaFlex is a fully 3D non-linear time domain finite element program capable of dealing with arbitrarily large deflections of the flexible from the initial configuration. A lumped mass element is used which greatly simplifies the mathematical formulation and allows quick and efficient development of the program to include additional force terms and constraints on the system in response to new engineering requirements.

In addition to the time domain features, modal analysis can be performed for either the whole system or for individual lines. RAOs can be calculated for any results variable using the Spectral Response Analysis feature.

OrcaFlex is also used for applications in the Defence, Oceanography and Renewable energy sectors. OrcaFlex is fully 3D and can handle multi-line systems, floating lines, line dynamics after release, etc. Inputs include ship motions, regular and random waves. Results output includes animated replay plus full graphical and numerical presentation,"[28].

As described in the OrcaFlex manual above, OrcaFlex is a finite element program. In this thesis OrcaFlex is used to conduct results of forces in wire with different wave headings, vessel motion and irregular wave results, appendix E. Further in this appendix a more detailed presentation of the results are described through the figures below.

In the tables below "most likely" means the values that is based on the periods that have a possibility to occur according to the scatter diagrams in appendix D.

North Sea

Table 28 Forces [kN] at end B with Hs =1,5m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
	5,79	4,5	2968	2974	2964	2904	2876	2887
	7,07	5,5	2977	2978	2971	2861	2840	2907
	8,36	6,5	2983	2981	2974	2865	2871	2893
	9,64	7,5	3002	2996	2993	2817	2833	2835
1,5	10,93	8,5	3012	3002	2990	2717	2735	2834
	12,22	9,5	3019	3011	2988	2672	2689	2833
	13,50	10,5	3018	3025	2987	2670	2708	2784
	14,79	11,5	3007	3005	2987	2699	2725	2775
	16,07	12,5	3001	2995	2989	2766	2794	2879
		Extremes	**3019**	**3025**	**2993**	**2670**	**2689**	**2775**
		DAF_{conv}	0,91	0,91	0,90			
		Slack				0,80	0,81	0,83
		Most likely	3019	3025	2993	2670	2689	2784
		DAF_{conv}*	0,91	0,91	0,90			
		Slack*				0,80	0,81	0,83

Table 29 Forces [kN] at end B with Hs=2,0m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
	5,79	4,5	2978	2986	2972	2750	2594	2673
	7,07	5,5	2988	2993	2981	2570	2535	2803
	8,36	6,5	2998	2997	2985	2721	2723	2793
	9,64	7,5	3016	3013	3001	2656	2680	2700
2,0	10,93	8,5	3028	3019	3006	2547	2575	2703
	12,22	9,5	3028	3030	3004	2494	2524	2685
	13,50	10,5	3043	3057	3002	2486	2578	2636
	14,79	11,5	3019	3014	3001	2523	2558	2625
	16,07	12,5	3017	3013	3007	2599	2634	2684
		Extremes	**3043**	**3057**	**3007**	**2486**	**2524**	**2625**
		DAF_{conv}	0,91	0,92	0,90			
		Slack				0,75	0,76	0,79
		Most likely	3043	3057	3006	2486	2524	2636
		DAF_{conv}*	0,91	0,92	0,90			
		Slack*				0,75	0,76	0,79

Table 30 Forces [kN] at end B with Hs=2,5m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,5	5,79	4,5	2987	2999	2980	2423	2060	2315
	7,07	5,5	2998	3015	2991	2114	2047	2652
	8,36	6,5	3019	3013	2997	2497	2519	2649
	9,64	7,5	3025	3017	3006	2479	2520	2499
	10,93	8,5	3042	3037	3023	2417	2435	2579
	12,22	9,5	3037	3035	3020	2336	2381	2541
	13,50	10,5	3056	3063	3018	2338	2341	2502
	14,79	11,5	3032	3029	3017	2362	2403	2489
	16,07	12,5	3035	3028	3023	2438	2482	2546
		Extremes	**3056**	**3063**	**3023**	**2114**	**2047**	**2315**
		DAF_{conv}	0,92	0,92	0,91			
		Slack				0,63	0,61	0,69
		Most likely	3056	3063	3023	2114	2047	2499
		DAF_{conv}*	0,92	0,92	0,91			
		Slack*				0,63	0,61	0,75

Table 31 Forces [kN] at end B with Hs=3m and z=1,0m

Hs	Tp	**Tz**	**Max force 165 degrees**	**Max force 180 degrees**	**Max force 195 degrees**	**Min force 165 degrees**	**Min force 180 degrees**	**Min force 195 degrees**
3,0	5,79	4,5	3012	3139	3059	1795	1468	1863
	7,07	5,5	3013	3056	3001	1459	1431	2412
	8,36	6,5	3033	3028	3006	2248	2196	2450
	9,64	7,5	3132	3083	3010	2266	2339	2248
	10,93	8,5	3064	3196	3035	2146	2388	2455
	12,22	9,5	3053	3055	3035	2155	2116	2401
	13,50	10,5	3088	3086	3035	2061	2122	2382
	14,79	11,5	3060	3059	3036	2227	2272	2363
	16,07	12,5	3059	3040	3040	2288	2328	2416
		Extremes	**3132**	**3196**	**3059**	**1459**	**1431**	**1863**
		DAF_{conv}	0,94	0,96	0,92			
		Slack				0,44	0,43	0,56
		Most likely	3132	3196	3035	1459	1431	2248
		DAF_{conv}*	0,94	0,96	0,91			
		Slack*				0,44	0,43	0,67

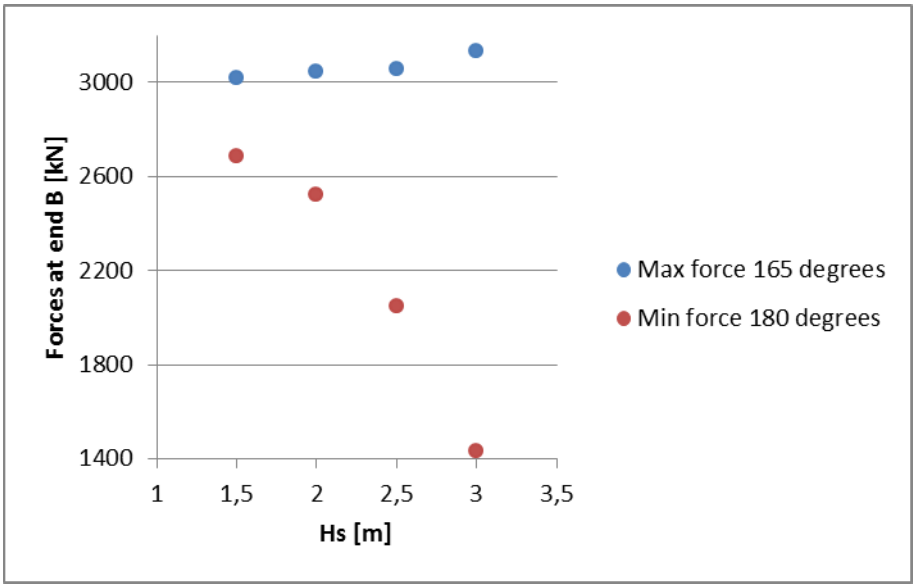


Figure 8-17 Forces at end B when module is located z=1,0m

Table 32 Forces [kN] at end B with Hs=1,5 and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	5,79	4,5	3137	3465	2532	1422	1326	1457
	7,07	5,5	2258	2843	2351	1599	1514	1566
	8,36	6,5	2706	2459	2588	1471	1505	1516
	9,64	7,5	2671	2545	2848	1533	1434	1320
	10,93	8,5	3001	2826	2288	1539	1552	1542
	12,22	9,5	2654	2677	2544	1439	1378	1591
	13,50	10,5	2662	2628	2244	1392	1374	1452
	14,79	11,5	2608	2511	2246	1432	1453	1607
	16,07	12,5	2535	2511	2277	1403	1429	1421
		Extremes	**3137**	**3465**	**2848**	**1392**	**1326**	**1320**
		DAF_{conv}	0,94	1,04	0,85			
		Slack				0,62	0,59	0,59
		Most likely	3001	2843	2848	1392	1374	1320
		DAF_{conv}*	0,90	0,85	0,85			
		Slack*				0,62	0,61	0,59

Table 33 Forces [kN] at end B with Hs=2,0m and z=-3,0m

Hs	Tp	Tz	**Max force 165 degrees**	**Max force 180 degrees**	**Max force 195 degrees**	**Min force 165 degrees**	**Min force 180 degrees**	**Min force 195 degrees**
2,0	5,79	4,5	3441	3577	3155	1218	1176	1032
	7,07	5,5	3005	3037	2595	1419	1407	1420
	8,36	6,5	2728	2678	2790	1412	1449	1406
	9,64	7,5	3163	3217	2889	1262	1255	1304
	10,93	8,5	3161	3154	2459	1459	1470	1454
	12,22	9,5	2770	2799	2668	1352	1302	1423
	13,50	10,5	2811	2854	2400	1316	1194	1323
	14,79	11,5	2911	2674	2734	1307	1329	1569
	16,07	12,5	2934	2657	2425	1274	1286	1284
		Extremes	**3441**	**3577**	**3155**	**1218**	**1176**	**1032**
		DAF_{conv}	1,03	1,07	0,95			
		Slack				0,54	0,52	0,46
		Most likely	3163	3217	2889	1262	1194	1304
		DAF_{conv}*	0,95	0,96	0,87			
		Slack*				0,56	0,53	0,58

Table 34 Forces [kN] at end B with Hs=2,5m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,5	5,79	4,5	3840	3672	3156	454	740	1240
	7,07	5,5	3298	3057	2595	1106	1230	1409
	8,36	6,5	3152	3171	3118	1235	1303	1305
	9,64	7,5	2980	3733	3157	1150	1088	1203
	10,93	8,5	3476	3140	2646	1351	1200	1377
	12,22	9,5	3392	3022	2716	1156	1082	1259
	13,50	10,5	3198	3123	2573	1405	1045	1179
	14,79	11,5	2926	2856	2835	1176	1201	1514
	16,07	12,5	3016	2861	2578	1158	1201	1149
		Extremes	**3840**	**3733**	**3157**	**454**	**740**	**1149**
		DAF_{conv}	1,15	1,12	0,95			
		Slack				0,20	0,33	0,51
		Most likely	3476	3733	3157	1106	1045	1179
		DAF_{conv}*	1,04	1,12	0,95			
		Slack*				0,49	0,46	0,52

Table 35 Forces [kN] at end B with Hs=3,0m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
3	5,79	4,5	3703	4367	3650	237	297	561
	7,07	5,5	3660	3404	3582	1164	842	961
	8,36	6,5	3517	3201	3590	1170	1084	1117
	9,64	7,5	3211	3879	3362	1288	1136	1080
	10,93	8,5	4146	3501	2877	818	1023	1290
	12,22	9,5	3920	3834	2809	1136	1039	1138
	13,50	10,5	3441	3285	2772	916	1096	1020
	14,79	11,5	3087	3012	2914	1046	1071	1332
	16,07	12,5	3181	3028	2742	1104	1033	1025
		Extremes	**4146**	**4367**	**3650**	**237**	**297**	**561**
		DAF_{conv}	1,24	1,31	1,09			
		Slack				0,11	0,13	0,25
		Most likely	4146	4367	3590	818	842	961
		DAF_{conv}*	1,24	1,31	1,08			
		Slack*				0,36	0,37	0,43

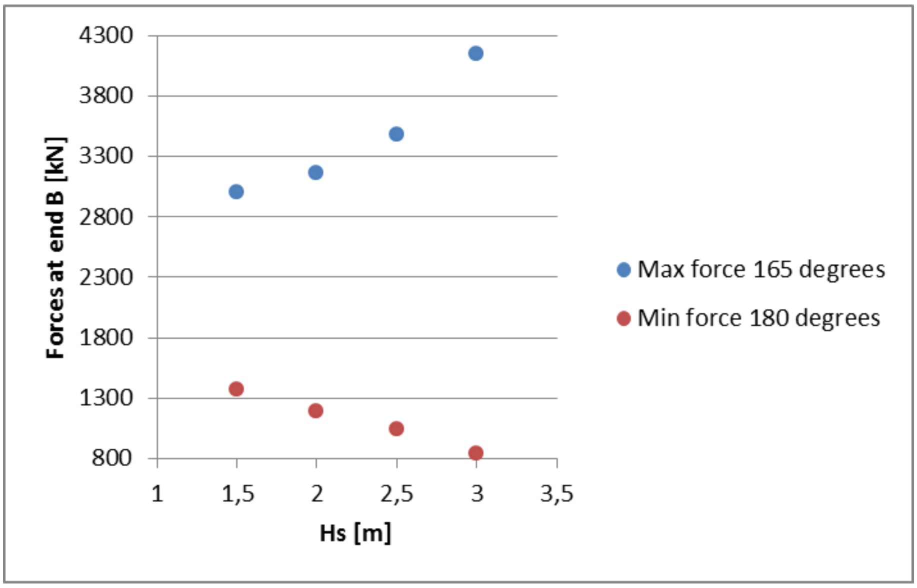


Figure 8-18 Forces at end B when module is located z=-3,0m

Table 36 Forces [kN] at end B with Hs=1,5m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	5,8	4,5	1913	2254	2159	523	506	536
	7,1	5,5	2841	2085	1475	605	607	612
	8,4	6,5	2050	1886	1170	646	543	630
	9,6	7,5	1562	1373	1096	678	594	698
	10,9	8,5	1429	1675	1107	685	597	680
	12,2	9,5	1280	1358	1083	709	666	694
	13,5	10,5	1871	1657	1250	700	674	717
	14,8	11,5	2150	1738	1209	732	736	722
	16,1	12,5	2750	1966	1279	731	721	756
		Extremes	**2841**	**2254**	**2159**	**523**	**506**	**536**
		DAF_{conv}	0,85	0,68	0,65			
		Slack				0,45	0,44	0,46
		Most likely	2841	2085	1475	605	543	612
		DAF_{conv}*	0,85	0,63	0,44			
		Slack*				0,52	0,47	0,53

Table 37 Forces [kN] at end B with Hs=2,0m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,0	5,8	4,5	2612	3214	2465	558	369	444
	7,1	5,5	2863	2767	2809	520	528	504
	8,4	6,5	1854	2232	1177	594	526	687
	9,6	7,5	2190	1878	1279	566	548	668
	10,9	8,5	1402	1588	1234	639	560	668
	12,2	9,5	2588	1909	1227	653	622	672
	13,5	10,5	3174	2232	1353	698	627	663
	14,8	11,5	2230	2139	1863	720	693	732
	16,1	12,5	2181	2145	1826	713	701	751
		Extremes	**3174**	**3214**	**2809**	**520**	**369**	**444**
		DAF_{conv}	0,95	0,96	0,84			
		Slack				0,45	0,32	0,38
		Most likely	3174	2767	2809	520	526	504
		DAF_{conv}*	0,95	0,83	0,84			
		Slack*				0,45	0,45	0,43

Table 38 Forces [kN] at end B with Hs=2,5m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
	5,8	4,5	3598	6073	3076	483	393	496
	7,1	5,5	3479	2571	4494	535	494	481
	8,4	6,5	2440	2528	1911	548	535	618
	9,6	7,5	2473	2924	1284	552	511	636
2,5	10,9	8,5	2407	1821	1389	466	540	658
	12,2	9,5	3429	1792	1506	588	615	594
	13,5	10,5	3708	2307	2382	680	682	698
	14,8	11,5	2787	2142	2027	718	666	734
	16,1	12,5	3365	2380	1778	691	682	730
		Extremes	**3708**	**6073**	**4494**	**466**	**393**	**481**
		DAF_{conv}	1,11	1,82	1,35			
		Slack				0,40	0,34	0,41
		Most likely	3708	2924	4494	466	494	481
		DAF_{conv}*	1,11	0,88	1,35			
		Slack*				0,40	0,42	0,41

Table 39 Forces [kN] at end B with Hs=3,0m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
	5,8	4,5	4376	6808	4493	227	337	340
	7,1	5,5	3654	3630	2111	271	344	444
	8,4	6,5	3106	2546	1971	536	430	518
	9,6	7,5	2977	4047	1521	506	453	596
3,0	10,9	8,5	2621	2412	2024	460	505	483
	12,2	9,5	3978	2554	1913	570	472	627
	13,5	10,5	3565	2845	2173	583	594	667
	14,8	11,5	3359	2723	1971	722	457	696
	16,1	12,5	2793	2744	2041	673	658	729
		Extremes	**4376**	**6808**	**4493**	**227**	**337**	**340**
		DAF_{conv}	1,31	2,04	1,35			
		Slack				0,19	0,29	0,29
		Most likely	3978	4047	2173	271	344	444
		DAF_{conv}*	1,19	1,21	0,65			
		Slack*				0,23	0,30	0,38

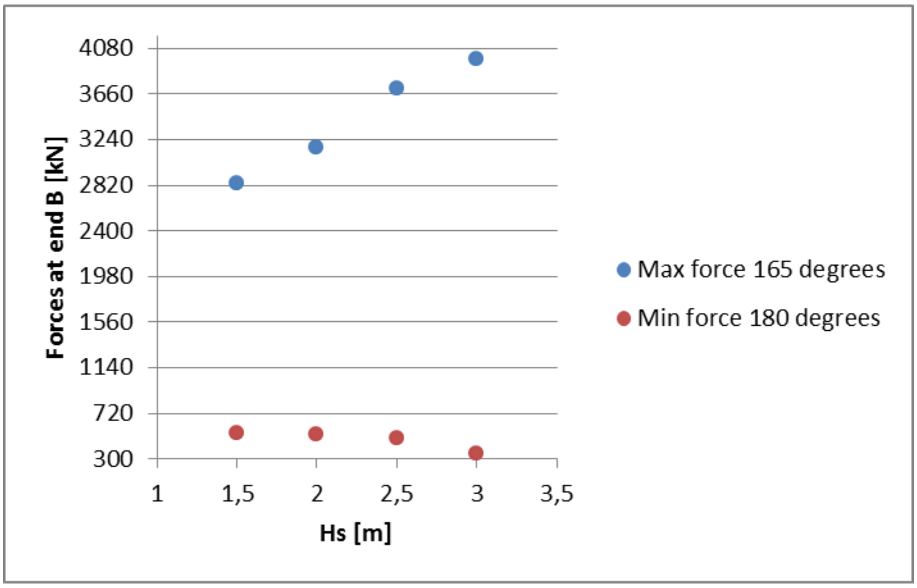


Figure 8-19 Forces at end B when module is located z=-6,0m

Offshore Angola

Table 40 Forces [kN] at end B with Hs=1,0m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	5,62	4	2989	2992	3066	2728	2810	2871
	7,02	5	2996	2999	3053	2743	2749	2865
	8,43	6	2997	3005	3108	2787	2749	2815
	9,83	7	3009	3012	3060	2801	2824	2849
	11,24	8	3007	3002	3058	2759	2783	2842
	12,64	9	3005	2998	3067	2738	2756	2845
	14,05	10	3006	3005	3135	2776	2775	2798
	15,45	11	3015	3013	3101	2597	2609	2834
	16,86	12	3007	3009	3082	2754	2762	2854
	18,26	13	3024	3023	3083	2603	2629	2852
		Extremes	3024	3023	3135	2597	2609	2798
		DAF_{conv}	0,91	0,91	0,94			
		Slack				0,78	0,78	0,84
		Most likely	3009	3012	3135	2738	2749	2798
		DAF_{conv}*	0,90	0,90	0,94			
		Slack*				0,82	0,82	0,84

Table 41 Forces [kN] at end B with Hs=1,5m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	5,62	4	2993	2997	3068	2499	2702	2867
	7,02	5	3009	3007	3052	2650	2659	2860
	8,43	6	3018	3044	3112	2651	2597	2808
	9,83	7	3018	3037	3065	2693	2726	2842
	11,24	8	3017	3009	3062	2665	2677	2760
	12,64	9	3024	3016	3079	2560	2583	2834
	14,05	10	3019	3016	3136	2639	2662	2789
	15,45	11	3032	3031	3106	2428	2447	2793
	16,86	12	3019	3019	3086	2658	2672	2759
	18,26	13	3035	3032	3085	2461	2497	2850
		Extremes	3035	3044	3136	2428	2447	2759
		DAF_{conv}	0,91	0,91	0,94			
		Slack				0,73	0,73	0,83
		Most likely	3024	3044	3136	2560	2583	2760
		DAF_{conv}*	0,91	0,91	0,94			
		Slack*				0,77	0,77	0,83

Table 42 Forces [kN] at end B with Hs=2,0m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,0	5,62	4	3026	3002	3080	2209	2550	2515
	7,02	5	3018	3016	3049	2521	2545	2801
	8,43	6	3049	3105	3107	2427	2385	2802
	9,83	7	3033	3056	3069	2576	2611	2737
	11,24	8	3038	3033	3080	2543	2563	2639
	12,64	9	3038	3036	3096	2410	2427	2776
	14,05	10	3039	3030	3134	2471	2505	2769
	15,45	11	3051	3043	3109	2260	2288	2641
	16,86	12	3035	3031	3087	2495	2538	2636
	18,26	13	3044	3040	3086	2330	2377	2732
		Extremes	3051	3105	3134	2209	2288	2515
		DAF_{conv}	0,91	0,93	0,94			
		Slack				0,66	0,69	0,75
		Most likely	3049	3105	3134	2410	2385	2639
		DAF_{conv}*	0,91	0,93	0,94			
		Slack*				0,72	0,72	0,79

Table 43 Forces [kN] at end B with Hs=2,5m and z=1,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,5	5,62	4	3172	3053	3155	1854	2207	1953
	7,02	5	3026	3021	3044	1800	2242	2599
	8,43	6	3134	3292	3106	2177	2149	2617
	9,83	7	3055	3060	3070	2428	2494	2609
	11,24	8	3050	3056	3101	2417	2452	2497
	12,64	9	3053	3049	3108	2226	2286	2638
	14,05	10	3046	3043	3125	2326	2356	2657
	15,45	11	3063	3057	3101	2102	2145	2492
	16,86	12	3047	3046	3086	2324	2375	2521
	18,26	13	3058	3054	3084	2205	2272	2590
		Extremes	3172	3292	3155	1800	2145	1953
		DAF_{conv}	0,95	0,99	0,95			
		Slack				0,54	0,64	0,59
		Most likely	3134	3292	3125	1800	2149	2497
		DAF_{conv}*	0,94	0,99	0,94			
		Slack*				0,54	0,64	0,75

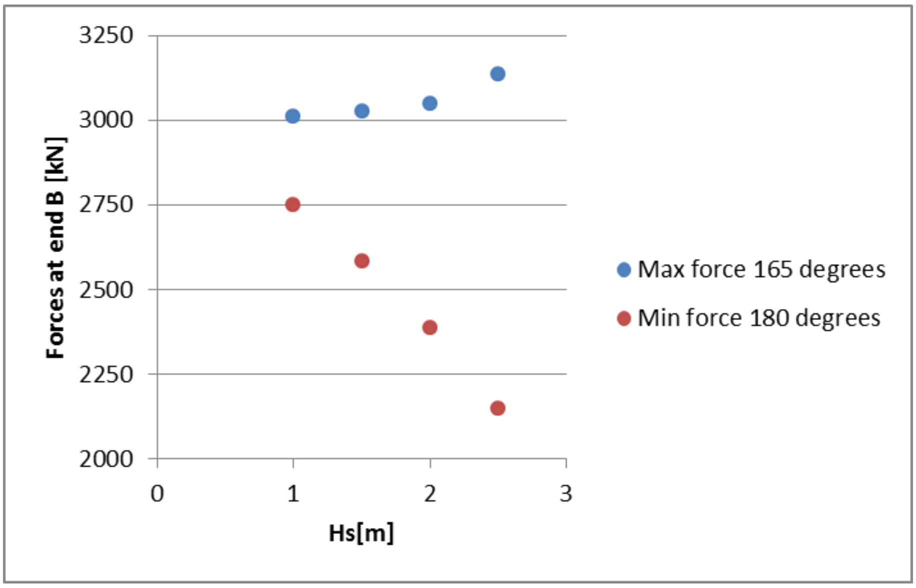


Figure 8-20 Forces at end B when module is located z=1,0m

Table 44 Forces [kN] at end B with Hs=1,0m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	5,62	4	3094	2967	2630	1404	1357	1419
	7,02	5	2856	2927	2470	1458	1476	1546
	8,43	6	2702	2654	2348	1293	1403	1517
	9,83	7	2499	2470	2228	1356	1347	1599
	11,24	8	2687	2608	2331	1454	1488	1611
	12,64	9	2515	2506	2292	1372	1385	1631
	14,05	10	2670	2627	2393	1530	1534	1652
	15,45	11	2498	2532	2332	1349	1371	1622
	16,86	12	2520	2502	2273	1411	1416	1571
	18,26	13	2916	2884	2212	1465	1493	1650
		Extremes	3094	2967	2630	1293	1347	1419
		DAF_{conv}	0,93	0,89	0,79			
		Slack				0,57	0,60	0,63
		Most likely	2856	2927	2470	1293	1347	1517
		DAF_{conv}*	0,86	0,88	0,74			
		Slack*				0,57	0,60	0,67

Table 45 Forces [kN] at end B with Hs=1,5m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	5,62	4	4032	3138	2759	1278	1181	1401
	7,02	5	2961	3209	2616	1389	1268	1373
	8,43	6	2981	2880	2476	1158	1321	1490
	9,83	7	2910	2760	2353	1471	1388	1507
	11,24	8	2871	2887	2530	1389	1423	1556
	12,64	9	2905	2773	2364	1271	1292	1515
	14,05	10	2845	2767	2571	1357	1451	1555
	15,45	11	2672	2729	2416	1313	1383	1499
	16,86	12	2643	2605	2485	1251	1275	1504
	18,26	13	2952	2949	2303	1331	1344	1541
		Extremes	4032	3209	2759	1158	1181	1373
		DAF_{conv}	1,21	0,96	0,83			
		Slack				0,51	0,53	0,61
		Most likely	2981	3209	2616	1158	1268	1373
		DAF_{conv}*	0,89	0,96	0,78			
		Slack*				0,51	0,56	0,61

Table 46 Forces [kN] at end B with Hs=2,0m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,0	5,62	4	4026	3562	3080	1107	1216	1288
	7,02	5	3555	3596	2768	1376	1096	1281
	8,43	6	3376	3368	2668	1097	1272	1482
	9,83	7	2973	3020	2505	1342	1322	1421
	11,24	8	3308	3282	2828	1343	1361	1507
	12,64	9	3116	2972	2487	1190	1202	1399
	14,05	10	3003	3200	2764	1213	1228	1424
	15,45	11	2892	3152	2542	1103	1371	1368
	16,86	12	2946	2928	2748	1179	1159	1453
	18,26	13	3041	3022	2419	1143	1175	1435
		Extremes	4026	3596	3080	1097	1096	1281
		DAF_{conv}	1,21	1,08	0,92			
		Slack				0,49	0,49	0,57
		Most likely	3555	3596	2828	1097	1096	1281
		DAF_{conv}*	1,07	1,08	0,85			
		Slack*				0,49	0,49	0,57

Table 47 Forces [kN] at end B with Hs=2,5m and z=-3,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,5	5,62	4	4447	4064	4624	714	975	756
	7,02	5	3781	3172	3094	1217	1104	1375
	8,43	6	3441	3402	2857	1010	973	1408
	9,83	7	3144	3114	2749	1194	1205	1336
	11,24	8	3250	3436	3007	1361	1276	1463
	12,64	9	3106	3063	2627	1082	1289	1310
	14,05	10	3161	3195	2993	1157	1221	1303
	15,45	11	2975	3064	2693	975	968	1226
	16,86	12	3157	3161	3028	1118	1145	1386
	18,26	13	3072	3119	2539	925	998	1331
		Extremes	4447	4064	4624	714	968	756
		DAF_{conv}	1,33	1,22	1,39			
		Slack				0,32	0,43	0,34
		Most likely	3781	3436	3094	1010	973	1303
		DAF_{conv}*	1,13	1,03	0,93			
		Slack*				0,45	0,43	0,58

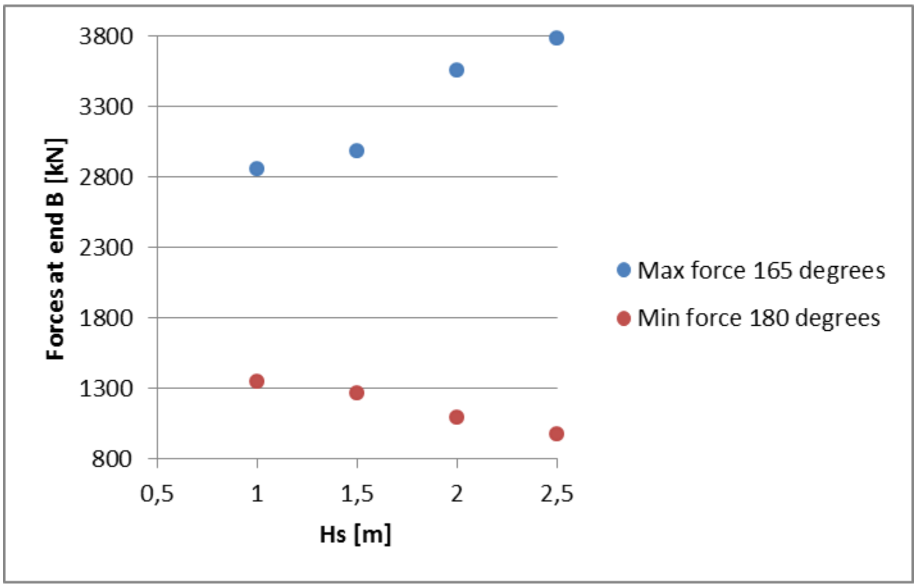


Figure 8-21 Forces at end B when module is located z=-3,0m

Table 48 Forces [kN] at end B with Hs=1,0m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,0	5,62	4	2217	2221	1467	638	631	617
	7,02	5	1810	2002	1441	575	595	576
	8,43	6	2318	2632	1565	684	688	696
	9,83	7	2209	2401	1436	708	643	716
	11,24	8	1719	1765	1219	692	690	713
	12,64	9	2338	2219	1304	714	720	742
	14,05	10	1939	2136	1360	681	692	731
	15,45	11	2589	1715	1735	753	742	726
	16,86	12	1780	2099	1541	717	707	736
	18,26	13	2455	1848	1167	717	722	740
		Extremes	2589	2632	1735	575	595	576
		DAF_{conv}	0,78	0,79	0,52			
		Slack				0,49	0,51	0,49
		Most likely	2338	2632	1565	575	595	576
		DAF_{conv}*	0,70	0,79	0,47			
		Slack*				0,49	0,51	0,49

Table 49 Forces [kN] at end B with Hs=1,5m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
1,5	5,62	4	2497	2667	1555	489	488	570
	7,02	5	2600	2536	1603	587	492	528
	8,43	6	2183	2836	1694	564	626	652
	9,83	7	2865	1904	1532	591	556	656
	11,24	8	2682	1905	1383	668	633	688
	12,64	9	2317	2602	1919	699	697	738
	14,05	10	1812	1760	1424	682	664	697
	15,45	11	2617	1912	1793	718	726	726
	16,86	12	2251	2336	1415	736	736	735
	18,26	13	2357	2409	1442	715	721	747
		Extremes	2865	2836	1919	489	488	528
		DAF_{conv}	0,86	0,85	0,58			
		Slack				0,42	0,42	0,45
		Most likely	2865	2836	1919	564	492	528
		DAF_{conv}*	0,86	0,85	0,58			
		Slack*				0,48	0,42	0,45

Table 50 Forces [kN] at end B with Hs=2,5m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,0	5,62	4	3148	3829	2018	477	495	553
	7,02	5	3719	2520	1831	525	468	615
	8,43	6	3228	3476	1860	574	579	667
	9,83	7	2109	2368	1437	609	478	663
	11,24	8	3301	3435	1421	598	612	658
	12,64	9	2364	2885	2001	655	549	727
	14,05	10	2913	2939	2412	690	689	703
	15,45	11	2614	2348	1869	684	661	727
	16,86	12	3216	2139	2004	716	725	725
	18,26	13	3090	2703	1885	640	686	764
		Extremes	3719	3829	2412	477	468	553
		DAF_{conv}	1,12	1,15	0,72			
		Slack				0,41	0,40	0,48
		Most likely	3719	3476	2412	525	468	615
		DAF_{conv}*	1,12	1,04	0,72			
		Slack*				0,45	0,40	0,53

Table 51 Forces [kN] at end B with Hs=2,5m and z=-6,0m

Hs	Tp	Tz	Max force 165 degrees	Max force 180 degrees	Max force 195 degrees	Min force 165 degrees	Min force 180 degrees	Min force 195 degrees
2,5	5,62	4	4389	4189	3413	258	503	445
	7,02	5	3235	3701	3043	440	419	506
	8,43	6	3214	2975	1757	538	463	548
	9,83	7	2532	3366	1790	507	610	620
	11,24	8	2932	3422	1601	596	515	630
	12,64	9	2662	3111	2253	564	592	718
	14,05	10	3246	2608	1791	683	680	729
	15,45	11	2594	2436	2174	663	694	724
	16,86	12	2255	2387	2175	696	674	715
	18,26	13	2537	3448	1945	669	623	767
		Extremes	4389	4189	3413	258	419	445
		DAF_{conv}	1,32	1,26	1,02			
		Slack				0,22	0,36	0,38
		Most likely	3246	3701	3043	440	419	506
		DAF_{conv}*	0,97	1,11	0,91			
		Slack*				0,38	0,36	0,43

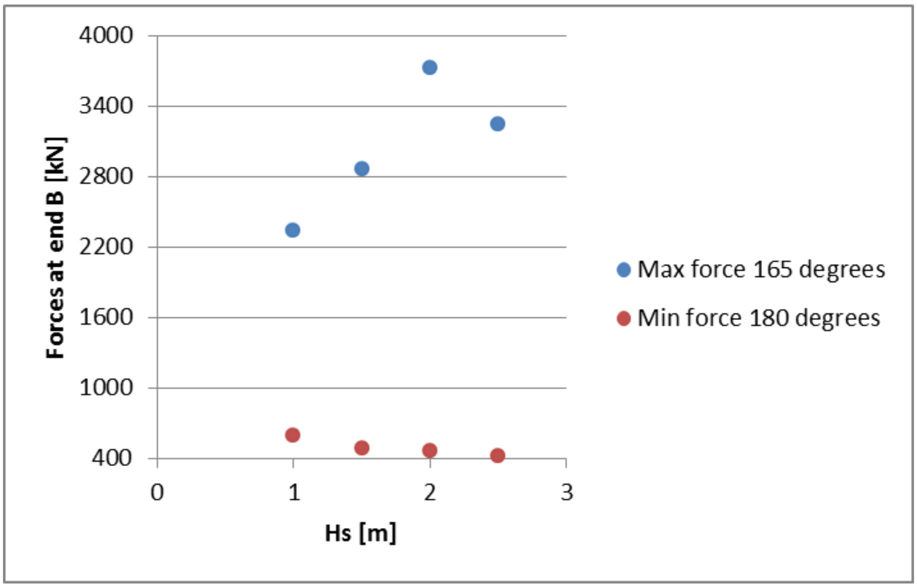


Figure 8-22 Forces at end B when module is located z=-6,0m

Extreme values of the forces at end B

In the figures below we have presented the Rayleigh, Weibull and Generalised Pareto distribution, to show how they change due to significant wave height.

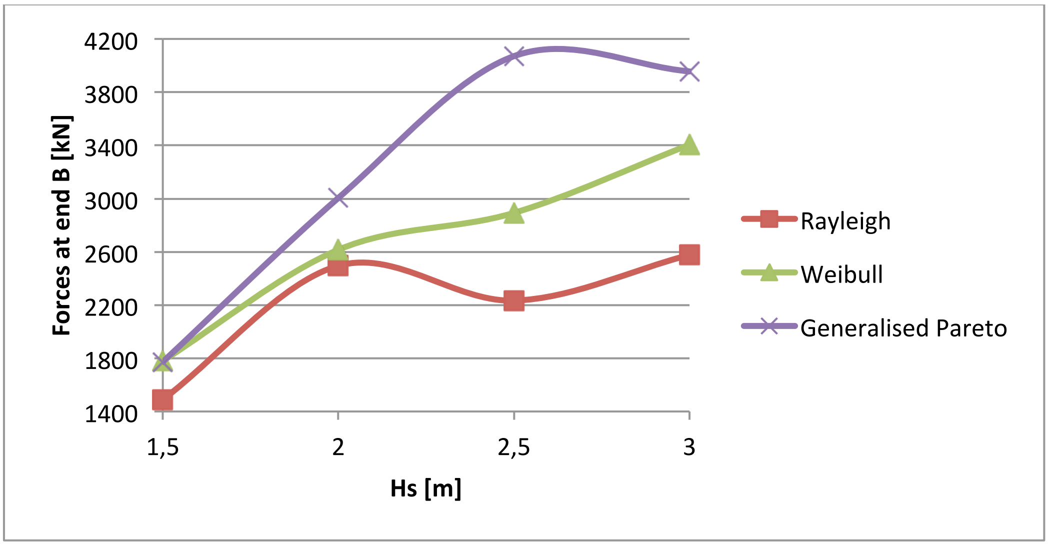


Figure 8-23 Extreme values for the North Sea z=-6,0m

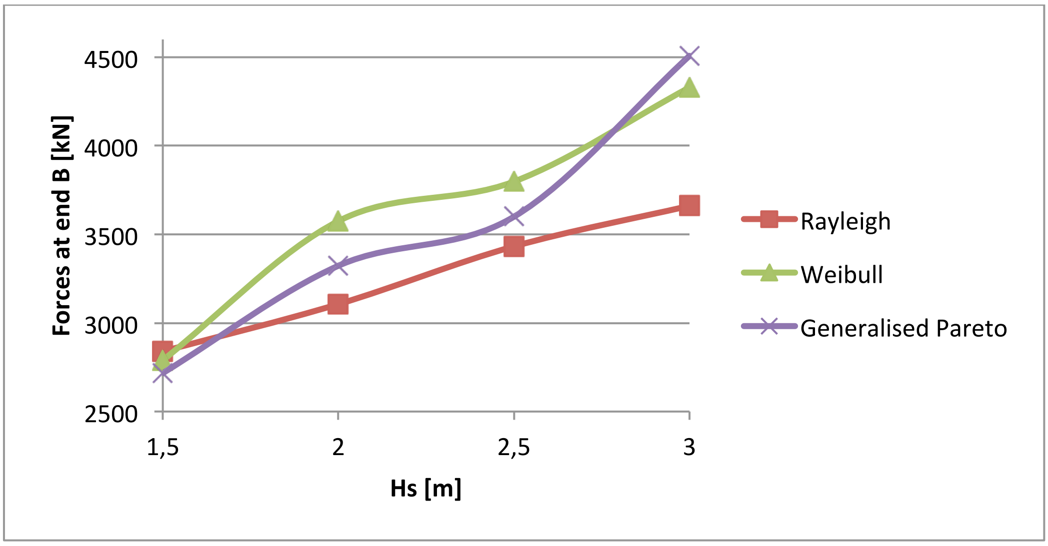


Figure 8-24 Extreme values for the North Sea z=-3,0m

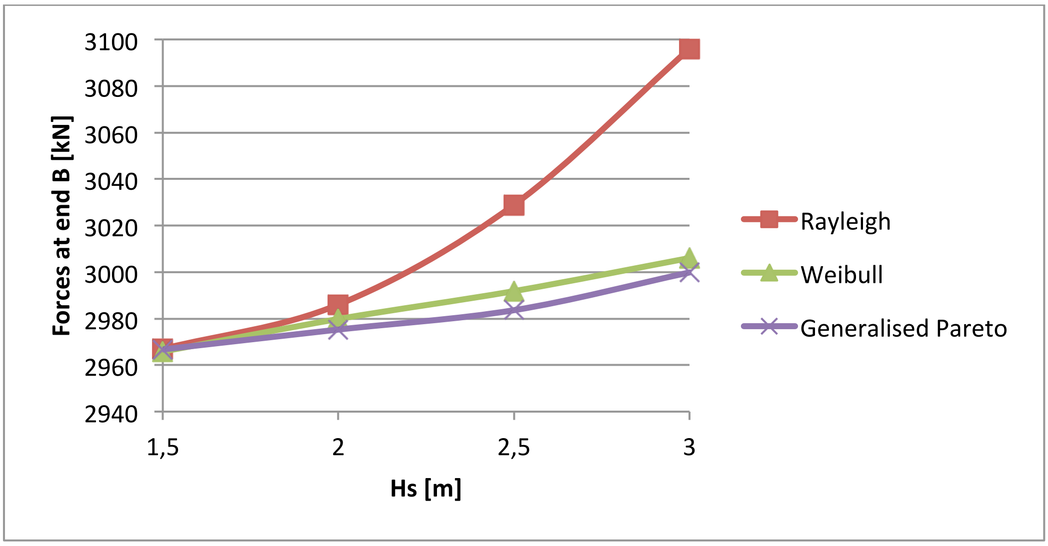


Figure 8-25 Extreme values for the North Sea z=1,0m

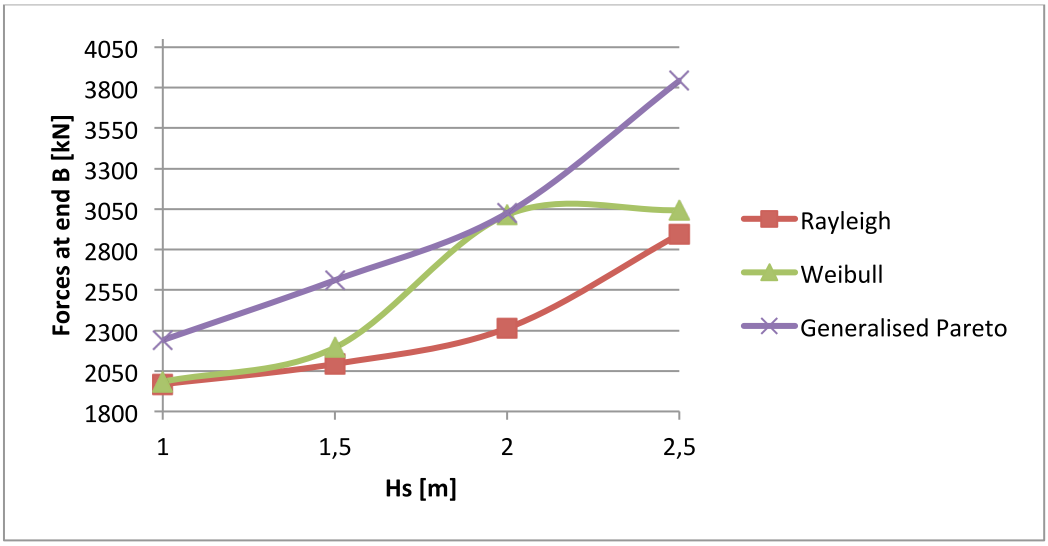


Figure 8-26 Extreme values for offshore Angola z=-6,0m

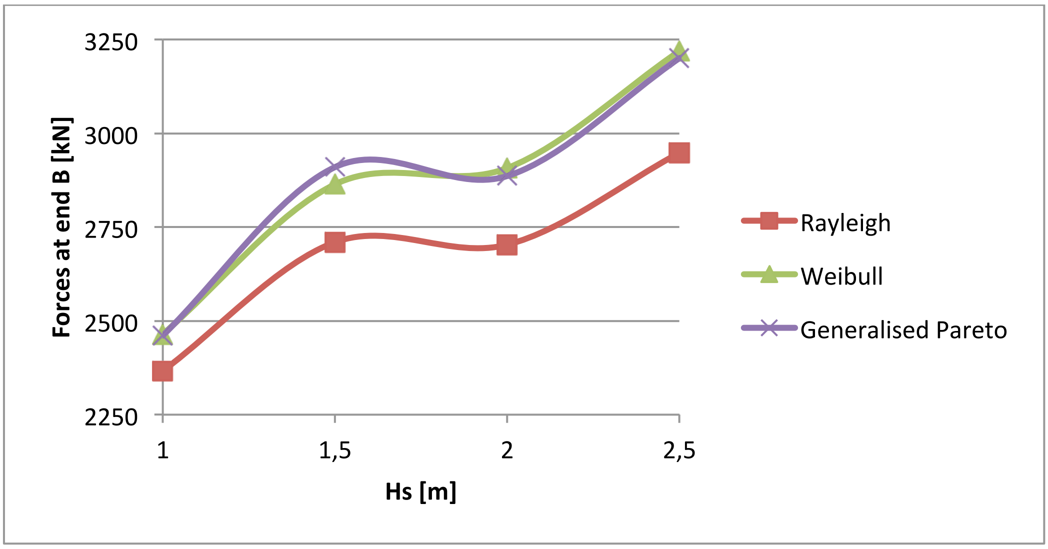


Figure 8-27 Extreme values for offshore Angola z=-3,0m

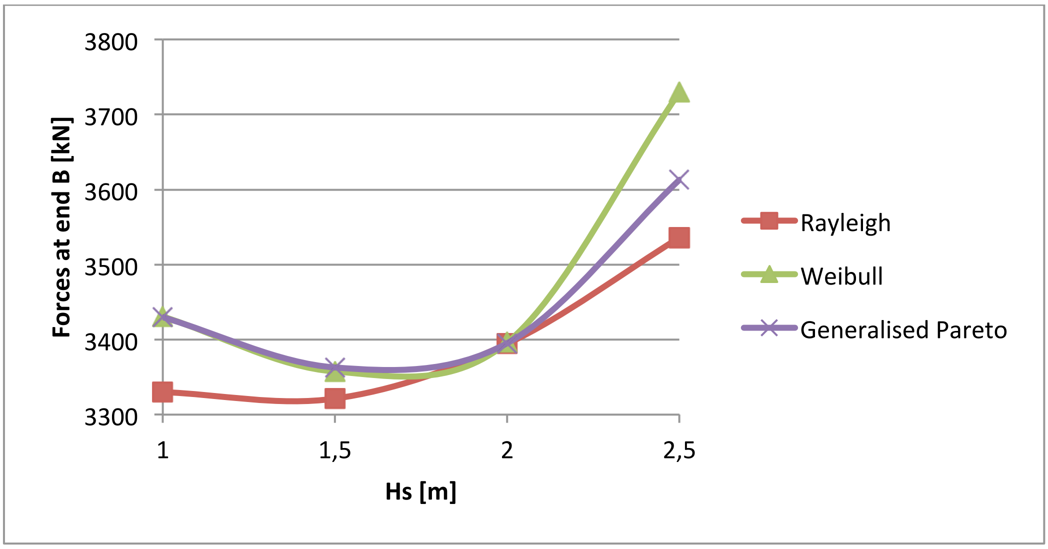


Figure 8-28 Extreme values for offshore Angola z=1,0m