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Preface

This thesis marks the end of the study in master in constructions and materials at the Institute for structural engineering and materials science, specialization offshore Structures, at UIS. Based on my specialization in offshore structures, I have in the spring of 2015 completed a master's thesis with the purpose to study the feasibility of the Versatruss technology.

The subject for the project and the master thesis was proposed by Øyvind Haugsdal from Statoil. I found the subject interesting and relevant for learning more about marine operations, statics, hydrodynamics and calculation methods used to compute/predict vessel motions. The master thesis started as a project in the course marine operations where I looked at different float-over technologies and at the principles for computing RAOs. In connection with the thesis I have received guidance and support from specialists at Statoil.

It was very rewarding to write a thesis for Statoil. The thesis was challenging, but also very interesting to work with and very informative.

I hereby take this opportunity to thank my supervisor Øyvind Haugsdal at Statoil and Professor Jonas Odland at UIS, for good guidance and support along with the work. Thanks also goes to Rune Bjørkli and Tjerand Vigesdal at Statoil, for having responded to questions and made suggestions to the task.

Stavanger 11. June 2015

Per Steinar Bjørheim

Abstract

For the installation of a topside onto jacket, lift method with crane barge has been a common concept. However the increasing weight and offshore exposure hours has led designers to consider the float-over method as an alternative. Float-over installation exceeds the maximum capacity of crane vessels and allows platform topsides be installed as a single integrated package without heavy lift crane vessel. This allows topsides to be completed onshore eliminating the substantial costs associated with offshore hook-up and commissioning, reducing the offshore exposure hours according to ref. [25].

This thesis investigate the float-over technology Versatruss which uses two floating barges equipped with lifting booms to install a topside. Today it a trend in the offshore business to pursue low CAPEX. Therefor a cheap Standard Viking barge (day rates 40-50 000 NOK/per day), which is relative cheap compared SAIPEM S7000 and THIALF where the day rates is (6 000 000 NOK/per day). The barges are maneuvered around the legs of the jacket and the topside is lowered down to mate the topside onto the jacket. During the mating operation the topside and jacket experience impacts through the contact points.

The effect of impact is converted into a limiting acceleration and velocity, and the accelerations and velocities are evaluated with non-linear time domain analysis in SIMA. The purpose of this report is to find the limiting wave height for the Versatruss system based on the limiting acceleration and velocity. The structural limitations has not been investigated.

In order to do time domain analysis a conceptual model of the Standard Viking barge is made in GeniE and a hydrodynamic analysis is done to get the correct input (added mass, stiffness etc.) in SIMA. In addition hand calculations are done to verify the results from the hydrodynamic analysis. In SIMA the system is coupled in a Versatruss configuration and non-linear time domain analysis of the system is done with different wave heights, periods and directions.

In SIMA the model is coupled with fenders and wires to satisfy the assumption that the barges are free to move relative to each other. Since the Versatruss lifting system is allocated along the centreline of the barge individual roll motion of the barges does not influence the motion of the topside.

To assure that the results are correct a small time integration interval of 2,5e-3s is chosen. The most probable maximum (MPM) is taken from several analysis and the value with 10 % probability of exceedance (P90) is taken as the maximum value. This led to the limiting significant wave height (H_S) and peak period (T_P). In addition bootstrapping (ref. Section 3.5) is done to illustrate the confidence behind the numbers.

Nomenclature

Symbol	*Description*	*Unit*
A	*Areal*	*[mm²]*
A_{jk}	*Added mass matrix elements*	*[-]*(1)
A_n, B_n	*Coefficients Fourier transformation*	*[-]*
A_w	*Waterline area*	*[m²]*
A_γ	*Normalizing factor*	*[-]*
B	*Breadth*	*[m]*
BM	*Buoyancy to metacentre*	*[m]*
CDF	*Cumulative distribution function*	*[-]*
C_B	*Block coefficient*	*[-]*
C_a, β_1	*Added mass coefficients*	*[-]*
$D(\theta)$	*Directional function*	*[-]*
DAF	*Dynamic amplification factor*	*[-]*
E	*Effective length of superstructure in m*	*[m]*
E	*Elasticity module*	*[MPa]*
F	*Force*	*[N]*
F_0	*Static force*	*[N]*
F_{Fk}	*Froude-Krylov force*	*[N]*
$F_{M,33}$	*Added mass force*	*[N]*
$G(x;\zeta)$	*Green function*	*[-]*
GM	*Metacentric height*	*[m]*
GM_L	*Metacentric height transverse*	*[m]*
GM_T	*Metacentric height longitudinal*	*[m]*
$\overline{GZ}$	*Up righting arm*	*[m]*
$H(\omega)$	*RAO function*	*[-]*(1)
H_s	*Significant wave height*	*[m]*
I	*Moments of inertia*	*[kgm²]*
$I_{44}, I_{46}, I_{55}, I_{66}$	*Moments of inertia and location in matrix*	*[kgm²]*
I_{jk}	*Mass matrix moments of inertia*	*[-]*(1)
I_{xx}, I_{yy}, I_{zz}	*Moments of inertia*	*[kgm²]*
I_{xy}, I_{yz}, I_{xz}	*Products of inertia*	*[kgm²]*
J_0	*Bessel function of the first kind (zero order)*	*[-]*
KB	*Keel to buoyancy*	*[m]*
KG	*Keel to centre of gravity*	*[m]*
L	*Length*	*[m]*
L_d	*Length design (96 % of the total length on a waterline at 85% of the least moulded depth measured from the top of the keel*	*[m]*
L_w	*Length of wire*	*[m]*
M	*Mass*	*[kg]*
M_B	*Mass barge*	*[kg]*
M_{jk}	*Mass matrix elements*	*[-]*(1)
N_t	*Number of time steps*	*[-]*
OP_{Lim}	*Operational limit*	*[-]*
OP_{WF}	*Operational limit based on weather forecast*	*[-]*
$P90$	*90 % probability*	*[-]*
PDF	*Probability distribution function*	*[-]*
Q	*Total flux or the source strength (flow rate) on the wetted body surface*	*[m³/s]*
R	*Radial distance from the source and field point*	*[m]*
$\dot{R}$	*Velocity*	*[m/s]*

S	*Surface*	*[m²]*
$S(\theta)$	*Spectrum in given direction*	*[-]*
S_J	*JONSWAP spectrum*	*[m^2s]*
S_{PM}	*Pierson-Moskowitz (PM)*	*[m^2s]*
T_C	*Contingency time (cover uncertainty)*	*[s]*
T_H	*Time history*	*[s]*
T_P	*Peak period*	*[s]*
T_{POP}	*Planned operation time*	*[s]*
T_R	*Reference period*	*[s]*
$T_{n,jk}$	*Natural period*	*[s]*
$T_{p,r}$	*Time series repetition period*	*[s]*
T_z	*Zero-up-crossing period (period between two successive up crossings of mean sea level).*	*[s]*
U_0	*Wave velocity*	*[m/s]*
V	*Volume*	*[m^3]*
X	*Displacement*	*[m]*
a_3	*Acceleration of wave particles in z direction*	*[m/s^2]*
a_{jk}	*Two dimensional added mass*	*[-]*
c	*Damping*	*[Ns/m]*
c_c	*Critical damping*	*[Nm/s]*
c_{ii}	*Damping matrix elements*	*[-] (1)*
d	*Draft*	*[m]*
e	*Exponent*	*[-]*
f	*Freeboard*	*[m]*
$f(R)$	*Characteristic force fender*	*[N]*
g	*Gravity*	*[9,81 m/s^2]*
k	*Stiffness*	*[N/m]*
k	*Wave number in shallow water*	*[rad^2/m]*
k_{33}	*Stiffness heave*	*[N/m]*
$k_{33}, k_{35}, k_{44}, k_{55}$	*Stiffness and location in matrix*	*[-](1)*
k_R	*Stiffness rotation*	*[Nm/rad]*
k_T	*Stiffness translation*	*[N/m]*
k_{jk}	*Stiffness elements*	*[-](1)*
m_0	*Spectral moment zero order (standard deviation of the surface elevation)*	*[m]*
m_2	*Spectral moment second order*	*[$m^{2(}rad/s)^2$]*
m_i	*Mass element*	*[kg]*
n_j	*Normal*	*[-]*
r	*Arm*	*[m]*
r_i	*The position of a particle*	*[m]*
s	*Standard deviation*	*[-]*
s, v, a	*Displacement, velocity and acceleration*	*[m, m/s, m/s^s]*
$\ddot{x}, \dot{x}, x$	*Acceleration, velocity and displacement*	*[m/s^2,m/s, m]*
x_g, y_g, z_g	*Vector position of the centre of gravity*	*[m]*
x_i, y_i, z_i	*Cartesian coordinates*	*[m]*
$\bar{y}$	*Average*	*[-]*
Γ	*Gamma function*	*[-]*
α	*Alfa factor*	*[-]*
β, a	*Scale and location parameter Gumbel distribution*	*[-]*
γ	*Peak shape parameter*	*[-]*

δ_{jk}	*Kronecker delta function*	*[-]*
δ_{st}	*Static displacement*	*[m]*
$\zeta\ (\xi, \eta, \zeta)$	*Coordinates on the body surface (source point)*	*[m]*
n, s	*Exponent for wave spreading*	*[2]*
θ	*Angle, phase angle*	*[rad]*
θ_p	*Main wave direction*	*[rad]*
λ_d	*Damping ratio*	*[-]*
ν	*Wave number in deep water*	*[rad^2/m]*
ρ_w	*Density of water*	*[kg/m^3]*
σ_a, σ_b	*Spectral width parameters*	*[-]*
$\omega_{n,jk}$	*Natural frequencies*	*[rad/s]*
ω_n	*Natural frequency*	*[rad/s]*
ω_p	*Peak frequency*	*[rad/s]*
$\Delta\omega_k$	*Frequency increment*	*[rad/s]*
Φ	*Potential function*	*[m^2/s^3]*
Δt	*Time step*	*[s]*
∇	*Submerged volume*	*[m^3]*
∇	*Gradient*	*[-]*

List of abbreviations

abbreviations	Definition
BM	*Buoyancy to metacentre*
CAPEX	*Capital expenditures*
COB	*Centre of buoyancy*
COG	*Centre of gravity*
DAF	*dynamic amplification factor*
DNV	*"Det Norske Veritas"*
DOF	*Degrees of freedom*
DP	*Dynamic positioning*
DSF	*Deck support frame*
FE	*Finite Element*
GBS	*Gravity Base Structure*
GM	*Metacentric height*
H_s	*Significant wave height*
JONSWAP	*Joint North Sea Wave Project*
KB	*Keel to buoyancy*
KG	*Keel to gravity*
LMU	*Leg mating unit*
MIT	*Massachusetts Institute of Technology*
MPM	*Most probable maximum*
PM	*Pierson-Moskowitz*
RAO	*Response amplitude operator*
SIMA	*Simulation of marine operations*
T_C	*Contingency time*
T_P	*Peak period*
T_{POP}	*Planned operation time*
T_R	*Reference period*
WOW	*Waiting on weather*
W_{st}	*Static hook load*

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1 Introduction

There are several installation approaches for topside installation offshore and they can be grouped differently, for example according to methodology as following heavy lift, external and internal float-over. The installation approach for topside installations heavily depends on weight and type. For heavy lift the topside is equipped with trunnions and lifted off the transportation vessel by one or several crane vessel and lowered onto the substructure (jacket or GBS).

The basic concept in float-over is to transport the topsides on one or two vessels in one piece. Additional steel trusses are therefore required to transfer the weight of the topside into these temporary supports. The vessel is maneuvered between the legs of a fixed platform jacket and positioned, and ballasted downwards until the load is transferred completely from the barge to the jacket. The jacket have to be made stronger to compensate for the missing diagonal bracing in the area of the docking slot. For external float-over a transport vessel is optional, the basic concept is a catamaran u-shaped vessel or two vessels (barges) that support the topside. In this type of installation the area under the middle section of the topside is kept free to avoid clashing with substructure and catamaran or vessels are positioned around the substructure and lower the topsides onto the substructure (illustrated in Figure 1). The float-over method involves a transfer of a topside from a free-floating transport vessel under wave motion to a substructure. Traditionally the float-over method is particularly suited to conditions found in the benign shallow water area according to ref. [26].

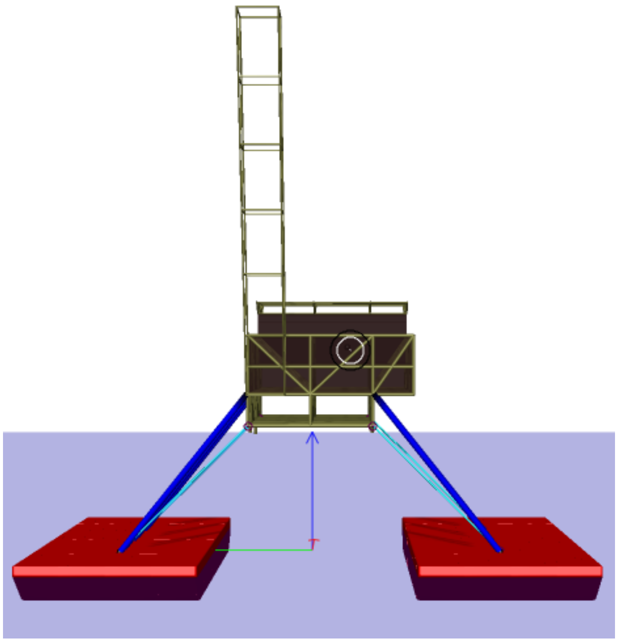


Figure 1 Illustration of the Versatruss lifting system

The report is divided into several chapters where the first chapter is informative, the purpose of the first chapter is to give an overview of different topside installation concepts and how the Versatruss concepts differs from other installation concepts. The second chapter explains the theory behind the hydrodynamic analysis and how it is possible to compute RAO curves by hand calculations. The third chapter explains the procedure and the fourth chapter explains how the waves system is introduced in SIMA.

1.1 Historical overview

1.1.1 Heavy lift

Heavy lift is the most common for installation of topsides. The main constraint associated with heavy lift installation is the lifting capacity of crane vessels. The lifting capacities of the floating crane vessels have increased over the years in parallel with the increase in platform sizes. Lifting topsides in larger modules reduces the cost of offshore hook-up and commissioning. The current offshore lifting record stands at 12,000 Te ref. [1], therefore the large topsides have to be installed as prefabricated topside modules and assembled in the field, while the smaller topsides can be install in one piece by cranes.

The availability of heavy lift vessels are limited, the global market contains a finite number of lift equipment capable of making very heavy lifts. The vessels are expensive. Waiting for one suitable crane vessel can cause significant project delays, which may lead to excessive rental and standby cost ref. [6]

Since the majority of heavy lift vessels are typically home-based in European waters, the costs can be costly for projects in Asian-Pacific waters according to ref. [26]. Therefore float-over techniques are applied to smaller topsides even in regions where suitable crane vessels are available. This opens the market to contractors without access to crane vessels, thereby providing a degree of additional competition during project tendering.

1.1.2 Float-over technology

For the past three decades various float-over technologies have been developed and successfully applied for offshore installations of topsides onto different fixed and floating platform substructures in challenging environments. In the 80s only about 5 float-overs had been executed, while nowadays about 5 float-overs are executed each year according to ref. [38].

A wide variety of load transfer systems and different configuration of float-over barge(s) has been developed, providing an installation solution that can accommodate a wide range of topsides sizes and environmental conditions.

The float-over installation exceeds the maximum capacity of crane vessels and allows platform topsides be installed as a single integrated package without heavy lift crane vessel. This allows the integrated topsides to be completed onshore eliminating the substantial costs associated with offshore hook-up and commissioning, reducing the offshore exposure hours according to ref. [25].

Float-over installations have seen an increase in demand as larger installation projects are on the horizon, exceed the lifting capacity of cranes. This installation method is well suited for platforms in remote locations with very heavy topsides according to ref. [25]. There are a number of reasons why the float-over method is becoming the preferred installation method for integrated topsides, rather than using heavy lift vessels. Some advantages are listed below:

- Flexibility due to increased capacity
- Reduces the time required to execute offshore hook-up and commissioning.
- Availability in the commercial market.
- Cost saving due to reduced operation time and very high day rates for crane vessels.
- Reduced risk due to minimized offshore exposure hours. Work done offshore is considered to pose a higher risk, less efficiency and higher rates as opposed to work done onshore.

However, a combination of deep water, rough open sea, or swell conditions still pose a challenge to provide a cost effective solution in offshore installations.

1.1.3 External float-over

External float-overs are less common than internal ones. These systems can have moving parts and complex dynamic properties and are more vulnerable to environmental loading than internal float-overs. The advantages are that it eliminates the need for the open substructure slot during docking and less requirement of water depth. In addition reducing the float-over support truss height and therefore improving transport barge stability.

The advantages of the different float-over methods is compared and the results is given in Table 1.

Summary, advantages of different float-over methods.				
Installation method	**Lift capacity**	**Availability**	**Mobility and productivity**	**Economics**
Heavy lift	The offshore record stands on 12 000 Te (SAIPEM S7000 and THIALF)	Only a few available, home-based in Europe.	Depends on the type and size of the lift vessel, DP or extensive mooring is required.	Rental rates can vary, depends on the required work window.
Internal float-over	Over 25 000 Te lift capacities can be achieved.	Several float-over systems are available in the offshore industry.	Most suitable for making only a few heavy lifts.	Simple equipment and cost effective under special circumstances.
External float-over	Catamaran: Up to 40 000 Te (Pioneering Spirit "Ex Pieter Schelte").		Depends on external float-over method. (catamaran/Versatruss)	

Table 1 Summary advantages of different float-over method

1.1.4 Versatruss

Versatruss is one of the external float-over technologies. With this method heavy prefabricated modules can be installed by relatively simple equipment in one single lift. The lift system consists of two barges each installed with three to four A-frame steel booms that are able to rotate and be raised and lowered (illustrated in Figure 2), winches and several wires (illustrated in Figure 3) assembled into a single lifting unit.

The A frame booms are manufactured from structural pipe and are mounted on frames attached to the centreline of the barge to eliminate vertical boom tip motion caused by individual roll motion of the barge during operation ref. [24]. The tip of each boom will be connected to a specially designed pin installed at the lower edge of the topside ref. [24].

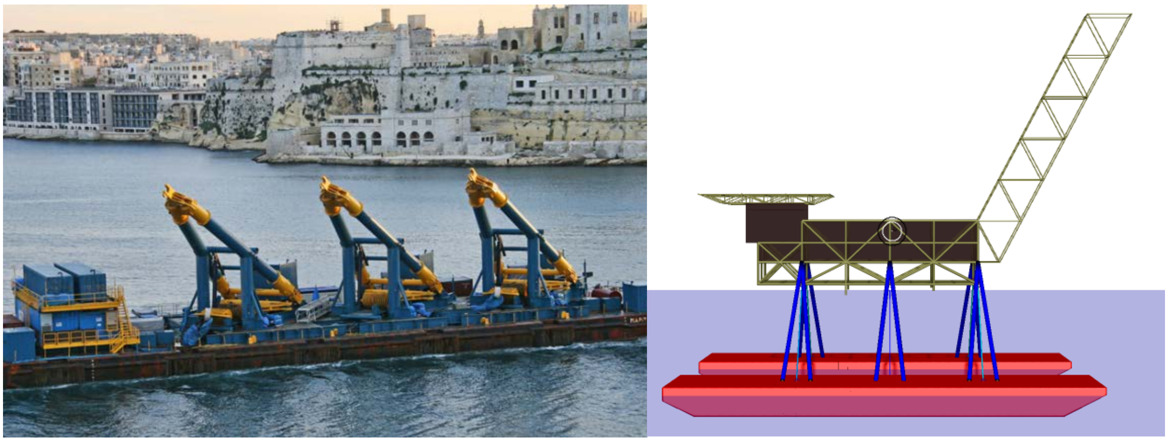


Figure 2 Illustration of the A-frame steel booms, ref. [24]

The topsides are lifted combining de-ballasting and tensioning of several wires. Tensioning of the wires introduce a vertical force component to the topside which effectively increase the inclination of the booms and vertical lift is achieved (illustrated in Figure 1). Boom angles are generally greater than 25 degrees at start of the lift and not more than 75 degrees at the end of the lift ref. [6]. There are practically no limitations on its lift capacities, however there are some installation limitations that will be discussed later in this document. Once the topside is in position, it is lowered by releasing the tension in the cables and increasing the spacing between the barges, ref. [24].

Figure 3 Illustration of the winches and wires, ref. [24]

The most critical type of loads are the loads that could result from relative motions (illustrated in Table 2), particularly the asymmetric pitch motions, of the two barges. Such loads have historically limited the application of this method to inshore sheltered locations, lakes and fjords according to ref. [1].

1.1.5 Critical loads

The responses illustrated in Figure 4 and Table 2 will normally be governing for global strength of the platform. The responses are normally calculated with respect to a point located on the centreline at still water plane and above the centre of gravity. These responses may be used to establish design wave data and limiting environmental criteria.

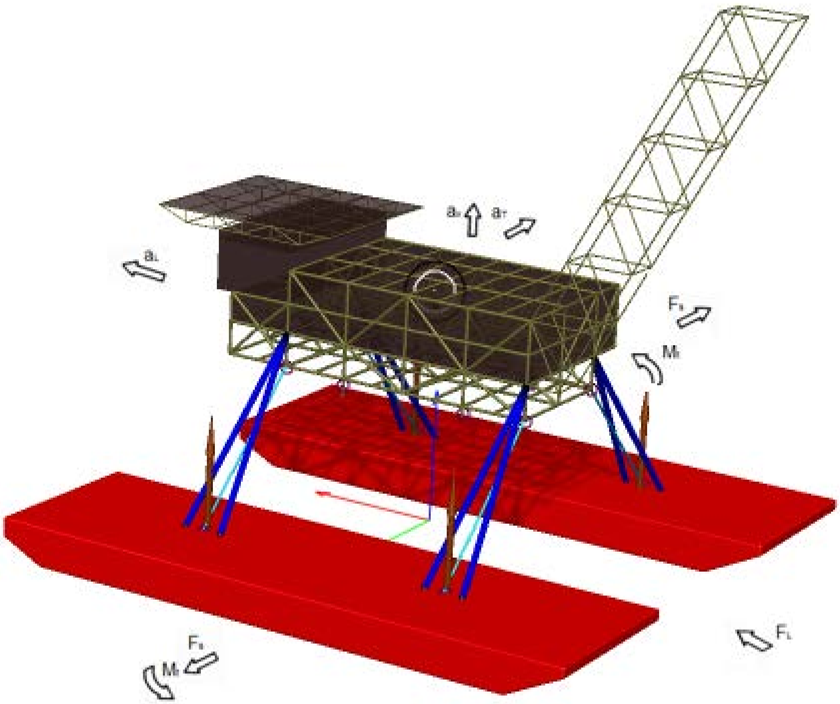


Figure 4 Illustrates the global responses and the forces acting on the Versatruss system. And the directions L (longitudinal), V (vertical) and T (transverse).

To account for the critical loads (forces and moments) a realistic and high stiffness is introduced into the wires and fenders (A-booms), in addition the A-booms and wires are placed far away from each other to introduce a large moment stiffness (M_t, in Figure 4). The critical loads are given in the Table 2 below.

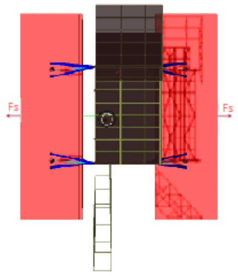
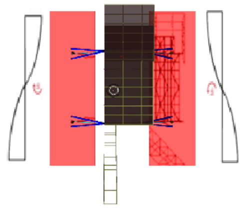
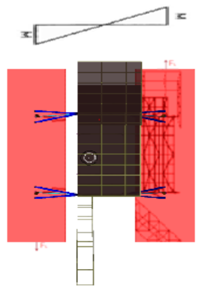
Critical load	Heading	Length	Illustration	Cause
Split force (asymmetric sway)	90^0	Wave length of approximately twice the outer breadth between the barges (174,7 m which corresponds to a period of 10,58 s).		This response will introduce axial force in the simple wires
Torsion moment (asymmetric pitch)	45^0 to 60^0	Wave length of approximately the distance of the diagonal between the barges (84,9 m which corresponds to a period of 7,37 s).		Without these bracing the topside has to be design for this moment.
Shear force (asymmetric surge)	45^0 to 60^0	Wavelength is 1.5 times the distance of the diagonal between the barges (127 m which corresponds to a period of 9,03 s).		A bending moment is introduced by longitudinal displacement for each barge-
This table is made on the basis of the documentation given in ref. [36]				

Table 2 Critical loads

1.2 Scope of work

The Versatruss method looks promising because it is less expensive, available, requires only two barges and requires no modifications to the substructure. This method will be studied during this master thesis study.

In order to get an overview over the hydrodynamics and the dynamics the literature is looked into. The literature that has been looked into are the books from Chakrabarti (ref. [1]), Faltinsen (ref. [2]), J.M.J. Journée and W.W. Massie (ref. [3]), Newman (ref. [4]) and Singiresu S. Rao (ref. [5]). The literature form the basis for some hand calculated response amplitude operators (RAOs) that will be compared with the output from the computer software HydroD, in order to validate that the model is correct.

The feasibility of the Versatruss lifting system will be considered. From a pre-study in the course in marine operations different float-over technologies and limitations of the float-over technology has been investigated. The limitations of the float-over technology can be sorted into three groups: handling difficulties, structural and installation limitations. In this report the installation limitations are investigated. The installation limitations are due to insufficient clearance and impact force. In order to investigate the installation limitations this report covers the response analysis of the Versatruss system. Different wave headings, wave heights and periods. The purpose of this report is to find the limiting wave height for the Versatruss system based on the installation limitations given in (Table 21 and Table 23).

For this purpose a model of the Standard Viking barge made in Genie (ref. Section 3.3.1) is made with correct dimensions in addition the compartments, plate thickness and the framework are included according to drawings to get the correct ballast condition, centre of gravity (COG) and moments of inertia. The panel model is discretized into a large number of discrete panels and a hydrodynamic analysis is performed in HydroD (ref. Section 3.3.2). The hydrodynamic analysis is compared with hand calculations to verify that the model and results are correct. The hydrodynamic results (added mass, mass, stiffness etc. ref. Section 5.2) is imported into SIMA where it is possible to do a time domain analysis, for the time domain analysis a small time integration of 2,5e-3 sec. is chosen. The motion, velocity and accelerations from the time domain analysis is compared with the limiting motion, velocity and acceleration. Since the same wave spectrum can be visualized with different wave heights and periods a random seed is included and it is done 10 realisations of the same wave spectrum to find the characteristic response with 10 % probability of exceedance. In addition a bootstrapping with Monte Carlo simulation is done to illustrate the confidence of the results.

All the assumptions that are used are documented, with the purpose to be able to look at the models limitations and verifications. The Versatruss set-up will be simulated in SIMA with different wave spectrums (wind induced waves and swells), and the critical response is considered.

1.3 Stages

1.3.1 Loadout

The topsides will be jacked up and placed on a deck support frame (DSF), which is normally a truss frame for its journey to the offshore site. This frame can be inserted under the topsides prior to loadout operation.

1.3.2 Transportation

Once completing the seafastening and float-over preparations and meeting the sail away criteria, the barge with the topsides departure fabrication yard bound for offshore installation site. The seafastening will be removed prior to mating according to ref. [26].

1.3.3 Standby

Upon arrival at installation site, the barge is kept a safe distance from the substructure and the cutting of sea fastening can start. The cutting of sea fastenings shall not start until the decision to proceed with the installation operation is made. In cases where the transportation sea fastening system is designed for transportation environmental conditions significantly more onerous than those prevailing at the installation location, partial removal of the sea fastenings may be considered upon arrival of the transport at location ref. [19].

The outrigger barges are brought along the centre barge (illustrated in Figure 5) one at a time for connecting boom tips with the topside and winch riggings. At this instant 100% topside load acts on centre cargo barge. Then tension up to transfer the topside load on the outrigger barges for preparing removal of the centre barge. Further tensioning up for a total lift and then ballast down the centre barge and avoid any potential impact ref. [28].

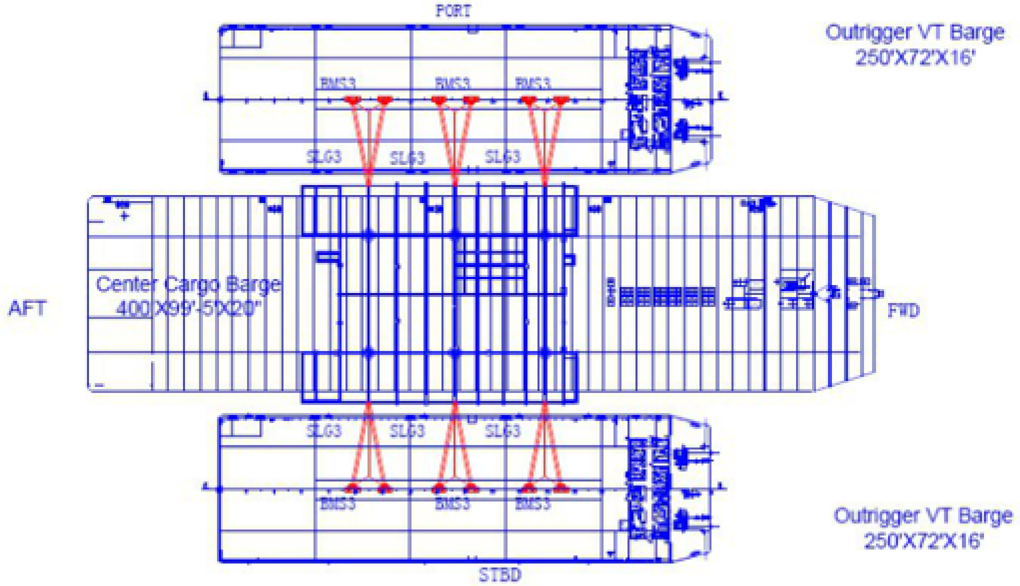


Figure 5 Trimaran configurations, the outrigger barges along the centre barge, ref. [28].

1.3.4 Docking

The twin barges are equipped with a guidance system to ensure precise positioning, within specified tolerances, of the topsides when set-down on the substructure and to protect against damage during the installation operation. The twin barges will be positioned and aligned with the substructure in middle.

Such systems can consist of:

- Passive guidance systems: bumpers and guides, pins and buckets, stabbing cones, stopper plates and fenders, designed to support the topside.
- Active guidance systems: jacking/winching systems that are connected to the topsides/transportation vessel to guide the topsides into position and to effect a load transfer from the transport barge to the structure.
- A combination of both passive and active guidance systems.

Ref. [19].

With the help of the soft-line rigging arrangement. The soft line positioning winching active guidance system is mainly used to suppress surge and sway motions within the slot. This is done in order to restrict the relative motions between the topside and the substructures such that the stabbing cone can be aligned with leg mating unit (LMU) (illustrated in Figure 6). The function of the LMU is to capture a stabbing cone placed at the bottom of the topside leg during initial mating.

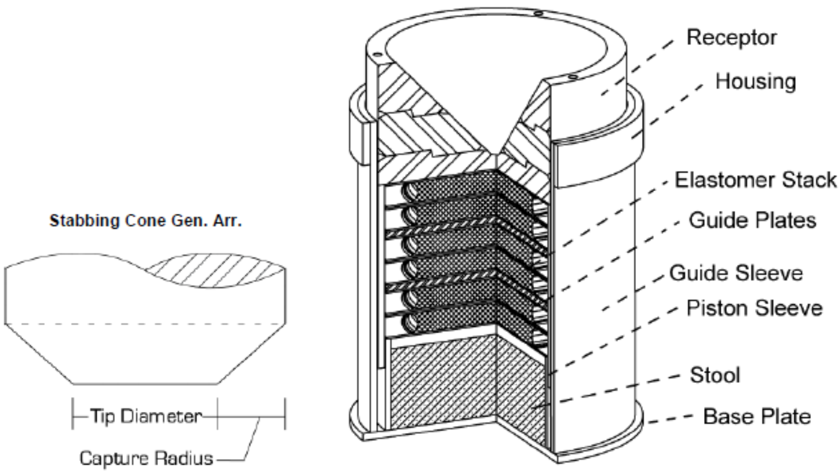


Figure 6 Stabbing cone to the left and a LMU to the right, ref. [27]

During the docking stage the barge motions should allow sufficient clearance between the topside and the top of the substructure in order to avoid unintended impacts and damage. When setting these clearances, consideration shall be given to the influence of factors such as relative motions, tide, current effects, water density, wind heel, bathymetry and draught measurement tolerances, as well as to deflections of structures. If the float-over is over a floating substructure the platform motions has to be accounted for and for a fixed substructure the tidal effects has to be accounted for according to [14]. The required clearances is given in Table 3.

The following minimum clearance are recommended:	
Sideways clearance	0.5 meters during positioning.
Vertical clearance	0.25 meters between the underside of the object and the top of the substructure during positioning. (1)
Under-keel clearance	0.5 meters if the substructure has underwater elements limiting the water depth.(2)
(1) As a guide the minimum vertical clearance between any part of the topsides and the structures legs or columns should not be less than 0,5 m for sheltered inshore locations, with due consideration of the local environmental conditions. For offshore locations, the minimum vertical clearances should take account of the operability requirements and of the relative motions between the topsides and structure under the design environmental conditions. [19].	
(2) Sufficient under-keel clearance for the substructure should be ensured at the maximum mating draught considering minimum tide and any possible heel, trim and/or motions.	
Note: Adequate clearances shall be ensured between object or vessel(s) and the substructure should be ensured throughout positioning, load transfer and removal of vessel(s).	

Table 3 Minimum clearance recommended in, ref. [14].

In addition the platform has to have sufficient stability (static and dynamic) and the structure has to be able to support the motions during operation

1.3.5 Initial mating

The stabbing cones are lowered to match the LMU by reducing the tension, it is critical that the motions are limited to suit the chosen LMU geometry. The mating process is facilitated by a LMU system that consist of a steel structure incorporating elastomer elements to achieve a specified spring rate. The spring rate depends on the expected loads and movements. The elastomer elements are designed to take up the static load, reducing the impact during initial mating and normalize dynamic loads during load transfer due to the wave conditions. In addition it may reduce impact during separation at the end of the process. Many different kinds of mechanical devices have been invented to facilitate the load transfer system, in order to minimizing the impact load during mating. This system typically consist of an LMU shock absorber between the topsides and substructures. It shall be documented that the selected LMUs will adequately dampen the maximum expected vertical and horizontal motions according to [14]. The minimum boom angle shall be determined for the initial contact while maintaining 100% topside loads on the outrigger barges.

1.3.6 Mating Operation (Load transfer)

The stabbing cones will be lowered further to active hydraulic devices which will transfer the topsides load from the barges onto the substructure. The requirement to maintain clearance does not arise here as the objective of this stage is to reduce that clearance to start load transfer. The load transfer systems are basically same for fixed or floating substructures, the difference is that floating substructures the substructure can be de-ballasted instead of lowering the topside.

An appropriate load transfer system should be provided to handle repeated impacts, taking into account the relative motions between the topsides, structure and transportation vessel, and the speed with which load transfer can take place. Where impacts are likely to occur, the topsides and the structure shall be designed for impact effects ref. [19]. The load transfer operation shall be designed to ensure completion without serious consequences, even in case of failure of any one system or component. Hydraulic jacks help shorten the installation period, the reliability of such devices shall be appropriately confirmed ref. [19].

The position of the topsides shall be verified when either sufficient weight of the topsides has been transferred to the structure to prevent any further movement or the topsides is engaged in the final guidance system, such that its accuracy of position is guaranteed upon set-down.

Where multiple barges support the topsides, the final load transfer sequences should be planned to maintain contact between each barge and the topsides until the removal stage.

1.3.7 Post mating

After having transferred the full topsides load all the rigging is disconnected and the outriggers with the booms are removed.

2 Hydro Mechanics

2.1 Motion of vessel

When planning a marine operation it is important to understand how the floating structures are affected by the environmental loads at sea. The floating structure respond to the environmental forces with translatory motions and angular motions. The motions of floating structures can be divided into wave-frequency motion, high-frequency motion and slow-drift motion.
The motions:

- The wave-frequency motion is mainly linearly-excited motion in the wave-frequency range of significant wave energy.
- High-frequency motion is often referred to as “ringing” and “springing”. “Ringing” is associated with transient effects (e.g. damped motion) and “springing” is steady state oscillation (e.g. harmonic motion).
- Slow drift and mean drift are mainly non-linear effects caused by wind, waves and current. Slow drift motions arises from resonance oscillations. Slow drift can be illustrated by using two sinus or cosines functions with slightly different frequencies (illustrated in Figure 7).

The oscillating translatory motions are referred to as surge, sway and heave. The oscillating angular motions are referred to as roll, pitch and yaw (described in Table 4). Any vessel motion is built up from these basis 6 degrees of freedom (DOF). Ref. [2]

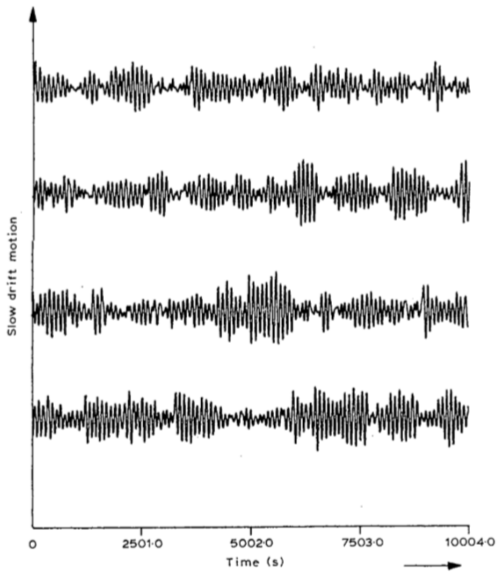


Fig. 5.23. Identical simulations of slow-drift motions of a moored two-dimensional body. The differences in the results are due to random selection of phase angles and wave amplitudes.

Figure 7 Slow drift motion, ref. [2]

Motion	Description	Formula
Surge	Longitudinal translation in x-direction, positive forwards. (forward/astern)	$x_b = Xsin(\omega_e t + \theta_x)$
Sway	Lateral translation in y-direction, positive to port side. (starboard/port)	$y_b = Ysin\left(\omega_e t + \theta_y\right)$
Heave	Vertical translation in z- direction, positive upwards. (up/down)	$z_b = Zsin(\omega_e t + \theta_z)$
Roll	Angular motion about the x-axis, positive right turning. (rotation about surge axis)	$\theta = \theta sin(\omega_e t + \theta_\theta)$
Pitch	Angular motion about the y-axis, positive right turning. (rotation about sway axis)	$\phi = \phi sin\left(\omega_e t + \theta_\phi\right)$
Yaw	Angular motion about the z-axis, positive right turning. (rotation about heave axis)	$\psi = \psi sin\left(\omega_e t + \theta_\psi\right)$

The coordinate system is given in Figure 8 below.

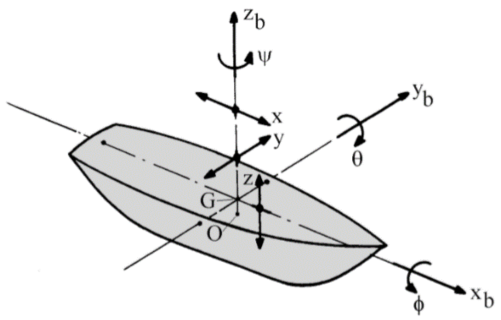


Figure 8 Vessel Motions in Six Degrees of Freedom (Figure 1.1, ref. [3])

Comment: Heave and pitch are the most important responses during crane installation or float-over. Usually marine lift operations are not performed if large pitch motions can occur.

Table 4 Motion of vessel

2.2 Stability

Stability is the ability of a body to resist the overturning moment and return to its undisturbed position after the disturbing forces are removed. These forces may arise from weather environment, tow lines, shifting of mass (cargo or passengers) or flooding due to damage.

When a floating vessel is at rest in static equilibrium, it is under the influence of two forces gravitational forces and buoyant forces. The gravitational forces are simply due to the weight of the vessel applied at the centre of gravity. This gravitational force is the product of mass and gravitational acceleration, while buoyancy is given by the weight of the displaced volume of water (**∇**) due to the presence of the body.

$$M_B = \nabla \rho_w = LBd\rho_w \qquad \text{(Eq. 2.1)}$$

From *(Eq. 2.1)*, it is possible to calculate the draft (d).

$$d = \frac{M_B}{L * B * \rho_w} \qquad \text{(Eq. 2.2)}$$

Sufficient freeboard is necessary in order to prevent sinking or green water (water on deck). The freeboard is the minimum vertical distance from the water surface to any opening illustrated in Figure 9. The minimum freeboard (1,27 m) is calculated for the Standard Viking barge and given in Table 5.

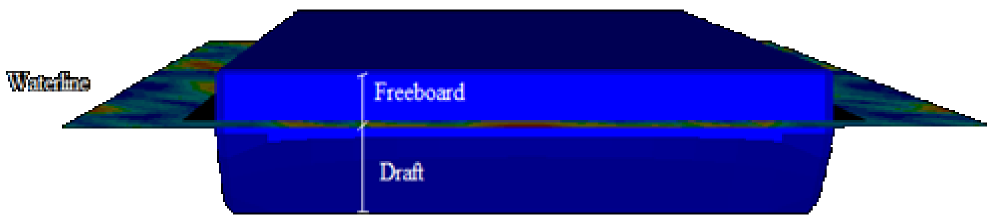


Figure 9 A cross section of a barge showing the relation between freeboard and draft

Freeboard correction	Formula/table	Value
Freeboard for Type "B" vessels (*) (f_c)	Table B Freeboard table for Type «B» vessels ref. [22][(1)]	1,03 m
Correction to freeboard for vessels under 100m in length (f_l)	$f_l = 7{,}5(100 - L_d)\left(0{,}35 - \frac{E}{L_d}\right)$ [(2)]	0,03 m
Correction for Block Coefficient (f_b)	$C_B = \frac{\nabla}{BL_d d}$ $f_b = \frac{C_B + 0{,}68}{1{,}36}$	0,22 m
Correction for Depth (f_d)	$f_d = \left(d - \frac{L_d}{15}\right)\left(\frac{L_d}{0{,}48}\right)$	0,04 m
Sheer (f_s)	Standard sheer profile ref. [22]	0,37 m
Reduction	Unmanned barges which have on the freeboard deck only small access openings closed by watertight gasketed covers of steel or equivalent material may be assigned a freeboard 25 percent less than those calculated in accordance with these regulations	
Sum	$f = (f_c + f_l + f_b + f_d + f_s)(0{,}75)$	1,27 m
(1) The Standard Viking barge is a Type B vessel. (2) The length (L_d) shall be taken as 96% of the total length on a waterline at 85% of the least moulded depth measured from the top of the keel. This table is made to illustrate the required freeboard for the Standard Viking barge. The table is made with respect to DNV ref. [22] Therefore a the freeboard has been selected as 2,0 meters.		

Table 5 Minimum freeboard for the Standard Viking barge, ref. [22]

The buoyancy is a static restoring force, from the buoyancy *(Eq. 2.3)* it is possible to find the vertical stiffness of the waterline area.

$$F = \nabla \rho_w g = A_w d \rho_w g = k_{33} d \qquad \text{(Eq. 2.3)}$$

$$k_{33} = A_w \rho_w g \qquad \text{(Eq. 2.4)}$$

2.2.1 Metacentre

The metacentric height is defined as following GM.

$$GM = KB + BM - KG \qquad \text{(Eq. 2.5)}$$

Where KB *(Eq. 2.6)* and KG *(Eq. 2.7)* are the distances from the keel of the vessel to the centre of buoyancy and gravity. BM is the distance between the centre of buoyancy and the metacentre.

$$KB = \frac{d}{2}, \quad \text{for a rectangular barge} \qquad \text{(Eq. 2.6)}$$

The centre of buoyancy depends on the shape/geometry of the bottom part and draft.

$$\overline{BM}_T = \frac{I}{\nabla} = \frac{LB^3}{12} * \frac{1}{LBd} = \frac{B^2}{12d} \qquad \text{(Eq. 2.7)}$$

The keel to centre of gravity (KG) depends on the mass distribution illustrated in *(Eq. 2.8)*.

$$KG = \frac{\sum m_i \overline{x_i}}{\sum m_i} \qquad \text{(Eq. 2.8)}$$

B and G must be located along the same vertical line and B=G. If not these two forces will create a moment that will tilt the vessel (illustrated in Figure 10).

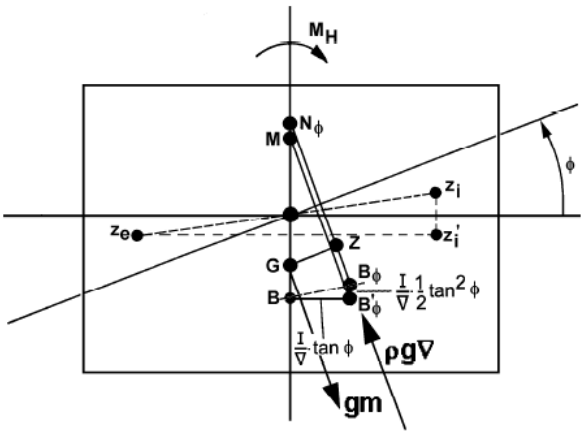


Figure 10 Illustration of the stability for a rectangular barge, ref. [3]

The axis of rotation should be perpendicular to the long axis of the vessel. All free-floating structures should have adequate stability to preclude capsizing. The vessel should also have a damaged stability such that it can sustain a moderate environment in a damaged condition, e.g. when one of its compartments is flooded. According to the equation for the metacentric height it is possible to achieve better stability by adding additional weight (ballasting). The description of different GM values are given in Table 6.

GM	Description
GM > 0 (initial stability)	The up-righting moment is larger than zero and will bring the vessel back to initial position. The up-righting moment is given in *(Eq. 2.9)*.
GM = 0 (indifferent equilibrium)	There will be no up-righting moment bringing the vessel back to initial position.
GM < 0 (unstable)	The vessel will usually take a "recovery position" or continue to incline until capsizing.

Table 6 Description of different GM values

The up-righting moment is given by the buoyancy force *(Eq. 2.3)* and the arm for small angles the up-righting moment is given by *(Eq. 2.9)*.

$$M_r = \overline{GZ} * \nabla \rho_w g = \overline{GM} sin\theta * \nabla \rho_w g = \nabla \rho_w g * \overline{GM} \theta \quad \text{(Eq. 2.9)}$$

The stability for a rectangular flat bottom barge is given in Table 7.

Term	Assumption	General formulas	Barge formulas
M_B	Constant water density. Rectangular, flat bottom barge	$\nabla \rho_w$	$LBd\rho_w$
k_{33}		$A_w \rho_w g$	$LB\rho_w g$
KB	Rectangular, flat bottom barge	$\frac{\sum \nabla_i \overline{x_i}}{\sum \nabla_i}$	$\frac{d}{2}$
$\overline{BM}_T$		$\frac{I_{xx}}{\nabla}$	$\frac{B^2}{12d}$
GM_T		$KB + BM - KG$	$\frac{d}{2} + \frac{B^2}{12d} - \frac{\sum m_i \overline{x_i}}{\sum m_i}$
$\overline{BM}_L$		$\frac{I_{yy}}{\nabla}$	$\frac{L^2}{12d}$
GM_L		$KB + BM - KG$	$\frac{d}{2} + \frac{L^2}{12d} - \frac{\sum m_i \overline{x_i}}{\sum m_i}$

Table 7 Summary stability

2.3 Hydrodynamic

Hydrodynamics are a collective term of fluid in motion, in contrast to hydrostatics. Marine hydrodynamics relates to the effects of the wave environment on floating structures and the oscillatory motions of floating structures to respond to the waves. Ref. [4]

2.4 Equation of motion

There is no structure that is infinite stiff, therefore all structures are dynamic which means they can be set into motion. If a structure is exposed to dynamic (time variable) loads, for example, a vessel exposed to wave loads. There will arise inertia forces, hydrostatic restoring forces from the waterline (A_w) and there will be energy lost due to damping in the water. This will lead to dynamic effects that have to be accounted for according to ref. [12]. In order to determine the response the equation of motion is introduced.

$$m\ddot{x} + c\dot{x} + kx = F(t) = F_0 \sin(\omega t) \qquad \text{(Eq. 2.10)}$$

The equation of motion *(Eq. 2.10)* is a product of Newton`s second law of motion which states that the force acting on an object equals the product of the mass and the acceleration. Harmonic loading is relevant for waves because all periodic motion can be given as a sum of harmonic functions through Fourier expansion.

Since the equation of motion is nonhomogeneous, its general solution u(t) is given by the sum of the homogeneous solution, $u_h(t)$ and the particular solution $u_p(t)$. The homogenous solution $u_h(t)$ is the solution to the homogeneous equation *(Eq. 2.11)*:

$$m\ddot{x} + c\dot{x} + kx = 0 \qquad \text{(Eq. 2.11)}$$

The equation *(Eq. 2.11)* represents the free vibration of the system and dies out with time under all conditions of damping and all possible initial conditions. The general solution of the equation of motion reduces to the particular solution $u_p(t)$, which represent the steady–state vibration. The steady-state motion is present as long as the forcing function is present as shown in *(Eq. 2.10)*. Since the force is harmonic the particular solution is also expected to be harmonic with an amplitude (X) and a small delay (θ):

$$x_p(t) = Xsin(\omega t - \theta) \qquad \text{(Eq. 2.12)}$$

Where X (amplitude) and θ (phase angle) are constants to be determined from the homogenous and particular conditions.

$$X[(k - m\omega^2)cos\theta + c\omega sin\theta]\sin(\omega t) = F_0\sin(\omega t) \qquad \text{(Eq. 2.13)}$$
$$X[(k - m\omega^2)sin\theta + c\omega cos\theta]\cos(\omega t) = 0$$

From these two equations the amplitude X and the phase angle θ are obtained.

$$\theta = \tan^{-1}\left(\frac{c\omega}{k - m\omega^2}\right) \qquad \text{(Eq. 2.14)}$$

$$X = \frac{Q_0}{\sqrt{(k - m\omega^2)^2 + c^2\omega^2}} \qquad \text{(Eq. 2.15)}$$

In order to simplify the equation, the numerator and the denominator in equation can be divided by the stiffness coefficient (k) and making the following substitutions *(Eq. 2.16)*.

$$k = m\omega_n^2, \qquad \lambda_d = \frac{c}{c_c} = \frac{c}{2m\omega_n}, \qquad r = \frac{\omega}{\omega_n}, \qquad \delta_{st} = \frac{F_0}{k} \qquad \text{(Eq. 2.16)}$$

The following relation is obtained *(Eq. 2.17)*.

$$X = \frac{\frac{F_0}{k}}{\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \frac{c^2\omega^2}{m\omega_n^2}}} = \frac{\delta_{st}}{\sqrt{(1 - r^2)^2 + (2\lambda_d r)^2}} = DAF * \delta_{st} \qquad \text{(Eq. 2.17)}$$

This function is often referred to as the transfer function, because it transfer the load function into a displacement function.

2.5 Dynamic amplification factor

To understand which frequencies that gives the largest response of the vessel, the dynamic amplification factor (DAF) is introduced *(Eq. 2.18)*. The amplification factor, DAF, states how much the dynamic response is compared to the static response (δ_{st}) caused by the load (Q_0) as shown in *(Eq. 2.17)*.

$$DAF = \frac{1}{\sqrt{(1-r^2)^2 + (2\lambda r)^2}} \qquad \text{(Eq. 2.18)}$$

This equation shows that DAF is a function of the damping ratio (λ_d) and the frequency ratio (r). At resonance the exciting frequency coincides with the systems natural frequencies (resonant frequency). At resonance the vibration amplitude is only limited by the systems damping ratio (λ_d), because the frequency ratio (r) becomes equal to one *(Eq. 2.19)*.

$$DAF = \frac{1}{\sqrt{(2\lambda_d)^2}} = \frac{1}{2\lambda_d} \qquad \text{(Eq. 2.19)}$$

The damping ratio decides how high the peak of the DAF curve will become in the damping controlled region (illustrated in Figure 11). If there is no damping the DAF will go towards infinity in this region.

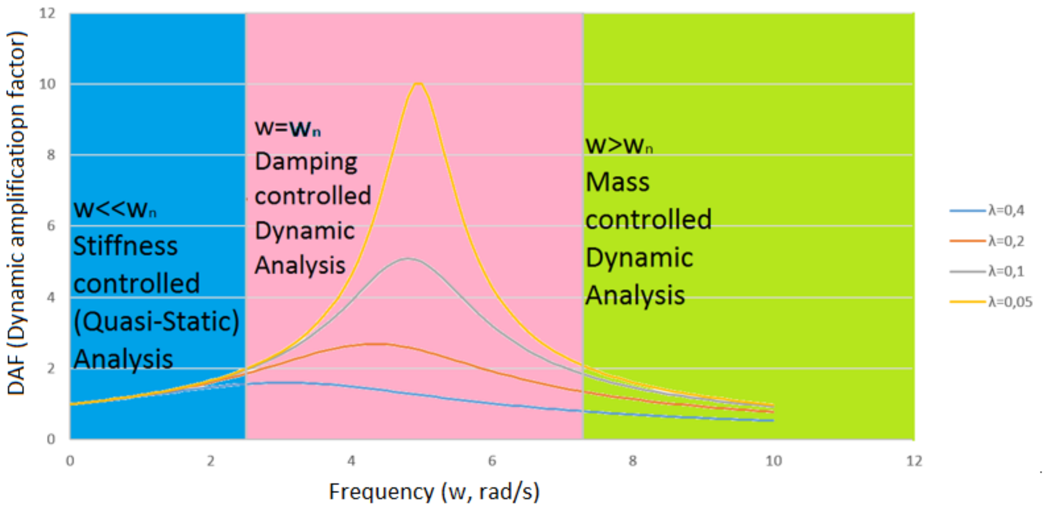


Figure 11 DAF the natural frequency (wn) for this diagram is 5 rad/s.

Every system with a mass and a stiffness have a natural frequency, if the driving wave force have the same frequency as the natural frequency resonance is obtained ($\omega \approx \omega_n$). The damping controlled region where the driving wave force frequencies are close to the natural frequency is in general undesirable.

The Figure 11 shows how much the force will influence the response of a system related to the frequency. If there is no motion DAF is equal to the static displacement (δ_{st}). In the damping controlled region a high damping ratio is desirable. For the stiffness controlled and mass controlled region the damping coefficient and the damping ratio is not that important as illustrated in Figure 11.

2.5.1 Added mass and mass

For unsteady flow around objects an additional force resulting from the fluid acting on the structure must be taken into account in the equation of motion. The added mass is actually a hydrodynamic force. A good way to think of the added mass components is to think of each term as mass associated with a force in a given direction on the body that gives a unit acceleration in the direction. Since the added mass force is in phase with the acceleration of the vessel, the force is taken into account by finding the equivalent mass.

The added mass depends on the ability to move additional fluid, this depends on the shape of the vessel. As a simplification some two dimensional added mass coefficients that depends on the shape has been developed. The two-dimensional added mass coefficients are independent of the wave frequency, in reality and in computer programs the added mass is dependent of the frequency.

Table A-1 Analytical added mass coefficient for two-dimensional bodies, i.e. long cylinders in infinite fluid (far from boundaries). Added mass (per unit length) is $A_{ij} = \rho C_A A_R$ [kg/m] where A_R [m^2] is the reference area

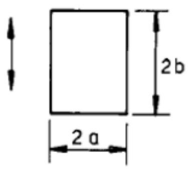
Section through body		*Direction of motion*	C_A	A_R	*Added mass moment of inertia* [(kg/m)*m^2] $\beta_1 \rho \pi a^4$ or $\beta_2 \rho \pi b^4$		
					a/b	β_1	β_2
	a / b = ∞	Vertical	1.0	πa^2	0.1	-	0.147
	a / b = 10		1.14		0.2	-	0.15
	a / b = 5		1.21		0.5	-	0.15
	a / b = 2		1.36		1.0	0.234	0.234
	a / b = 1		1.51		2.0	0.15	-
	a / b = 0.5		1.70		5.0	0.15	-
	a / b = 0.2		1.98		∞	0.125	-
	a / b = 0.1		2.23				

Figure 12 Analytical added mass coefficients for two dimensional bodies, ref. [15]

The coefficients of proportionality is the added mass or the effective mass of the fluid that surrounds the body and must be accelerated with it. For a barge which is floating (not submerged) the added mass is half the value given in Figure 12. The added mass is given as the following for surge, sway, heave and roll motion (Eq. 2.20).

$$a_{jk=1..4} = \int_0^L a_{jk=1..4}^{2D} dx \qquad \text{(Eq. 2.20)}$$

For the roll and yaw motion the added mass is given by *(Eq. 2.21)*.

$$a_{jk=5..6} = \int_0^L x^2 a_{jk=1..6}^{2D} dx \qquad \text{(Eq. 2.21)}$$

For vessels with lateral symmetry it follows that the added mass (or damping) coefficients are.

$$A_{jk}\ (or\ B_{jk}) = \begin{bmatrix} A_{11} & 0 & A_{13} & 0 & A_{15} & 0 \\ 0 & A_{22} & 0 & A_{24} & 0 & A_{26} \\ A_{31} & 0 & A_{33} & 0 & A_{35} & 0 \\ 0 & A_{42} & 0 & A_{44} & 0 & A_{46} \\ A_{51} & 0 & A_{53} & 0 & A_{55} & 0 \\ 0 & A_{62} & 0 & A_{64} & 0 & A_{66} \end{bmatrix} \qquad \text{(Eq. 2.22)}$$

Since the vessel motion is built up by 6 degrees of freedom the added mass matrix *(Eq. 2.23)* and the mass matrix *(Eq. 2.24)* have the same form.

$$[a]_{6x6} = [a_{jk}] \qquad \text{(Eq. 2.23)}$$

$$[m] = \begin{bmatrix} M & 0 & 0 & 0 & mz_g & -my_g \\ 0 & M & 0 & -mz_g & 0 & mx_g \\ 0 & 0 & M & my_g & -mx_g & 0 \\ 0 & -mz_g & my_g & I_{44} & 0 & -I_{46} \\ mz_g & 0 & -mx_g & 0 & I_{55} & 0 \\ -my_g & mx_g & 0 & -I_{46} & 0 & I_{66} \end{bmatrix} \qquad \text{(Eq. 2.24)}$$

Where x_g is the vector position of the centre of gravity. With the following assumptions; motions are linear and small with no transient effects, the vessel has port/starboard symmetry and the origin of the coordinate system coincides with the centre of gravity of the vessel. The inertia matrix reduce to the following *(Eq. 2.25)* for motions around the centre of gravity according to ref. [29].

$$[m] = \begin{bmatrix} M & 0 & 0 & 0 & 0 & 0 \\ 0 & M & 0 & 0 & 0 & 0 \\ 0 & 0 & M & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{44} & 0 & -I_{46} \\ 0 & 0 & 0 & 0 & I_{55} & 0 \\ 0 & 0 & 0 & -I_{46} & 0 & I_{66} \end{bmatrix} \qquad \text{(Eq. 2.25)}$$

Here the body mass is given by

$$M = \iiint_V p dV = p\nabla \qquad \text{(Eq. 2.26)}$$

And the moments of inertia can be defined by

$$I_{jk} = \iiint_V p[x' * x' \delta_{jk} - x'_j x'_k] dV \qquad \text{(Eq. 2.27)}$$

Where δ_{jk} is the Kronecker delta function. The roll-yaw product (I_{46}), is the only product of inertia that remains with the origin at the centre of gravity. The roll-yaw product vanishes if the vessel has fore-and-aft symmetry and is small otherwise and is often neglected according to ref. [29].

The added mass and mass for heave, roll and pitch are given in given in Table 8.

Term	Assumption	General formulas	Barge formulas
A_{33}	Strip theory (L/B>3). Added mass is unaffected by wave frequency. Deep water	$\int_0^L a_z^{2D}(x)dx$	$\rho_w C_a \frac{\pi B^2 L}{8}$
A_{44}		$\int_0^L a_z^{2D}(x)dx$	$0{,}5\beta_1 \rho_w \pi \left(\frac{B}{2}\right)^4$
A_{55}			$0{,}5\beta_1 \rho_w \pi \left(\frac{L}{2}\right)^4$
M_{33}	Rectangular, flat bottom barge	$\iiint \rho_w \, dV$	$\rho_w dLB$
I_{44}		$\iiint x^2 \rho_w \, dV$	$\frac{\rho_w dLB^3}{12}$
I_{55}		$\iiint x^2 \rho_w \, dV$	$\frac{\rho_w dBL^3}{12}$

Table 8 Summary added mass and mass

The topside moments and products of inertia are based on a weight list where the weights and points are given. It is assumed that the mass centrums can be treated as a system of n particle P_i, i=1,2,…,n (illustrated in Figure 13)

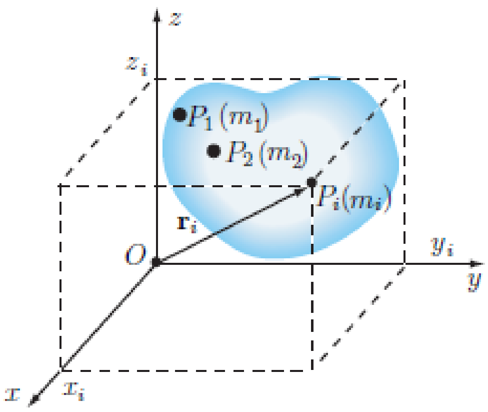


Figure 13 Illustrates the mass centrum O and the different particle points (pi) with mass (mi), ref. [34]

Where the position of the particle (Pi) is given in *(Eq. 2.28)*.

$$r_i = x_i i + y_i j + z_i k \qquad \text{(Eq. 2.28)}$$

The moments of inertia is given in *(Eq. 2.29)*.

$$I_{xx} = \sum_i m_i(y_i^2 + z_i^2), \quad I_{yy} = \sum_i m_i(z_i^2 + x_i^2), \quad I_{zz} = \sum_i m_i(x_i^2 + y_i^2) \qquad \text{(Eq. 2.29)}$$

The products of inertia of the system is given in *(Eq. 2.30)*.

$$I_{xy} = \sum_i m_i x_i y_i, \quad I_{yz} = \sum_i m_i y_i z_i, \quad I_{xz} = \sum_i m_i x_i z_i \qquad \text{(Eq. 2.30)}$$

The following equations ((Eq. *2.28*), (Eq. *2.29*) and (Eq. *2.30*)) have been used to calculate the moments and products of inertia, and the results can be found in Appendix B, (Table 38).

2.5.2 Damping

There are several ways to estimate the damping coefficients. The damping coefficient's are dependent on the frequency (ω), the damping is zero when ($\omega \rightarrow 0 \; or \; \infty$) and indifferent in between.

From energy conversation it can be shown that the damping coefficient of a two-dimensional body symmetric about x=0 is related to the amplitude of the far field waves generated by its motion by Newman's energy relation *(Eq. 2.31)* ref. [4]. The energy relation is based on how much water a vessel will displace ref. [2]. The formula is related to the radiation wave amplitude (ξ_a), vessel movement (ξ_i), and frequency (ω) of the waves as shown below.

$$c_{ii} = \frac{pg^2}{\omega^3}\left|\frac{\xi_a}{\xi_i}\right|^2 \qquad \text{(Eq. 2.31)}$$

Where the radiation amplitude has to be found from a forced motion test related to each force frequency. The equation takes the energy from each wave into consideration making this close to truth relation for calculating the damping of the system. The total damping is obtained by integrating over the length. For the heave motion the result of this equation *(Eq. 2.31)* is given in Table 10.

As mentioned earlier the damping coefficient is only important in the damping controlled region where the frequency is close to the natural frequency ($\omega \approx \omega_n$). The natural roll frequency often lies within the most energetic part of the wave spectrum. The roll motion therefore tend to be dominated by resonant motions at the natural period, and are sensitive to changes in the amount of damping present. For the other DOF the damping is not that important because the natural frequency lies outside the energetic part. Figure 14 shows various estimates of the roll damping of a "standard barge" with rectangular cross section. The calculations are based on a vessel with the following details (illustrated in Table 9).

	Model tested vessel	Viking barge
Overall length (L)	91,5 m	91,4 m
Breadth (B)	27,4 m	27,4 m
Draught (d)	2,74m	4,10 m
Displacement ($\nabla\rho_w$)	6581 Te	9636 Te
With a raked bow.	30^0	$27{,}4^0$
Rounded corners	R450 (B/60)	R400

Table 9 Comparison between the Viking barge and the barge used in the model test.

As illustrated in Table 9 the vessels are quite equal and it is therefore reasonable to believe that the same non dimensional roll damping coefficient is valid for the Standard Viking barge as well. The non-dimensional roll damping is given in Figure 14.

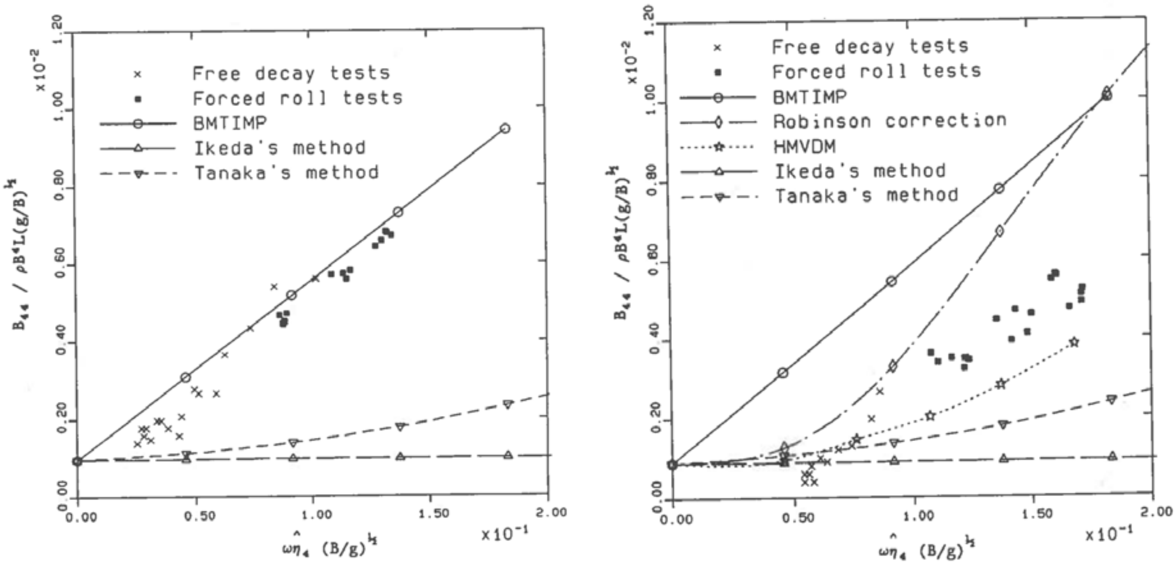


Figure 14 Non dimensional roll damping coefficients for a standard rectangular barge; theoretical predictions compared with measurements from free-decay and forced-roll model test. (Figure to the left sharp corners, right rounded corners), ref. [7]

Figure 14 shows that a small amount of rounding of the bilge corners substantially reduced the measured damping, particularly at small roll angles. The corner radius was only 1/60 of the vessels beam.

$$\omega_{n,44}\left(\frac{B}{g}\right)^{1/2} \approx 0{,}44 \qquad \text{(Eq. 2.32)}$$

Since the corners on the Viking barge is rounded (R400) the figure to the right (illustrated in Figure 14) will be used. From this table a roll damping of 10 % is chosen as a conservative value (illustrated in Table 10).

The damping for heave and roll are given in given in Table 10.

Term	Assumption	General formulas	Barge formulas
c_{33}	Only damping because of radiation. Energy relation in fluid from Newman linear theory	$\int_0^L \rho_w \left\lvert\frac{\xi_a}{\xi_i}\right\rvert^2 * \frac{g^2}{\omega^3} dx$	$\rho_w \left(\frac{\xi_a}{\lvert z\rvert}\right)^2 * \frac{g^2}{\omega^3} L$
c_{44}	Non dimensional roll damping coefficients from free-decay and forced-roll model test ref. [7].	$\lambda_d = \frac{c}{c_c} = \frac{c}{2m\omega_n}$	$0.2m\omega_n$

Table 10 Summary damping.

2.5.3 Stiffness

The hydrostatic restoring force coefficients give the net hydrostatic force acting on the vessel in the direction due to a unit displacement. The stiffness is found by comparing the force with the respective motion, therefore the stiffness comes from the following relation:

$$k_T = \frac{F}{x}$$
$$k_R = \frac{M}{\theta} \qquad \text{(Eq. 2.33)}$$

The water have a vertical stiffness but the horizontal stiffness is practically zero, if the vessel moves in the horizontal direction it will not arise any forces trying to push the vessel back into position.

$$k_{jk} = 0, \quad except\ for\ the\ values \qquad \text{(Eq. 2.34)}$$
$$k_{33} = pg\int_{-L/2}^{L/2} B(x)dx = pgA_w$$
$$k_{35} = -pg\int_{-L/2}^{L/2} xB(x)dx = 0$$
$$k_{44} = pg\int_{-B/2}^{B/2} y^2L(y)dx = pg\nabla GM_T$$
$$k_{55} = pg\int_{-L/2}^{L/2} x^2B(x)dx = pg\nabla GM_L$$

The stiffness for heave, roll and pitch are given in Table 11. The other stiffness are equal to zero.

Term	Assumption	General formulas	Barge formulas
k_{33}	Only wave force. The vertical difference between the COB COG is very small relative to the length of the vessel. COG in centre of vessel.	$k_T = \frac{F}{x}$	pgA_w
k_{44}		$k_R = \frac{M}{\theta}$	$pg\nabla GM_T$
k_{55}			$pg\nabla GM_L$

Table 11 Summary stiffness.

2.5.4 Force

The hydrostatic and hydrodynamic forces acting on the vessel are obtained by integrating the fluid pressure over the underwater portion of the hull. The components of the fluid forces acting in each of the six degrees of freedom are given by the Froude-Krylov force *(Eq. 2.35)* by introducing a normal n_j ref. [8]

$$F_{Fk} = \iint_S p_D n_j ds \quad j = 1,2 \dots.,6 \qquad \text{(Eq. 2.35)}$$

This force relates to the outer pressure on the exposed wetted surface area. To achieve the total force, the pressure function has to be integrated over the vessel wetted surface area. Where n_j is the normal to the hull surface into the hull, P is the fluid pressure and S is the underwater hull surface area. The components of the generalized normal are equal to the usual hull surface normals for the translation modes (j = 1, 2, 3) and equal to the moments of the unit normals for the rotational modes {j = 4,5,6) according to ref. [8] Consequently, it may be written that:

$$(n_1, n_2, n_3) = n \qquad \text{(Eq. 2.36)}$$
$$(n_4, n_5, n_6) = r\ x\ n$$

Where n is the unit normal to the hull surface out of the fluid and r is the vector from origin to a point on the hull (xi+yj+zk).

$$F_{ii} = \iint_S p_D n ds\, , i = 1,2,3 \qquad \text{(Eq. 2.37)}$$

$$M_{ii} = \iint_S p_D (r\ x\ n) ds\, , i = 4,5,6$$

The pressure on the body can be found using Bernoulli's equation. Assuming an inviscid and irrotational flow ($\nabla^2\Phi = 0$), the equation for the pressure is

$$P = \frac{1}{2} p_w U_0^2 - p_w \frac{\partial \Phi}{\partial t} - \frac{1}{2} p_w (\nabla^2 \Phi) - p_w g z \qquad \text{(Eq. 2.38)}$$

In *(Eq. 2.38)*, the first three terms represent the hydrodynamic contributions to the pressure and the last term represents the hydrostatic contribution. By assuming that the draft (z) and the forward speed (U_0) is small and neglect able, the hydrostatic contribution can be neglected. The limitation of this assumption is large draft and forward speed. The equation for the pressure then reduce to *(Eq. 2.39)* for deep water.

$$P_d = -\rho \frac{\partial \Phi}{\partial t} = \rho \frac{\xi_a g}{\omega} e^{-kd} sin(\omega t - kx) \qquad \text{(Eq. 2.39)}$$

The dynamic pressure is parallel with the wave and reaches its maximum under the wave crest and its minimum at wave troughs.

For the heave motion the added mass force (from Newton's second law) has to be included which is a product of the vertical particle acceleration (a_3) and the added mass (A_{33}).

$$F_{M,33}(t) = \int_{-\frac{L}{2}}^{L/2} a_{33} * a_3 \tag{Eq. 2.40}$$

The forces and moments are given in Table 12 the other forces and moments are equal to zero.

Term	Assumption	General formulas	Barge formulas
$F_3(t)$	Strip theory. Linear wave theory (Not applicable for steep waves). Only wave force and added mass force. Deep water.	$\iint p_D n_3 ds + a_z * a_3$	$\left[pg\xi_a B e^{-kD} - a_z \omega^2 \xi_a e^{-\frac{kD}{2}}\right] * \frac{2}{k} \sin\left(\frac{kL}{2}\right) \cos(\omega t)$
$M_1(t)$		$\iint p_D n_\theta ds$	$\left(\frac{L\rho_w g \xi_a e^{-kD}}{k^2}\right)\left(2 * \sin\left(\frac{Bk}{2}\right) - Bkcos\left(\frac{BK}{2}\right)\right) \sin\left(\omega t - \frac{\pi}{2}\right)$
$M_2(t)$			$\frac{2}{k} p_w g \xi_a B \left[e^{-kD} - k\frac{\pi B}{8} e^{-kD/2}\right]\left(\frac{L}{2}\cos\left(\frac{kL}{2}\right) - \frac{1}{k}\sin\left(\frac{kL}{2}\right)\right)$

Table 12 Summary force

2.6 The natural frequency and period

A natural frequency is a frequency at which a system vibrates when it is removed from the rest position and is left to vibrate without any external forces. The requirement for natural vibration is that the system possess both mass and stiffness. The natural frequency is given by *(Eq. 2.41)*.

$$\omega_{n,jk} = \sqrt{\frac{k_{jk}}{M_{jk} + A_{jk}}} \qquad \text{(Eq. 2.41)}$$

For continuous mass and stiffness distributions, the system possesses an infinite number of natural frequencies, even though only a relatively small numbers are usually of practical significance. When the system is removed from rest position it will vibrate at all of its natural frequencies, the degree of vibration will depend on the characteristics of the impulsive stimulus. Each different natural frequency of a system defines a mode of system vibration. The modes are ordered numerically upward from the natural frequency with the lowest frequency according to ref. [9].

The natural period is given by *(Eq. 2.42)*.

$$T_{n,jk} = \frac{2\pi}{\omega_{n,jk}} = 2\pi\sqrt{\frac{M_{jk} + A_{jk}}{k_{jk}}} \qquad \text{(Eq. 2.42)}$$

The natural periods for heave, roll and pitch are given in Table 13. The natural periods for surge sway and yaw are equal to "infinity".

Term	Assumption	General formulas	Barge formulas
$T_{n,33}$	Rectangular, flat bottom barge. Small angels. Added mass neglected.	$\frac{2\pi}{\omega_n}$	$2\pi\sqrt{\frac{D}{g}}$
$T_{n,44}$			$\frac{2\pi B}{\sqrt{12gGM_T}}$
$T_{n,55}$			$\frac{2\pi L}{\sqrt{12gGM_L}}$

Table 13 Summary natural period

2.7 Rao

The responses as a function of wave period for a unity load are called the transfer function or the response amplitude operator (RAO). The transfer function of a linear, time-invariant differential equation is defined as the ratio of the Laplace transform of the output or response function to the Laplace transform of the input or forcing function, assuming zero initial conditions. Ref. [5]. Since the linear differential equation consist of the variable and its derivates, the Laplace transform converts the differential equation into a polynomial equation in the Laplace variable. The transfer function can be represented as a block diagram as shown in Figure 15.

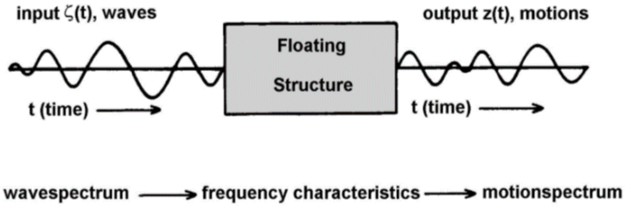


Figure 15 Relation between motion and waves, ref. [3]

Motions of floating objects shall be determined for the relevant environmental conditions and loads. A vessels motion in waves can be defined by displacement RAOs. The RAOs amplitude and phase vary for different types of vessel, and for a given vessel it vary with the draught, wave direction, forward speed and wave period. Vessel RAOs for seas approaching 45^o off the bow (135^o case) typically give the largest heave and lateral motions according to ref. [1]. The spacing between the analysed wave headings should not exceed 45^o. If short crested waves are considered the spacing between the analysed wave heading should normally not exceed 22,5^o according to ref. [16]. The wave heading and name of the different directions are given below in Figure 16.

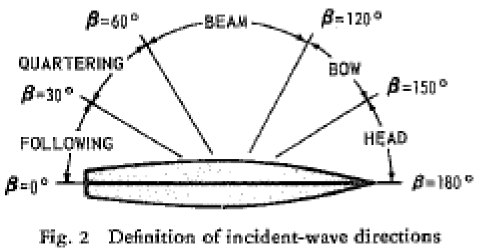


Figure 16 Definition of wave directions, ref. [2]

Each displacement RAO consists of a pair of numbers that define the vessel response, for one particular DOF, to one particular wave direction and period. The two numbers are an amplitude, which relates the amplitude of the vessel motion to the amplitude of the wave, and a phase, which defines the timing of the vessel motion relative to the wave motion. As mentioned above the vessel have 6 DOF, therefore the RAO data consists of 6 amplitudes and their phase pairs for each wave period and direction. It is important to obtain accurate values for the RAO amplitude and phase if the dynamics of the system should be correctly modelled. Vessel RAOs are used during the design process and defines the limitations for the design, therefore it is important that they are well-defined.

$$\sum_{k=1}^{6}\left[-\omega^2\left(M_{jk}+A_{jk}\right)+i\omega C_{jk}+K_{jk}\right]x_k=F_{jj}\,,\;\; j=1{,}2..6 \qquad \text{(Eq. 2.43)}$$

For a single degree of freedom system the frequency response function would be:

$$H(\omega)=\frac{x_k}{F_j}=\frac{1}{\left[-\omega^2\left(M_{jk}+A_{jk}\right)+i\omega C_{jk}+K_{jk}\right]} \qquad \text{(Eq. 2.44)}$$

$$X=H(\omega)*\xi_a*\cos(\omega t-\theta)$$

RAOs are usually obtained from models of vessels designs, tested in a model basin or using computer programs such as Wadam. Analysis are often carried out in two phases. In the first phase, the motion response to regular waves. This is done in accordance with hand calculation in order to confirm that the model is correct. In the second phase, the response to irregular waves where the wave spectrum is derived using the significant wave height and wave period. Then the data may be presented in tabular or graphical form. Ref. [1]. These RAOs may be used for calculation of significant maximum responses. Testing of models or full scale structure may be carried out where the relevance of theoretical approaches is uncertain, or where the design is particularly sensitive for motion. Ref. [16].

2.8 Boundary conditions for linear wave theory

Some boundary conditions are introduced in order to ensure that the fluid behave in the correct manner. By introducing a boundary condition a constraint is introduced, it is therefore important that the appropriate boundary conditions are introduced. In addition it is important to be sure that the boundary conditions doesn't constrain or limit the natural behaviour of the fluid. The following boundary conditions Table 14 are introduced to determine the velocity potential Φ:

Boundary condition	Description	Formulation
No forward speed	Zero mean forward speed	
Laplace equation	Three-dimensional Laplace equation for the velocity potential. It means that the flow is incompressible and irrotational in the fluid domain.	$\nabla\Phi = 0$
Free surface	Linear free-surface condition for steady-state harmonic oscillatory motion of circular frequency (ω)	$-\omega^2\Phi + g\frac{\partial\Phi}{\partial z} = 0, \quad For\ z = 0$
Kinematic boundary condition	Ensures no flow through the body surface (vessel). The unit normal vector is defined to be positive when pointing into the fluid domain.	$\frac{\partial\Phi}{\partial n} = n_3\frac{d\eta_3}{dt} = vn,$
Sea bed	No fluid flows through the sea bed. Where h is the distance from the surface to the sea bead.	$\frac{\partial\Phi}{\partial z} = 0\ on\ z = -h,$ Finite wd $\lvert\nabla\Phi\rvert \to 0\ when\ z \to \infty,$ Infinite wd wd= water depth
Symmetric or anti-symmetric condition	Surge, heave and pitch motion are symmetrical since the motion response will be the same on either side of the vessel and sway, roll and yaw are the anti-symmetric motions.	
Radiation condition (3D)	Ensure that the waves propagate away from the vessel in all directions. The body motion and diffraction potentials have to satisfy a radiation condition which states that great distance from the body these potentials disappear.	$\Phi \to 0, \quad$ when r $\to \infty$ An example of an outgoing wave potential in deep water is: $\Phi = \frac{\xi_a e^{kz}}{\sqrt{r}}\sin(kr - \omega t + \theta)$

Table 14 Boundary conditions, ref. [12].

2.9 Two dimensional sea

Regular waves (illustrated in Figure 17) is an important asset and a useful tool to make approximations. However, such waves do not occur in the real ocean environment. In reality the sea have a combination of different waves with different amplitude and periods. Fourier analysis can combine these waves as a sum of sinusoidal waves as a good approximation.

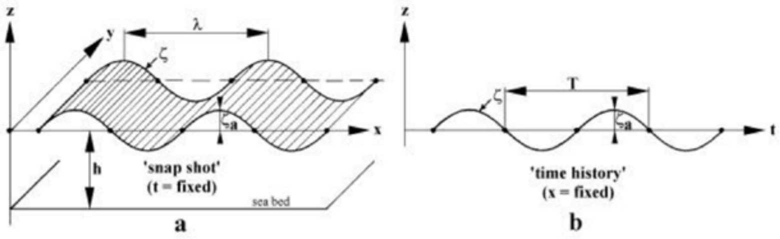


Figure 17 Harmonic wave, ref. [3]

Wave potential theory is the basis for calculating wave loads and motion for fixed and floating structures. Realistic fluid behaviour is very hard to calculate exactly, thus by idealising the fluid it is possible to perform calculations that are very useful in the design of an offshore structures. The formulas that contribute for a regular sinusoidal wave are given in Table 15.

.

Table 2.1. *Velocity potential, dispersion relation, wave profile, pressure, velocity and acceleration for regular sinusoidal propagating waves on finite and infinite water depth according to linear theory*

	Finite water depth	Infinite water depth
Velocity potential	$\phi = \frac{g\zeta_a}{\omega}\frac{\cosh k(z+h)}{\cosh kh}\cos(\omega t - kx)$	$\phi = \frac{g\zeta_a}{\omega}e^{kz}\cos(\omega t - kx)$
Connection between wave number k and circular frequency ω	$\frac{\omega^2}{g} = k \tanh kh$	$\frac{\omega^2}{g} = k$
Connection between wavelength λ and wave period T	$\lambda = \frac{g}{2\pi}T^2 \tanh\frac{2\pi}{\lambda}h$	$\lambda = \frac{g}{2\pi}T^2$
Wave profile	$\zeta = \zeta_a \sin(\omega t - kx)$	$\zeta = \zeta_a \sin(\omega t - kx)$
Dynamic pressure	$p_D = \rho g \zeta_a \frac{\cosh k(z+h)}{\cosh kh}\sin(\omega t - kx)$	$p_D = \rho g \zeta_a e^{kz}\sin(\omega t - kx)$
x-component of velocity	$u = \omega\zeta_a \frac{\cosh k(z+h)}{\sinh kh}\sin(\omega t - kx)$	$u = \omega\zeta_a e^{kz}\sin(\omega t - kx)$
z-component of velocity	$w = \omega\zeta_a \frac{\sinh k(z+h)}{\sinh kh}\cos(\omega t - kx)$	$w = \omega\zeta_a e^{kz}\cos(\omega t - kx)$
x-component of acceleration	$a_1 = \omega^2\zeta_a \frac{\cosh k(z+h)}{\sinh kh}\cos(\omega t - kx)$	$a_1 = \omega^2\zeta_a e^{kz}\cos(\omega t - kx)$
z-component of acceleration	$a_3 = -\omega^2\zeta_a \frac{\sinh k(z+h)}{\sinh kh}\sin(\omega t - kx)$	$a_3 = -\omega^2\zeta_a e^{kz}\sin(\omega t - kx)$

$\omega = 2\pi/T$, $k = 2\pi/\lambda$, T = Wave period, λ = Wavelength, ζ_a = Wave amplitude, g = Acceleration of gravity, t = Time variable, x = direction of wave propagation, z = vertical coordinate, z positive upwards, $z = 0$ mean waterlevel, h = average waterdepth. Total pressure in the fluid: $p_D - \rho g z + p_0$ (p_0 = atmospheric pressure).

Table 15 Velocity potential, dispersion relation, wave profile, pressure, velocity and acceleration for regular sinusoidal waves of finite water depth and infinite water depth according to linear theory, ref. [2].

2.10 Strip theory

In order to calculate the response and forces for a vessel, a numerical approach is used. The strip theory is a numerical theory considering the vessel is modelled as a finite number of transverse two-dimensional strips that are rigidly connected to each other. Each strip is treated hydrodynamically as if it is a segment of an infinitely long floating cylinder. The strips have a distance x_b from the Centre of gravity (COG) and thickness of dx_b and an infinite width (illustrated in Figure 18). A vessel is divided into as many strips as necessary, in order to get an accurate result. Ref. [3]

The strip theory can be used to predict the heave and pitch motion by adding the body-mass and hydrostatic forces. The result is a pair of coupled linear equations for the complex amplitudes of heave and pitch. In solving these equations of motion the principal task is the computation of the two-dimensional added mass and damping coefficients for each section of the vessel. Ref. [4]. Three-dimensional added-mass coefficients can be approximated by integrating the assumed locally two dimensional added-mass coefficients over the length of the barge.

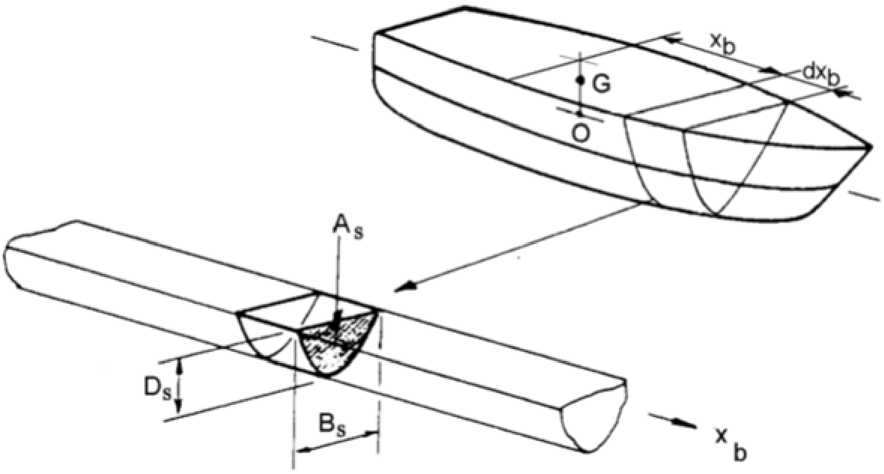


Figure 18 Two-dimensional strip theory, ref. [3]

Strip theory is limited to long and slender bodies, where the length-dimension is exceeding the others (beam and the depth) by an order of magnitude ref. [4]. Experiments have shown that strip theory can be applied successfully for floating bodies with a length to breadth ratio (L/B>3). In addition the rigid body motions have to be small ref. [29].

2.11 Panel method

For three-dimensional analysis a panel method is commonly used. The panel method is a numerical method which uses a numerical model based on a distribution of sources to calculate the source-potential around the submerged body surface. The source-potential, or Green function, is the fundamental element in the analysis of wave-induced motions and forces acting on floating or submerged vessels ref. [35]

The procedure can be justified by Green's theorem, which requires the solution of an integral equation of the body surface, either for the source strength or for the velocity potential ref. [35]. In practice the body surface is discretized into a large number of discrete “panel” elements (illustrated in Figure 19), typically between 100 and 1000 ref. [35]. The corresponding integral equation is replaced by a finite linear equations characterized by a square matrix of complex coefficients with the same dimension as the number of panel elements. This is an acceptable simplification for the majority of the fixed or floating structures in use today in the offshore industry according to ref. [3].

The required accuracy is an important factor in any numerical computation, the panels has to be small enough to justify that the source density is constant and that the quality of the results is within a reasonable degree of precession. A degree of precession can be attained by systematically increasing the number of panels, and the accuracy of the final hydrodynamic parameters can then be judged with some confidence ref. [35].

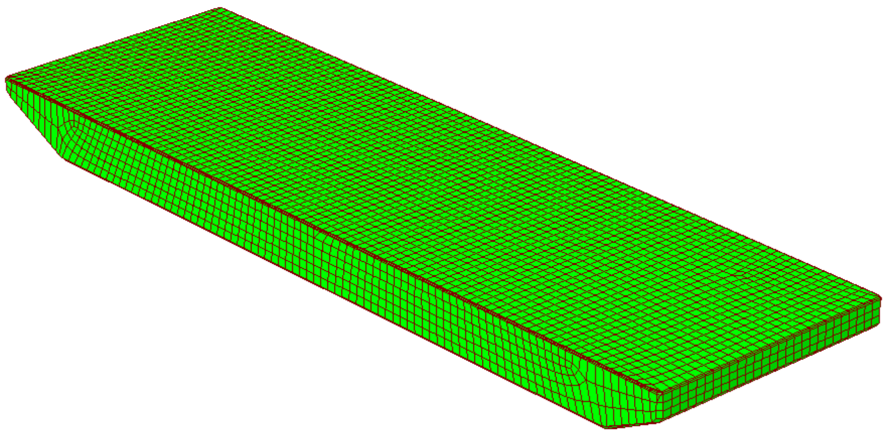


Figure 19 Surface divided in a number of panels

2.11.1 Potential theory

A streaming flow will be disturbed by the presence of a body, from a mathematical viewpoint such a disturbance requires the introduction of singularities; simplest source and sink potential. A source is a point from which fluid is imagined to flow outward uniformly in all directions, and a sink is simply a negative source (Q) (illustrated in Figure 20). The singularity violate the Laplace equation, therefore source and sinks should be located on the body boundary surfaces and is not allowed within the interior of the fluid. Ref. [4]. A "thin" vessel can be simulated by a distribution of sources on the centreline plane of the forebody and of sinks in the afterbody, the sum of their total strength being zero. The restriction to a "thin" vessel can be removed if the sources and sinks are distributed over the hull surface itself according to ref. [8].

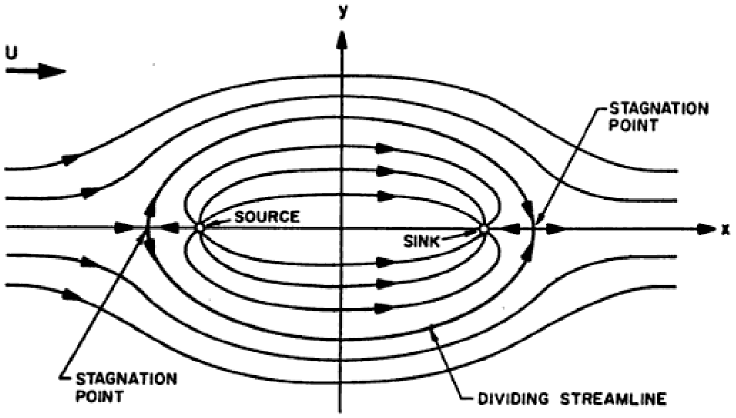


Figure 20 Source and sink, ref. [4]

The flow is called source flow because the amount of fluid passing through a circle at radius r is always Q, and the fluid is irrotational, because Q is constant in the fluid. Ref. [3]. The velocity potential of a source, situated at the origin is given by *(Eq. 2.45)*:

$$\Phi = -\frac{Q}{4\pi R} \qquad \text{(Eq. 2.45)}$$

$$R = [(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2]^{\frac{1}{2}}$$

Where R is the radial distance from the source and field point and Q is the total flux, or the source strength (flow rate) on the wetted body surface. The equation gives radial flow from a point. When R goes towards zero the velocities go to infinity at this point, therefore these points has to be excluded when carrying out the integration in the fluid.

2.11.2 Green's function

The Green's function $G(x;\zeta)$ which is referred to as the velocity potential of a source at the field point **x** due to a source strength at the point **(ζ)**. The vertical position of the source is assumed to be negative or zero. The fluid depth is assumed to be either infinite, or of constant depth h. The Green function satisfies the set of appropriate boundary conditions, and in infinite water depth it is defined by (*(Eq. 2.46)*, Welhausen and Laitone (1960))

$$G(x;\zeta) = \frac{1}{R} + \frac{1}{R'} + \frac{2\nu}{\pi}\int_0^\infty dk \frac{e^{k(z+\zeta)}}{k^2+\nu^2} J_0(kR) \qquad \text{(Eq. 2.46)}$$

$$R' = [(x-\xi)^2 + (y-\eta)^2 + (z+\zeta)^2]^{\frac{1}{2}}$$

$$k = \frac{\omega^2}{g}$$

Where $J_0(kR)$ is the Bessel function of the first kind, order zero *(Eq. 2.47)*, the function is a oscillating function that decays with the ratio $\frac{1}{\sqrt{kR}}$ meaning that the Green function satisfies the radiation condition for large R values.

$$J_0(\nu r) = \left(\frac{2}{\pi kR}\right)^{1/2} \cos\left(kR - \frac{\pi}{4}\right) \qquad \text{(Eq. 2.47)}$$

In finite water depth the green function is defined by *(Eq. 2.48)*.

$$G(x;\zeta) = \frac{1}{R} + \frac{1}{R''} + 2\int_0^\infty dk \frac{(k+\nu)\cosh k(z+h)\cosh k(\zeta+\mathrm{h})}{k\sinh kh - \nu\cosh kh} e^{-kh} J_0(kR) \qquad \text{(Eq. 2.48)}$$

$$R'' = [(x-\xi)^2 + (y-\eta)^2 + (z+\zeta+2\mathrm{h})^2]^{\frac{1}{2}}$$

According to (Lamb,1932), the potential Φ_j *(Eq. 2.49)* at a point (x,y,z) on the mean wetted body surface S_B due to the motion in the mode j (j=1,…6) and the diffraction potential Φ_7 can be represented by a continuous distribution of single sources on the body surface according to ref. [3].

$$\Phi_j(x,y,z) = \frac{1}{4\pi}\iint_{S_B} Q(\xi,\eta,\zeta)G(x,y,z;\xi,\eta,\zeta)\,dS \qquad \text{(Eq. 2.49)}$$

The integral equation represent a distribution of sources or sinks on the wet surface. Where the source strength function Q is found by satisfying the boundary condition. In order to solve the integral the mathematical model must be discretized into a finite number of panels. By solving the integral equation it is possible to find the added mass, damping coefficients and the wave forces. Finally the motions ξ_j are determined from the solution coupled equations of motion with six degrees of freedom *(Eq. 2.43)* and *(Eq. 2.44)*.

3 Methodology for analysis and hand calculation

3.1 Set up

The Versatruss system consist of two Standard Viking barges (illustrated in Figure 53) that will be installed with a lifting system that consist of A-frame booms and tensioned wires to lift a topside with the same characteristics as the Huldra topside (illustrated in Figure 54). The details are given below in Table 37 Table 38 and Table 39 in Appendix B. Connected together the system looks like illustrated in Figure 21.

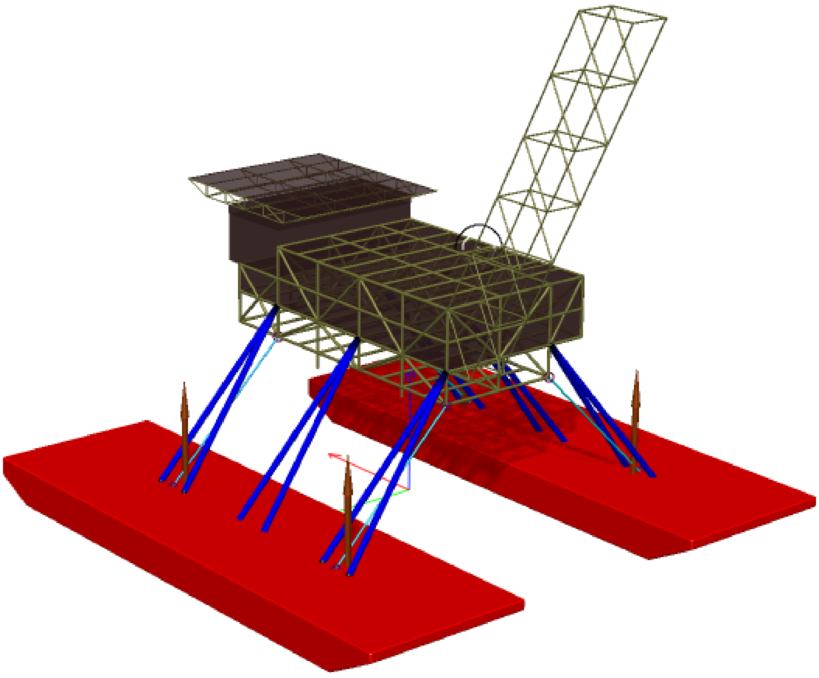


Figure 21 Huldra topside placed on the two barges in a Versatruss formation

3.2 Hand calculations

Strip theory has been used for some hand calculations to make an estimate of the expected transfer functions for the Standard Viking barge (illustrated in Figure 22). As mentioned the strip theory is limited to small motions, in addition the added mass is assumed to be constant. Therefore it is possible to see that the hand calculations differ from the results from HydroD around the natural period. This is done in order to verify that the model made in Genie is a correct representation of the Viking barge (the results are given in Appendix A).

For slender bodies (L>3B), the motion of the fluid can be formulated as a 2D problem. An accurate estimate of the hydrodynamic forces can be obtained by applying strip theory ref. [4]. Strip theory has the advantage that it is a simple and efficient tool for calculating the hydrodynamic forces and motions of a vessel. The figures shown in Appendix A illustrates that the strip theory is a very good and accurate estimate and verify that the model is a good representation of the Viking barge. There is some deviation for the roll motion, it is assumed that the reason for this appearance is because in this direction the barge is not slender.

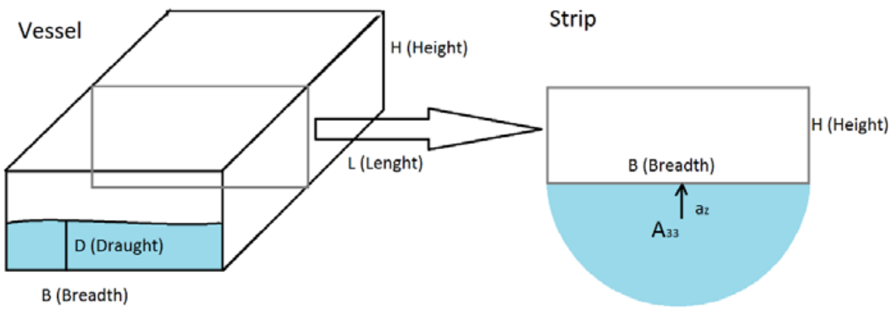


Figure 22 Illustrates the principle behind the strip theory for the heave motion.

3.3 Software calculations

The software used for these calculations is the Sesam package, which is a complete package for simulation of marine operations from modelling to final results. The panel model which is the “physical model” is first made in Genie, then the panel model is imported to HydroD where it is possible to run hydrodynamic analysis. Then the added mass, damping coefficients, motion transfer functions etc. are imported into SIMA (Sesam marine). SIMA is then used for feasibility evaluation (illustrated in Figure 23)

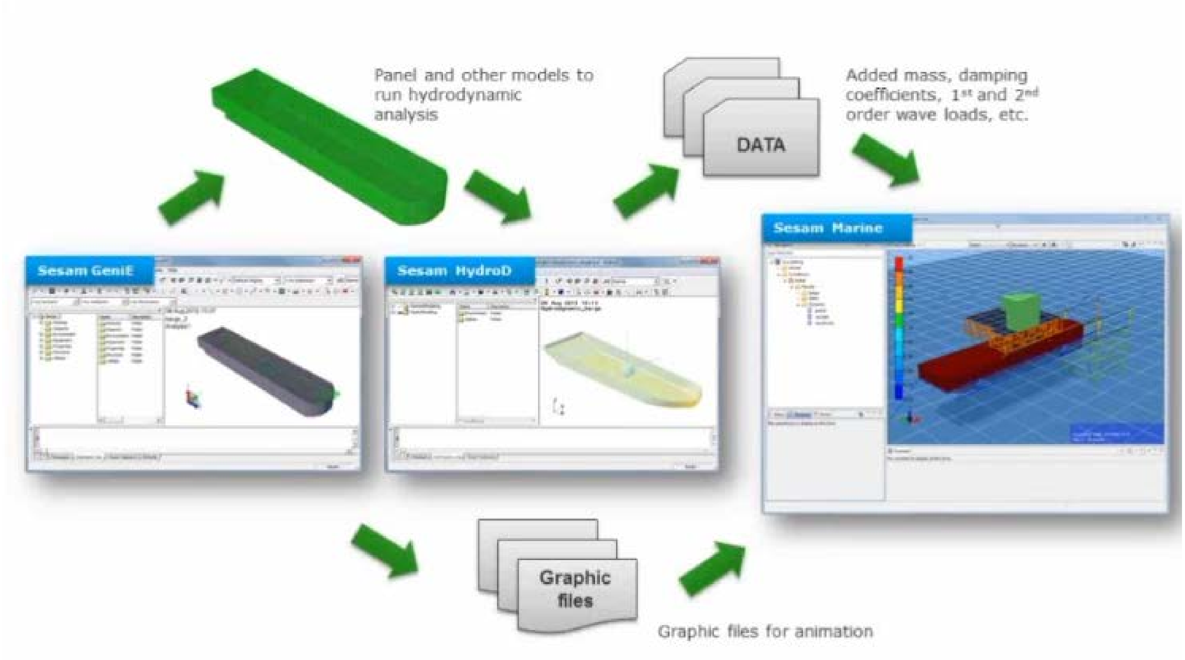


Figure 23 Shows the relation between Sesam Genie, HydroD and Marine (SIMA), ref. [30]

3.3.1 Genie

Sesam GeniE is a tool for design and analysis of offshore and maritime structures made up of beams and plates ref. [31]. The Sesam GeniE software facilitates efficient modelling and features 3D visualization of the conceptual model (illustrated in Figure 24). In addition it is possible to compute the mass, COG and the moment of inertia. The computed mass is compared with the lightweight of the vessel (1850 Te), the lightweight tonnage is the weight of the vessel when it was built including all framing, machinery etc. according to ref. [32]. This is done in order to verify that the conceptual model is consistent with the given model of the Standard Viking barge. There is some deviation, it is reasonable to believe that the deviation is because there is some reinforcement that are missing in the bow and stern as well as the machinery.

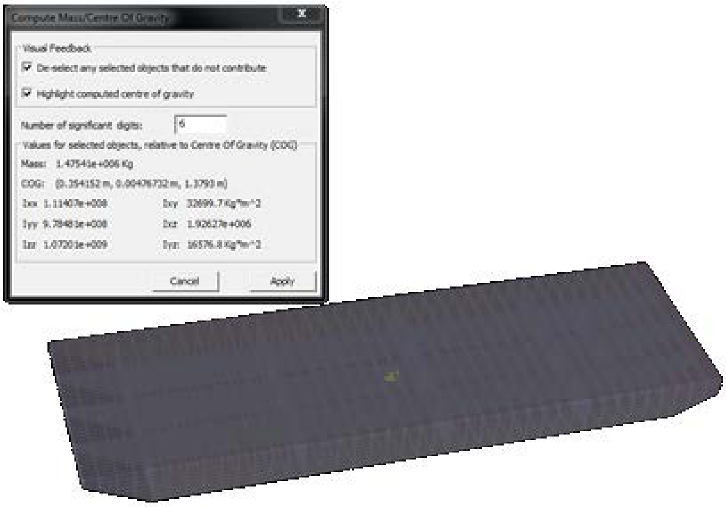


Figure 24 Conceptual model of a Standard Viking barge

GeniE may also be used to create panel models of fixed or floating structures for subsequent stability or hydrodynamic analysis in HydroD. The outer surface has been assigned wetted surface (illustrated in Figure 25) such that hydrodynamic loads and accelerations may be computed in HydroD (Wadam) according to ref. [40]. These loads may be transferred back to the finite element model (illustrated in Figure 26).

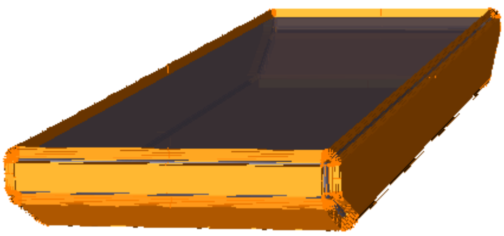


Figure 25 The wet surface

For the hydrodynamic analysis a FE-model is required, a finite element mesh generated for the panel model. In addition Genie provides finite element visualization (illustrated in Figure 26), which enables mesh control.

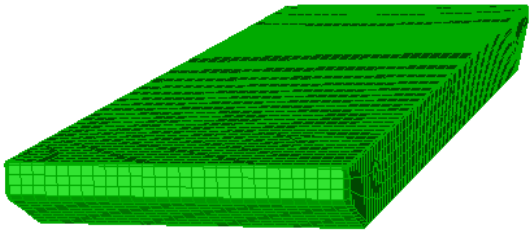


Figure 26 FE model Viking barge; mesh characteristic value of 2 m.

The FE-panel model is exported as T1.FEM. The panel model describes the surface of the barge and contributes to for example the added mass coefficients and displaced volume. Then the structural model has to be defined (T2.FEM) in the structural model the weight and compartments are specified. The weight is specified by defining the same properties (sections, thickness and material) on the model as specified on drawings.

3.3.2 HydroD

The FE-model from Genie is then imported into HydroD as a FEM file. HydroD is a software for hydrostatic (Wasim) and hydrodynamic (Wadam) analysis. This software uses the panel method to describe large-volume structures. The software fulfil the condition of no fluid penetration of the wet surface (illustrated in Figure 25), this makes the method suitable for arbitrary body shapes. The method is based on potential theory to compute wave loads and motion response, meaning oscillations are assumed small relative to the cross-sectional dimensions of the body**.**

The actual implementation is based on Wamit which uses a 3D panel method to evaluate velocity potentials and hydrodynamic coefficients ref. [41]. Wamit was developed by Professor Newman and co-workers at MIT in 1987, and it has the ability to analyse the complex structures with a high degree of accuracy and efficiency according to ref. [33].

In HydroD a set of parameter can be defined like the directions (beam/head sea), periods (which periods shall be included), location (water depth, density), draft, compartment content, mass model (weight and COG), off body points (contributes to the stiffness matrix) and critical damping matrix (damping ratio) etc. (illustrated in Figure 27) The periods are selected with a small interval close to the natural periods, and the water depth is assumed to be 120 m to represent a typical value for the North Sea. In addition the compartments are filled to get the correct centre of gravity (COG) and metacentric height (GM).

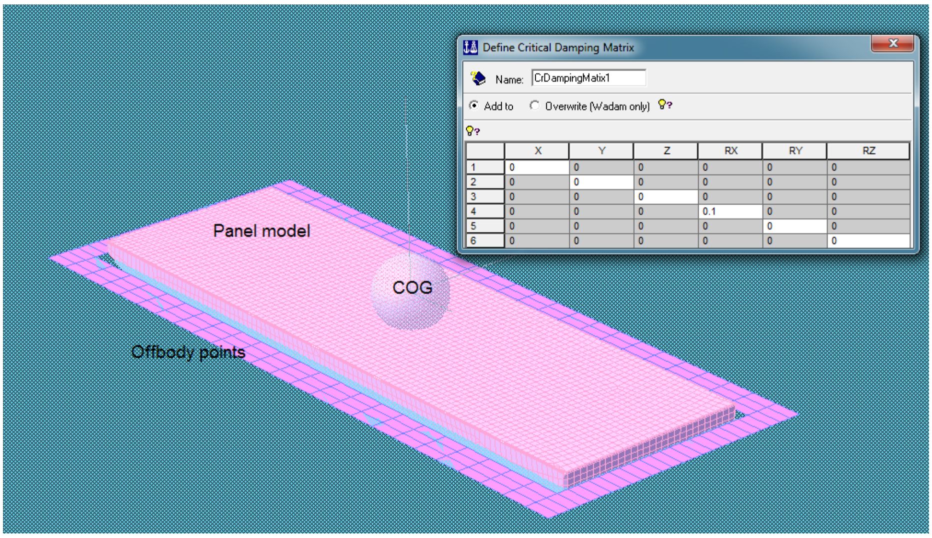


Figure 27 Illustration of the parameters in HydroD

The result file is saved as a Wamit file which contains the added mass, damping coefficients, motion transfer functions etc. and can be imported into SIMA. The result file is saved and can be found in Appendix C.

3.3.3 SIMA

The Wamit file from HydroD and the graphical file from Genie is then imported to SIMA. SIMA is a software carries several features like INPMOD, STAMOD, DYNMOD, OUTMOD and SimVis which makes it possible to do complete dynamic analysis with 3D visualization. The description of the different modulus is described in Table 16.

Software	Modules	Communication	Description
SIMA	INPMOD	File system for communication between modules.	Input generation and presentation, interface to external sources of data. (for example results from diffraction analysis)
	STAMOD		Read input data, static analysis, define initial condition for dynamic simulation. A static equilibrium position may be calculated with or without environmental forces applied. (which is a good alternative to check that the model behave in an appropriate manner)
	DYNMOD		Dynamic analysis, calculate responses in the time domain. Which involves time integration of the equation of motion.
	OUTMOD		Read time series files generated in DYNMOD, generate print and plot of time series and statistical parameters. (Post-processing)
	SimVis		3D visualization tool

Table 16 General descriptions of the features in SIMA, ref. [43]

In SIMA it is possible to define the location (gravity, water density, water depth etc.), environmental parameters (wave, swell, wind and current), metocean (wave statics, direction and spreading), mass and moment of inertia etc. SIMA is used for managing risk and feasibility evaluation of marine operations with visual simulation of calculations.

The wave-induced motion is based on some simplifying assumptions, in particular linearization of the hydrostatic, diffraction and radiation forces about the still water plane and the body's hydrostatic equilibrium. The assumption of linearity for vessel response allows us to use many powerful analysis techniques. To partly overcome this deficiency SIMO offers a way to account for the nonlinearity in the restoring force and the wave force in a quasi-static manner during the simulation (illustrated in Figure 28). The local nonlinear corrections are integrated over the panel area to give the total nonlinear correction in the 6 DOF generalized rigid body forces and moments in the body-fixed coordinate system according to ref. [42].

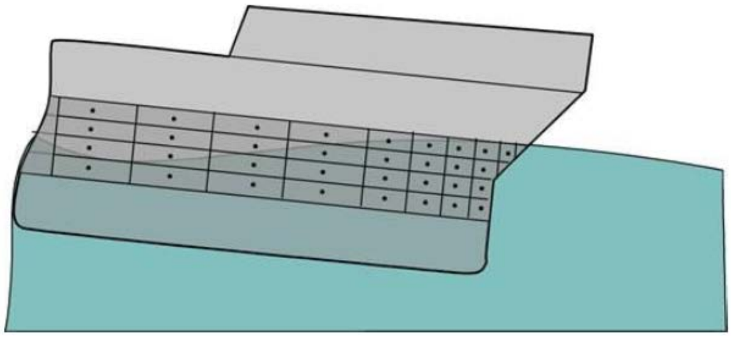


Figure 28 Nonlinear correction of wave force and restoring force on body. (product of panel area and pressure applied on panel cell (M x g x vertical distance between the wave surface and cell centroid), ref [42].

3.3.3.1 Coupling

In SIMA it is possible to couple the model together (illustrated in Figure 29). The coupling contributes to boundary conditions, it is important that the boundary conditions reflect the natural behaviour and doesn't introduce some constraints or introduce some unnatural motions. Therefore it is important that the coupling corresponds with the coupling that is intended for the Versatruss system.

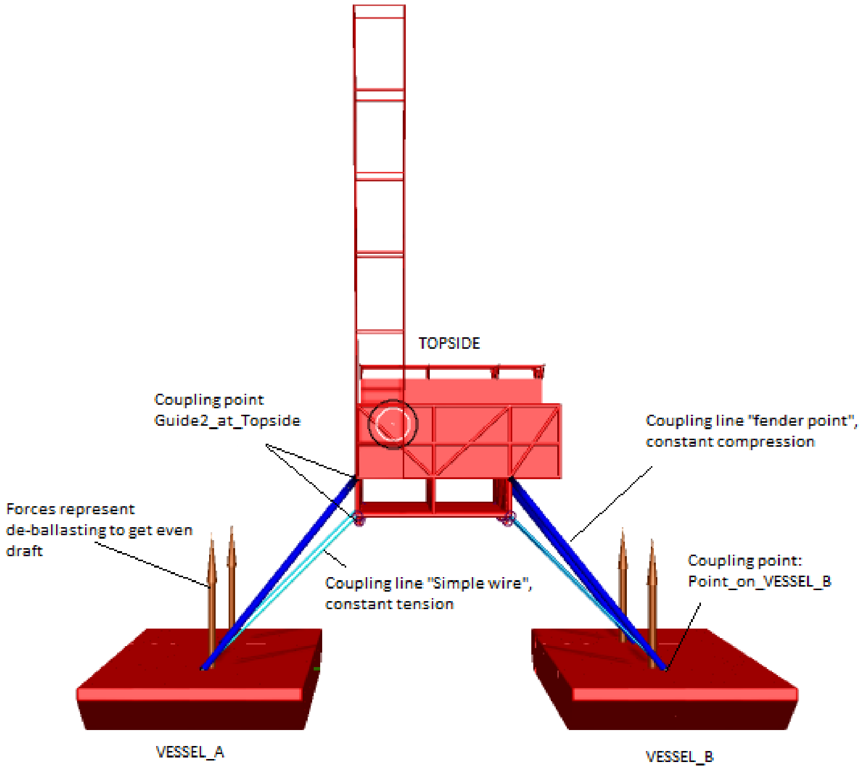


Figure 29 Coupling in SIMA

A fender point, which is a coupling element between two bodies, represents the A-booms, the fender point is attached to the topside and the fender plane is located at the vessel. The fender plane gives contact force (compressive) between a fender point and a plane at a given position. The contact force is zero for a distance larger than a specified value, and the compression force normal to the plane calculated from a specified deformation-force relation. The fender points act as a pinned connection satisfies the concept that the barges can have individual roll motion (illustrated in Figure 30). Thereby giving a correct representation of the A-booms.

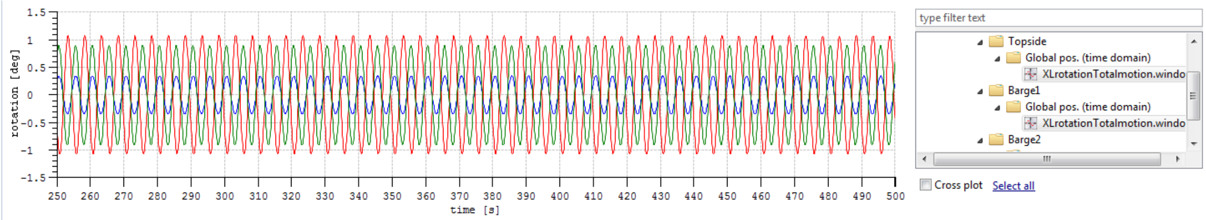


Figure 30 Illustrates the individual roll of the barges (red and green line). The topsides roll motion (blue line) is a function of the difference in the heave motion for the two barges.

The compressive force in the fender is given by *(Eq. 3.1)*.

$$F = -\left(f(R) + c\left|\dot{R}\right|^{e} * \frac{\dot{R}}{\left|\dot{R}\right|}\right)\vec{n} \qquad \text{(Eq. 3.1)}$$

Since the damping (c) is proportional with the velocity (R) the exponent (e) is specified as one. The damping value is found from Table 17.

System	Damping ratio
Metals	<1%
Continuous metal structures	2-4 %
Metal structures with joints	3-7 %
Small diameter piping systems	1-2%
Large diameter piping systems	2-3 %
Ref. [11] (Table 18.2 Representative damping ratios as percent of critical damping.)	

Table 17 Representative damping ratios as percent of critical damping

A simple wire coupling, which is a coupling between two bodies in constant tension represent the constant tension winch and wire. The wire cross section stiffness is given in *(Eq. 3.2)*.

$$k = \frac{EA}{L_w} \qquad \text{(Eq. 3.2)}$$

For the wire the damping can normally be set to 1-2% of EA, where E is the modulus of elasticity and A is the cross-sectional area ref. [42]. The damping value used for the fender and wire is given in Table 18.

Name	Stiffness	Mass (Topside)	Eigen frequency (wn)	Critical damping (c_c)
Fender	2,24e+09 N/m	4,87e+06 kg	21,4 rad/s	2,09e+08 Ns/m
2 % of critical damping	4,18e+06 Ns/m			
3 % of critical damping	6,26e+06 Ns/m			
The damping value in the software is specified as 5,0 e+06 Ns/m for the fenders.				

Name	E-modulus	Area	EA
Wire	210 GPa	6,02e+05 mm^2 (multiple wires)	1,26e+11 N
1,5 % of EA	1,26e+09 Ns/m		
2 % of EA	2,53e+09 Ns/m		
The damping value in the software is specified as 1,90e+09 Ns/m for the wires.			

Table 18 Damping values specified for fenders and wires

The vessels and topside are modelled as a large volume bodies in order to get 6 degrees of freedom where the total motion is simulated in time domain. By transformation of an input signal (motion of the topside) the motion in four different points (representing the stabbing cones) can be found. The velocities and accelerations are found by derivation and double derivation of the motion in the given point.

$$s = x(t), \qquad v = \frac{dx(t)}{dt}, \qquad a = \frac{d^2x(t)}{d^2t} \qquad \text{(Eq. 3.3)}$$

3.3.3.2 DP system

The horizontal stiffness is practically zero, if the vessel moves in the horizontal direction (surge, sway and yaw) it will not arise any forces trying to push the vessel back into position. In order to restrain this motion tug boats (with DP) are used to maintain the position and guide it at seas (Illustrated in Figure 31).

Figure 31 Illustrates the Versatruss system and the tug boats, ref. [37] (owner: Versatruss Americas; lift capacity 20,000 Te)

In SIMA the tug boats are modelled as a DP system, which is introduced as a hydrodynamic stiffness and critical damping in the horizontal directions (surge, sway and yaw). The stiffness (Table 19) is calculated from following equation *(Eq. 3.4)* by assuming a natural period of 300s in surge, sway and yaw.

$$T_n = 2\pi\sqrt{\frac{m_{jk} + a_{jk}}{k}} \rightarrow k_{jk} = \frac{4\pi^2 m_{jk}}{T_n^2} \qquad \text{(Eq. 3.4)}$$

The tug boats are directly connected to the barges therefore a high damping value from the thruster equal to 70% of critical damping (illustrated in Table 20) is assumed.

Symbol	Stiffness	Formula
k_{11}	4,38e+03 N/m	*(Eq. 2.16)*
k_{22}	4,71e+03 N/m	
k_{66}	3,06e+06 N/m	

Table 19 Stiffness in surge, sway and yaw

Symbol	Stiffness	Formula
c_{11}	2,93e+05 Ns/m	*(Eq. 2.16)*
c_{22}	3,15e+05 Ns/m	
c_{66}	2,04e+08 Ns/m	

Table 20 Damping in surge, sway and yaw

To verify that the natural period is 300 seconds the system is removed from equilibrium position because then the system will oscillate around the equilibrium position by the natural period (illustrated in Figure 32).

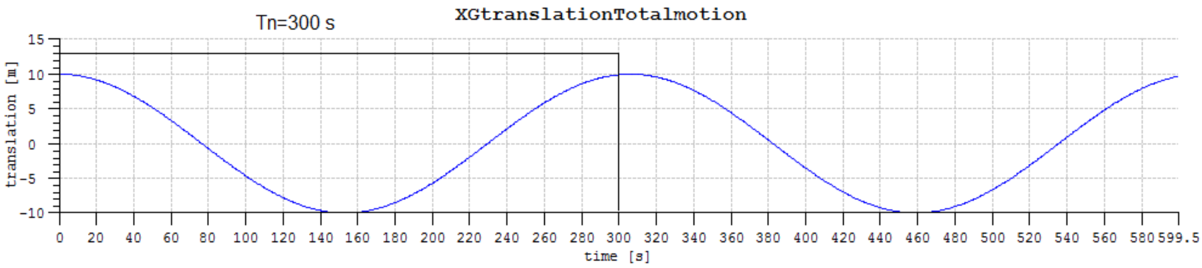


Figure 32 Illustrate that the system oscillate with a natural period of 300 s

3.3.4 Criteria

Float-over installations are weather restricted marine operations. The design situation includes several types of actions according to ref. [19], it will be very time consuming to look at all the situations. For that reason the thesis will be limited to the environmental actions and the dynamic response.

As a guiding principle, the minimum clearance should be sufficient to allow unimpeded operation of the installation system and should be based on motion analysis of the two bodies being positioned. Where there is a risk of contact between structures, a suitable fendering system should be installed. Fender dimensions should be taken into account when determining minimum clearances.

The maximum object movements during installation should be defined (illustrated in Table 21); they depend on the vessel and the local weather conditions. Typical values for maximum object motion amplitudes are:

Typical values for maximum object motion amplitudes	
Vertical movements	$\pm 1{,}00\ m$
Horizontal movements	$\pm 1{,}50\ m$
Longitudinal tilt	$\pm 2^0$
Transverse tilt	$\pm 2^0$
Plan rotation	$\pm 3^0$
Note: The plan rotation limit is applicable only when the object is close to its final position or adjacent to another structure on a cargo barge.	

Table 21 Typical values for maximum object motion amplitudes, ref. [19].

The substructure and the topside needs to be designed for the potential impact loads from self-weight, motions, direct hydrodynamic loads as well as barge deflections. An assessment of impact loads on bumpers and guides should be based on considerations of impact conditions and deformation energy, which should, in turn, be based on realistic assumptions of velocities, impact positions and deformation patterns. In the absence of more detailed calculations, typical loadings for the design of bumpers and guides during offshore lifts are given in Table 22 ref. [19].

The values are given as a percentage of the static hook load (W_{st}), equal to the sum of the gross weight and the rigging weight according to ref. [19].

Vertical sliding bumpers	
Horizontally directed force in plane of bumper, F_h	0,10 W_{st}
Horizontally directed (friction) force out-of-plane of bumper, F_l	0,05 W_{st}
Vertically directed (friction) force, F_v	0,01 W_{st}
Pin/bucket guides	
Horizontally directed force on cone/end of pin, F_h	0,05 W_{st}
Vertically directed (or stabbing) force on inclined cone/end of pin, F_v	0,10 W_{st}
Horizontal "cow-horn" type bumpers with vertical guide	
Horizontally directed force in any direction, F_h or/and F_l	0,10 W_{st}
Vertically directed (friction) force, F_v	0,01 W_{st}
Vertical "cow-horn" type guide with horizontal bumper	
Horizontally directed force in any other direction, F_h or/and F_l	0,05 W_{st}
Vertically directed (stabbing) force on inclined face of guide	0,10 W_{st}
[a] See figures in Clause A.6.	

Table 22 Bumper and guide loading, ref. [19].

The configurations for a pin/bucket is illustrated in Figure 33. The configurations of bumpers and guides given in Table 22 are explained in ref. [19].

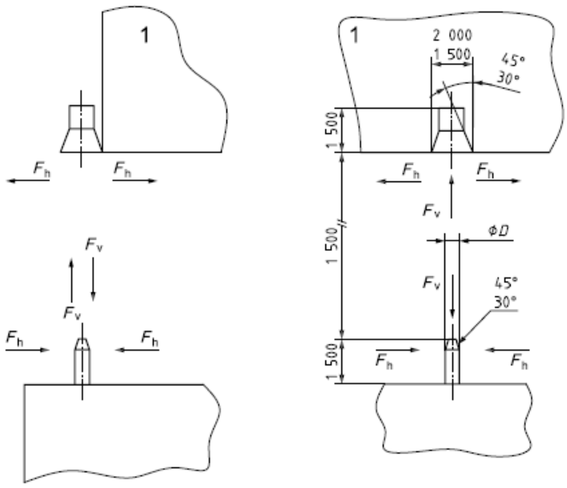


Figure 33 Pin bucket configurations, ref. [19].

For each of the configurations in Table 22, the loads in all relevant directions shall be combined to establish the most onerous loading condition. For inshore lifts under controlled conditions, bumpers and guides may be designed to 70 % of the forces shown in Table 22 according to ref. [19].

The criteria given in Table 22 leads to a limiting acceleration and velocity (given in Table 23) because both the velocity *(Eq. 3.5)* and acceleration *(Eq. 3.6)* term introduce impact loads.

$$E = \frac{1}{2}kx^2 = \frac{1}{2}mv^2 \qquad \text{(Eq. 3.5)}$$

$$v = \sqrt{\frac{F^2}{km}} = \frac{F}{\sqrt{km}}$$

$$F = ma \qquad \text{(Eq. 3.6)}$$

Pin bucket guides	Weight static	Motion
Horizontal acceleration	0,05 W_{st} t	0,4905 m/s^2
Horizontal velocity (*)		0,5 m/s
Vertical acceleration	0,1 W_{st}	0,981 m/s^2
Vertical velocity (*)		0,4 m/s
(*) Recommendations from specialist in Statoil. Since the acceleration is a function of the natural frequency and the natural frequency is less than one, the velocity will limit the operation.		

Table 23 Pin bucket loading; acceleration and velocities

3.4 Time domain

A time domain analysis is usually used to predict extreme load effects, which involves numerical integration of the equation of motion. The advantages of a time domain analysis is that it can capture non-linear-force-displacement relationships and give the response without making assumptions regarding response distribution according to ref. [15].

The duration of the time simulation should be sufficient to provide adequate statistics. It is recommended to perform 3 hour time domain simulations in irregular sea states. The time domain simulation includes 3 hours + build up time. Build up time is included because the time domain requires a proper simulation length to have a steady result particularly in surge, sway and yaw motion. It is important to be sure that the time series generated don't repeat themselves with a period that is less than the intended simulation time. Because then the actual simulation time will be less than intended. In SIMA the time series will repeat themselves with a period:

$$T_{p,r} = \frac{2\pi}{\Delta\omega_{kmin}} \qquad \text{(Eq. 3.7)}$$

Where:

$$\Delta\omega_k = \frac{2\pi}{N_t \Delta t} \qquad \text{(Eq. 3.8)}$$

To prevent repetition the duration of the time series is limited to:

$$T_{p,r} = \frac{2\pi}{\Delta\omega_{kmin}} = N_t \Delta t \qquad \text{(Eq. 3.9)}$$

A heading controlled vessel will not be able to keep the exact same direction continuously. It is therefore important that the analysis are performed for the intended direction ±15 degrees according to ref. [15]

3.5 Statics

In reality the wave condition is random, for the irregular sea one has to specify a seed for generation of random phase angles for the wave components. For the time domain analysis an alternative to one long simulation, is to simulate several (10-20) realisations of duration 3 hours. Where the extremes values from each simulation is estimated as the most probable maximum (MPM) of the extreme value distribution. The extreme value distribution will for increasing number of maxima approach a Gumbel distribution ref. [13] illustrated in Figure 34.

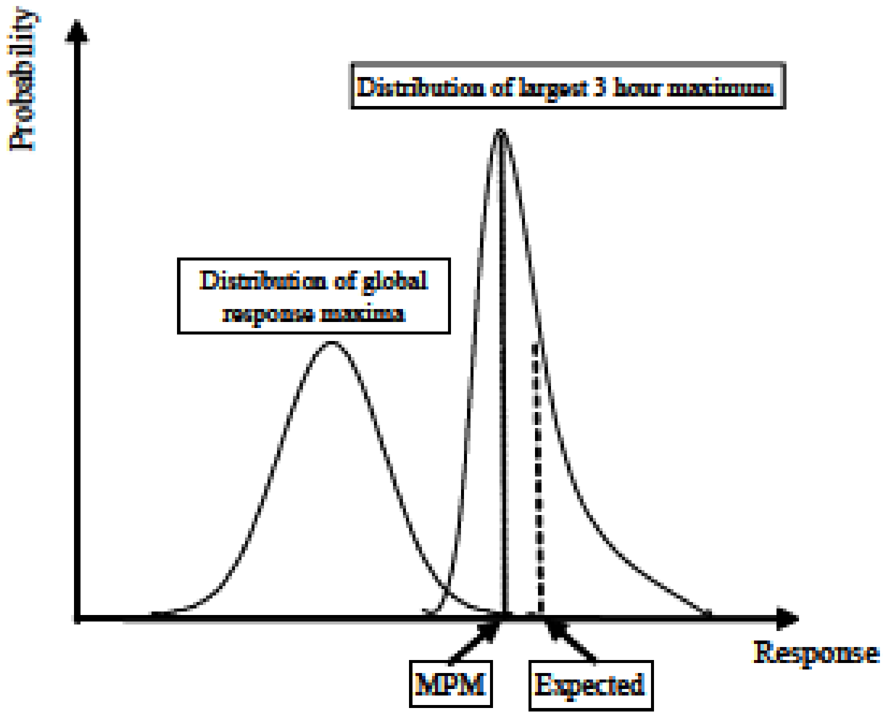


Figure 34 Statistical distribution, ref. [13].

In addition boot strapping and Monte Carlo simulation are done to give an estimate of the confidence. The Monte Carlo simulation is done by assuming that the MPM follows a calculated Gumbel distribution. Then random numbers from 0-1 are generated, because the probability cannot be negative or exceed one. Then new MPM values are calculated from the cumulative distribution function. If the random generated numbers and the numbers from the simulation coincides confidence is achieved.

The extreme value is taken as the P90 value, which represents the extreme value which have a 10% probability of exceedance. The formulas that are used to obtain the P90 value is given in Table 24.

Term	Assumption	General formulas	Gumbel
Probability distribution function	The extreme value distribution will for increasing number of maxima approach a Gumbel distribution ref. [13]	$PDF = f(y)$	$\frac{1}{\beta} * e^{-\frac{y-a}{\beta}} * e^{-e^{-\frac{y-a}{\beta}}}$
Cumulative distribution function		$CDF = \int f(y)dx$	$CDF = e^{-e^{-\frac{y-a}{\beta}}}$
90 % percentile		$P90 = 0{,}9 = \int_0^X f(x)dx$	$x = y - \beta Ln\big(-Ln(0{,}9)\big)$
Average	-	$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} y_i$	-
Standard deviation		$s^2 = \frac{1}{N-1}\sum_{i=1}^{N}(y_i - \bar{y})^2$	
Scale parameter	The parameters is estimated using the moment principle. (Prediction of characteristic response Statoil)	-	$\beta = 0{,}7797s$
Location parameter			$a = \bar{y} - 0{,}57722\beta$

Table 24 Formulas statics

4 Metocean

4.1 Description of ocean waves

Regular waves are often used for hand calculations. However, such waves do not occur in the real ocean environment. In reality the sea have a combination of different waves with different amplitude and periods. Therefore the irregular sea can be illustrated as a sum of sinusoidal waves (illustrated in Figure 35).

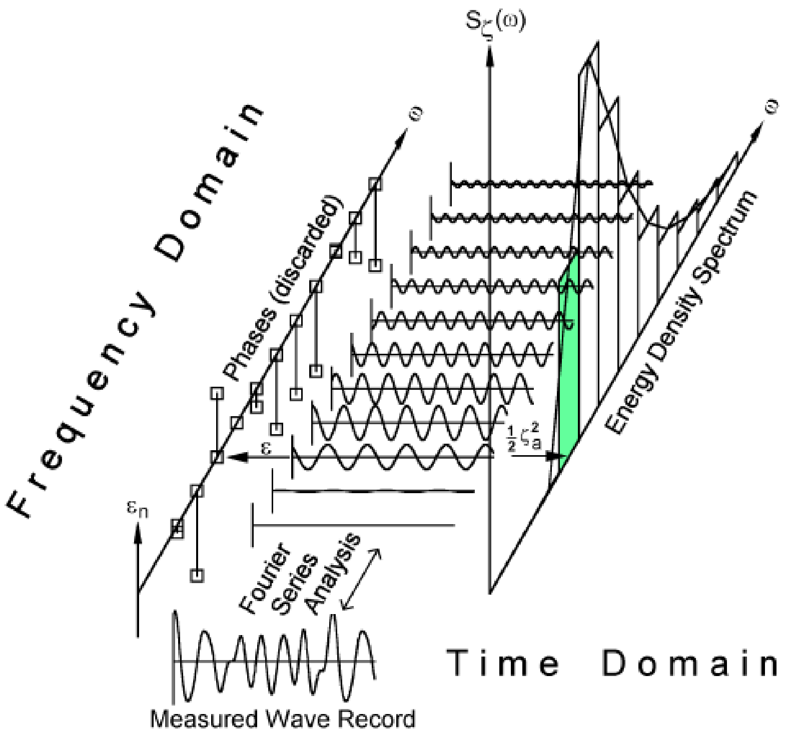


Figure 35 Illustration of the sum of sinusoidal waves, ref. [3]

Fourier analysis can combine these waves as a sum of sinusoidal waves as a good approximation. In order to get a mathematical model that is much easier to understand and operate for a given time history (T_H).

$$\xi(t) = \overline{\xi_0} + \sum_{n=1}^{\infty} A_n \cos(\omega_n t) + B_n \sin(\omega_n t) \qquad \text{(Eq. 4.1)}$$

Where the equally spaced frequencies are given by

$$\omega_n = \frac{2\pi n}{T_H}, with\ n = 1,2 \ldots \infty \qquad \text{(Eq. 4.2)}$$

The coefficients are given by

$$A_n = \frac{2}{T_H}\int_0^{T_H} \xi(t)\cos(\omega_n t)\,dt \qquad \text{(Eq. 4.3)}$$

$$B_n = \frac{2}{T_H}\int_0^{T_H} \xi(t)\sin(\omega_n t)\,dt$$

(Eq. *4.1*) may be written as

$$\xi(t) = \bar{\xi}_0 + \sum_{n=1}^{\infty} \xi \cos(\omega_n t + \theta) \quad \text{(Eq. 4.4)}$$

Where the coefficients are

$$\xi = \sqrt{A_n^2 + B_n^2} \quad \text{(Eq. 4.5)}$$

And the phase angles are given by

$$tan\theta = -\frac{B_n}{A_n} \quad \text{(Eq. 4.6)}$$

(Eq. *4.4)* represents the irregular record by the sum of an infinite number of sine waves of amplitude (ξ) and frequency (ω_n). These frequencies correspond to (Eq. *4.2*).

4.2 Spectrum model

Waves are usually generated from wind, called wind induced waves (illustrated in Figure 36). The wave formation are dependent on water depth, wind duration, width of area affected, the fetch length and the wind speed. There are at least two physical processes involved, these being the friction between air and water and the local pressure fields associated with the wind blowing over the wave surface. A great deal of work has been done on the theory of wave generation by wind, but no completely satisfactory mechanism has yet been devised to explain the transfer of energy from wind to sea according to ref. [8].

Since the wind is fluctuating the waves will also be fluctuating, but it is common to assume that the sea state is stationary for a duration of 20 minutes to 3-6 hours. A stationary sea state can be characterised by a set of environmental parameters such as significant wave height H_s and spectral peak period T_p. Ref. [15].

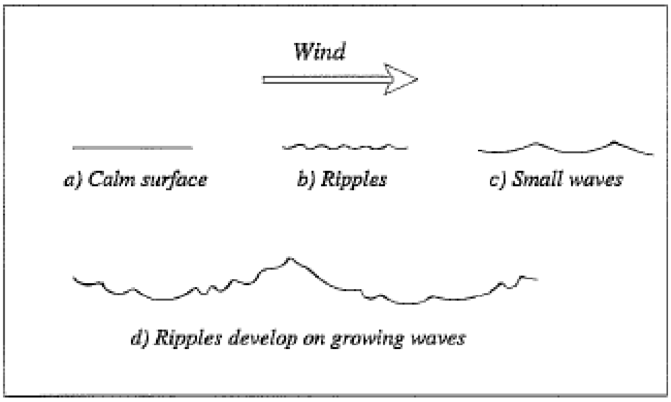


Figure 36 How waves develop, ref. [10]

Short term stationary irregular sea states may be described by a wave spectrum. A wave spectrum is the power spectral density function of the vertical sea surface displacement. The wave spectrum is often defined in terms of H_s and T_p. When the time increase the sea spectrum changes to a fully developed sea the wave spectrum grow wider, increasing the standard deviation (σ).

There are several spectrum formulas that are used in the design of offshore structures. These formulas are derived from the observed properties of ocean waves. The most appropriate wave spectrum depends on the geographical area with local bathymetry and the severity of the sea state. The Pierson-Moskowitz (PM) spectrum and JONSWAP (Joint North Sea Wave Project) spectrum are frequently applied for wind seas.

Swells are generally of long period and comparatively regular. Locally generated wave systems may therefore be contaminated by swells generated by distant storms. Moderate and low sea states in open seas areas are often composed of both wind-sea and swell. Any local environmental effects, e.g. the possibility of swell/waves at the lift-off site, should be identified and considered according to ref. [14]. A two peak spectrum may be used to account for both wind sea and swell. The Ochi-Hubble spectrum and the Torsethaugen spectrum are two-peak spectra which account for the swell waves according to ref. [15]

Different spectrum models for the same energy content distributes the energy differently across the frequency band. Thus the response of the structure will be different if a different spectrum models are used according to ref. [1]

4.2.1 Spectral moments

If the time history has a zero mean and the number of observations is very large. A time history represented by (Eq. *4.4*) therefore has a variance (m_0). The variance of the irregular wave time history is equal to the area under the wave energy spectrum.

$$m_n = \int_0^\infty \omega^n \xi(\omega)\, d\omega_N \qquad \text{(Eq. 4.7)}$$

Where ω is the angular wave frequency, and n =0,1,2.. according to ref. [21].

4.2.2 Significant wave height

The significant wave height is a commonly used measure of the height of the ocean waves. The significant wave height (H_s) is traditionally defined as the average of the highest one third of all the waves ($H_{1/3}$) in the indicated time period from the trough to crest (Eq. *4.8*). Nowadays it is usually defined as four times the square root of the standard deviation of the surface elevation (Eq. *4.9*). The different definitions is given bellow:
Deterministic definition:

$$H_s = \sum_{i=1}^{n_{1/3}} \frac{H_i}{n_{1/3}} \qquad \text{(Eq. 4.8)}$$

Statistically definition:

$$H_s = 4\sqrt{m_0} \qquad \text{(Eq. 4.9)}$$

The significant wave height is an important parameter during planning of marine operations.

4.2.3 Spectral peak period and crossing period

The spectral peak period T_P is the wave period determined by the inverse of the frequency at which a wave spectrum has its maximum value. The zero-up-crossing period T_Z is the average time interval between two successive up crossings of the mean sea level (illustrated in Figure 37).

$$T_z = 2\pi \sqrt{\frac{m_0}{m_2}} \quad \text{(Eq. 4.10)}$$

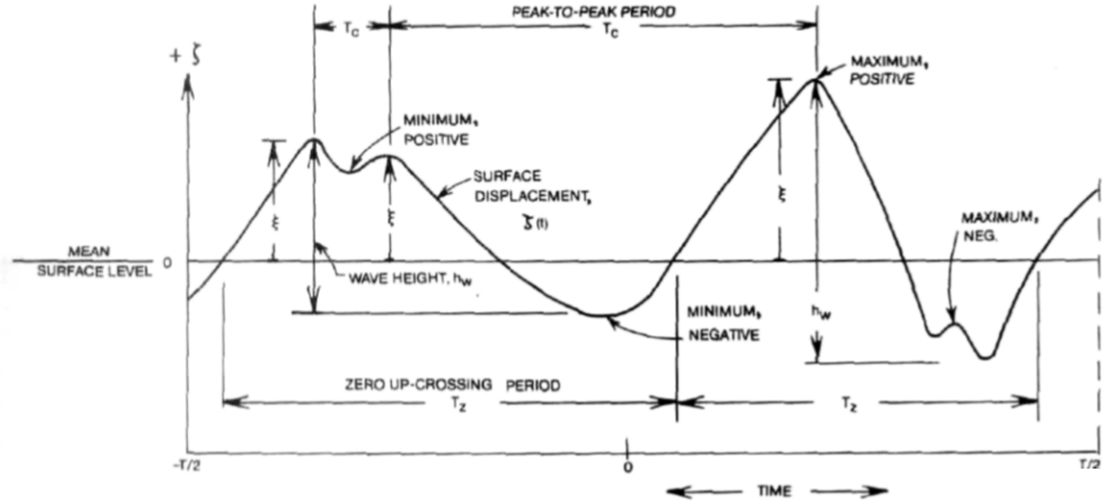


Figure 37 Typical wave record at a fixed point with definition of terms, ref. [8]

4.2.4 JONSWAP

The JONSWAP spectrum extends Pierson-Moskowitz (PM) to include fetch limited seas. Both spectra describe wind sea conditions that often occur for the most severe seastates according to ref. [21] . The PM-spectrum was originally proposed for fully-developed sea according to ref. [15]. The PM is given below in (Eq. 4.11).

$$S_{PM}(\omega) = \frac{5}{16} H_s^2 \omega_p^4 \omega^{-5} eksp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right) \qquad \text{(Eq. 4.11)}$$

The JONSWAP spectrum *(Eq. 4.12)* is formulates as a modification of the PM spectrum for a developing sea state in a fetch limited situation.

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\gamma^{\exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma-\omega_p}\right)^2\right)} \qquad \text{(Eq. 4.12)}$$

Where γ is a non-dimensional peak shape parameter, σ is the spectral width parameter *(Eq. 4.13)* and A_γ is a normalizing factor *(Eq. 4.17)*. Average values for the JONSWAP experiment data are $\gamma = 3.3$, $\sigma_a = 0.07$ and $\sigma_b = 0.09$ according to ref. [1] and [42]. The shape parameter (γ) typically varies between 1 and 7, and for $\gamma = 1$ the JONSWAP spectrum reduces to the PM spectrum (illustrated in Figure 38) according to ref. [15]

$$\sigma = \sigma_a \; for \; \omega \leq \omega_p \qquad \text{(Eq. 4.13)}$$
$$\sigma = \sigma_b \; for \; \omega > \omega_p$$
$$A_\gamma = 1 - 0.287\ln(\gamma) \qquad \text{(Eq. 4.14)}$$

If no particular values are given for the peak shape parameter γ, the following value may be applied:

$$T_P \leq 3.6\sqrt{H_s} \rightarrow \gamma = 5 \qquad \text{(Eq. 4.15)}$$
$$T_P \geq 5\sqrt{H_s} \rightarrow \gamma = 1$$
$$\sqrt{H_s}3.6 < T_P < 5\sqrt{H_s} \rightarrow \gamma = \exp(5.75 - 1.15T_p/\sqrt{H_s})$$

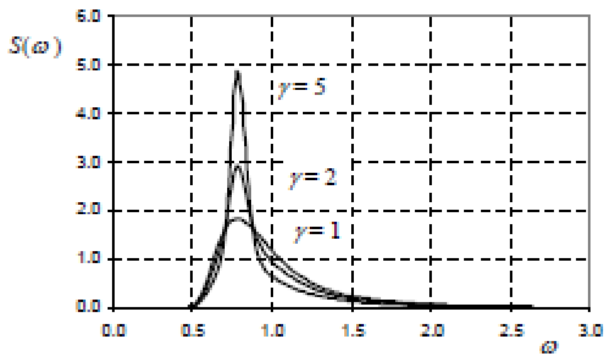


Figure 38 JONSWAP spectrum for Hs=4.0 m, TP=8.0s for shape parameter 1, 2 and 5, ref. [15]

4.2.5 Wave spreading

In ideal conditions in the open ocean all the waves travel in the same direction. However changes in wind direction, the influence of coastlines and bottom topography and the presence of waves generated elsewhere ensure that the true long crested one directional wave systems is rarity. It is much more likely that the real waves in the ocean travel in many different directions, although an easily recognized “primary” direction more or less aligned with the local wind may be discernible according to ref. [10].

The presence of more than one wave system results in enhancement and cancelation of wave crest and troughs, and this phenomenon gives rise to the term short crested to describe the appearance of a wave system with a spread of wave directions (illustrated in Figure 39) according to ref. [10].

$$S(\theta) = S(\omega)D(\theta) \qquad \text{(Eq. 4.16)}$$

The wave energy spectrum derived from a record of surface elevations obtained at a particular point in the ocean will invariably contain contributions from several different wave directions. The wave spreading have a profound influence on some vessel motions particularly roll.

$$\int D(\theta) = 1 \qquad \text{(Eq. 4.17)}$$

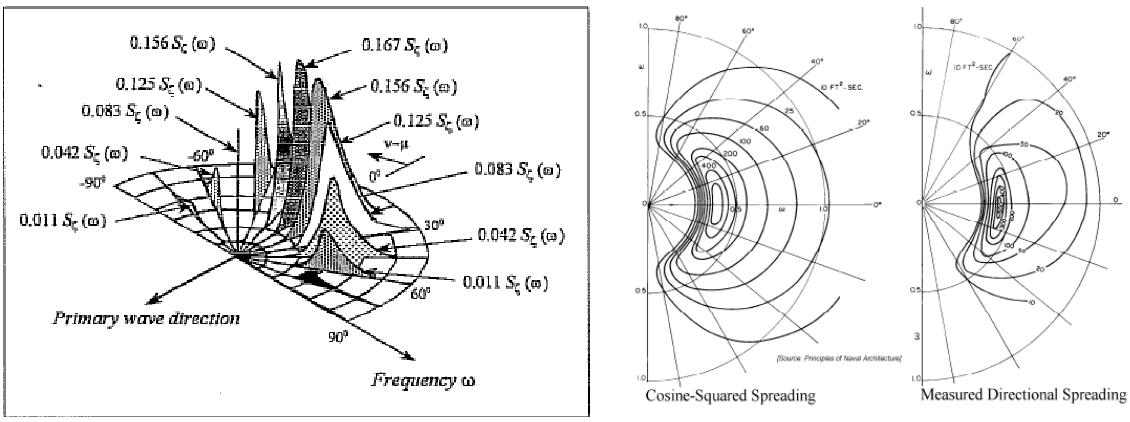


Figure 39 Illustrates the principle behind wave spreading, ref. [10] and [3]

A common directional function often used for wind sea is

$$D(\theta) = \frac{\Gamma(s+1)}{\sqrt{\pi}\,\Gamma\left(\frac{1}{2}+\frac{n}{2}\right)}\cos^{n}(\theta-\theta_p) \qquad \text{(Eq. 4.18)}$$

Where Γ is the Gamma function and $|\theta - \theta_p| \le \frac{\pi}{2}$.

Short crested sea with spreading n = 2 used in the directional function, should be applied for operations that are independent of vessel heading according to ref. [20].

4.3 Operational criteria

For each specific phase of a marine operation the design and operational metocean criteria shall be defined. A marine operation with operational reference period (T_R) less than 96 hours and planned operation time (T_{POP}) less than 72 hours may be defined as weather restricted according to ref. [17]. For a weather-restricted operation the operational metocean criteria are that set of values for the metocean parameter (wind, wave, current) which are not exceeded at the start of the operation and which a forecast not to be exceeded for the duration of the operation, allowing for contingencies.

These operations may be planned with weather conditions selected independent of statistical data, i.e. set by an owner, an operator, etc. according to ref. [15]. Usually low environmental limits are set for operations that can be completed within a short period of time because they can be carried out under a controlled condition. The downside is then that the operation is not that flexible and may lead to excessive waiting time on a good weather forecast a so called weather window. Expected waiting on weather (WOW) should be determined to establish realistic assumptions/restrictions.

4.3.1 Reference periods

Metocean criteria for marine operations depends on the planned duration of the marine operation including contingency. The contingency time (T_C) is added to cover the uncertainty in the planned operation time (T_{POP}) and cover possible contingency situations, for example equipment failure that will require additional time. The reference period should be less than the horizon of a reliable weather forecast if operation cannot be aborted without large consequences.

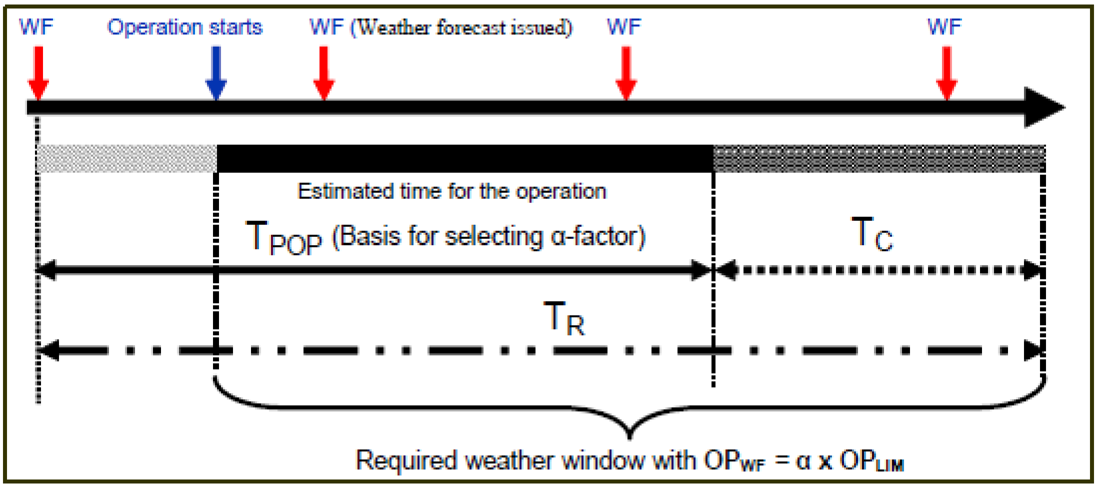


Figure 40 Operational periods, ref. [17]

If T_{POP} uncertainties and required time for contingency situations is not assessed in detail the reference period should normally at least be taken as twice the planned operation period, i.e. TR ≥ 2 × T_{POP}. An applied contingency time less than 6 hours is normally not acceptable according to ref. [17].

$$T_R = T_{POP} + T_C \qquad \text{(Eq. 4.19)}$$

The operation reference period ($T_{R,}$ illustrated in Figure 40) should be established at an early stage. The start and stop points for the lift-off should be clearly defined according to ref. [14]. Strict environmental limitations normally apply for a float-over. Such conditions could be difficult to obtain offshore and this should be considered in the planning. The system should have sufficient capacity to complete the mating operation within the planned operational time T_{POP} according to ref. [14]. The T_{POP} should be as short as practical possible, and if relevant the point of no return should be clearly defined according to [14].

4.4 Weather forecast

For weather restricted operation the time of reliable weather and the uncertainties in the weather forecast shall be considered. In order to deal with the uncertainty in the weather forecast a shape factor (α, given in Appendix E) is introduced to reduce the operational limit of the environmental parameter (e.g. H_S). The characteristic significant wave height ($H_{s,c}$) is then reduced as shown below:

$$OP_{WF} = \alpha * OP_{Lim}$$

4.5 Condition

Marine operations are of a limited defined duration carried out for overall handling of an object at sea offshore, subsea, inshore and to/from shore. The mating operation consist of several temporary sub operations, for example turning of barge, de-ballasting of barge, mooring of barge and ballasting of barge. And each of these can be divided into an infinite number of load cases, structural integrity has to be demonstrated for the governing ones.

4.6 Uncertainty

The weather criteria and availability analysis shall be based on reliable data and accuracy of the data shall be indicated. The data applied shall be given for a location or an ocean area where an operation takes place. It is recommended to use reliable instrumental data, if available or data generated by recognized weather prediction models. Further, it is recommended that the data are sampled at least each 3rd hour and interpolated between the sampling intervals. Ref. [15].

4.6.1 Instrumental data

Accuracy of environmental data may vary widely and is very much related to the observation method and type of instrument used. Because of data inaccuracy it is recommended to use several data sources in analysis (if available) specifying weather criteria for comparison according to ref. [15]. Procedures shall be established to ensure that collected data are processed and standard analysis carried out in such a way that the quality of the data may be verified. The analysis should be sufficiently extensive to allow all significant errors to be discovered. Ref. [18]. Particular attention shall be given to ocean areas where data covering is poor according to ref. [15].

4.6.2 Climate

Historical data used for specification of operational weather criteria may be affected by climatic uncertainty. Climatic uncertainty appears when the data are obtained from a time interval that is not fully representative for the long-term variation of the environmental condition. This may result in over/under –estimation of the operational weather criteria. The database needs to cover at least 20 years or preferably 30 years or more in order to account for climatic variability according to ref. [15].

4.6.3 Human errors

The vast majority of incidents are a direct result of human error. The human errors can be divided into slips and mistakes. A slip is typically something that should have been accounted for but is overseen, while a mistake can refer to some input which is specified incorrect. To reduce the probability of human errors it is important to understand the cause and result of human errors. The cause is related to the fact that every human being does a certain amount of errors, to reduce the probability of human errors the model has been reviewed. In addition the results can be compared with the expected result (e.g. hand calculations), this reduce the probability of severe errors.

5 Analysis and results

5.1 Stability

The results from the stability calculations is given in Table 25 and Table 26.

Stability hand calculations		
Component	Hand calculations	Formula
draft	4,10 m	*(Eq. 2.1)* and *(Eq. 2.2)*
L (*)	89,8 m	-
B	27,4 m	-
Buoyancy	9.64e+06 kg	*(Eq. 2.1)*
KB	2,11 m	*(Eq. 2.6)*
I_{xx}	154e+03 m^4	*(Eq. 2.7)*
I_{yy}	165e+04 m^4	*(Eq. 2.7)*
BM_T	16,6 m	*(Eq. 2.7)*
BM_L	178 m	*(Eq. 2.7)*
KG	3,09 m	*(Eq. 2.8)*
GM_T	15,6 m	*(Eq. 2.5)*
GM_L	177 m	*(Eq. 2.5)*
(*) The length of the barge in the waterline, in addition the bow and stern geometry is taken into account.		

Table 25 Stability hand calculations

Stability computer calculations	
Component	HydroD calculations
draft	4,10 m
Buoyancy	9.64e+06 kg
KB	2,11 m
KG	3,09 m
GM_T	15,4 m
GM_L	178 m

Table 26 Stability computer calculations

In addition a stability analysis (illustrated in Figure 41) was performed for the Standard Viking barge, with the following ballast condition (illustrated in Figure 42)

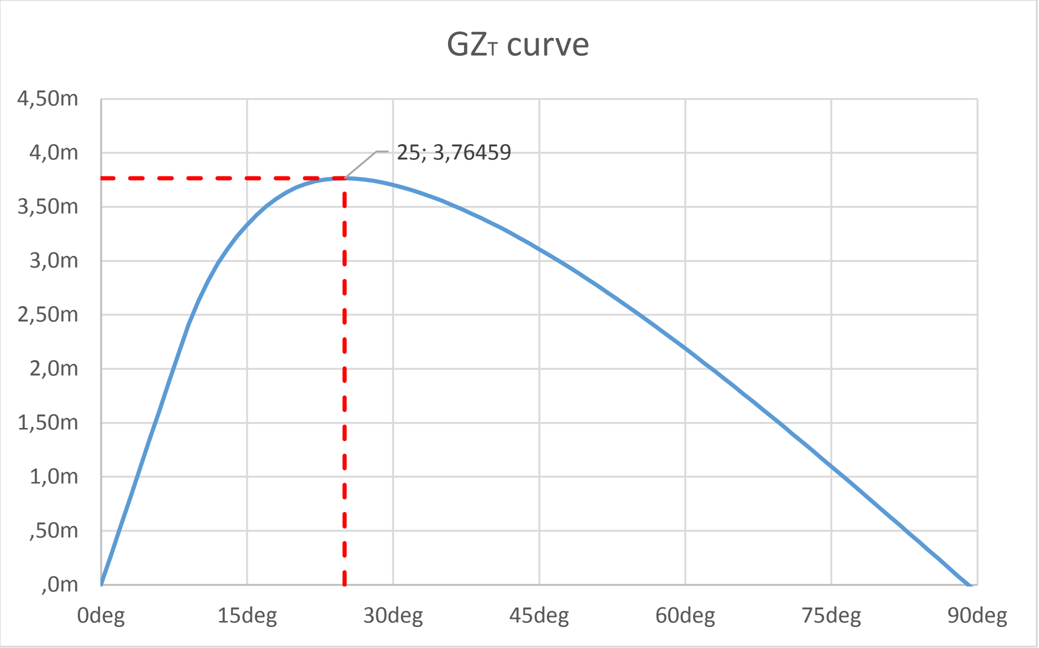


Figure 41 Transversal stability analysis (Standard Viking barge, draft 4,10 m)

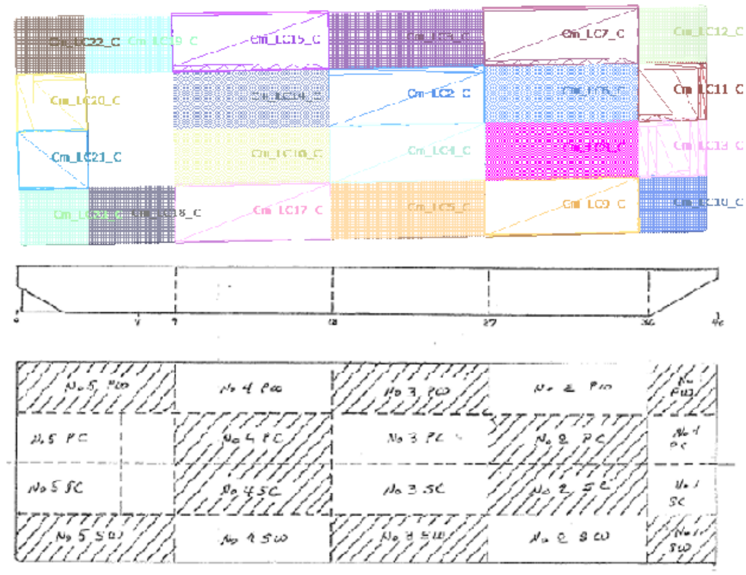


Figure 42 Ballast condition

5.2 Dynamics

The equations given in chapter 2 has been used to compare the output from HydroD with hand calculations done in Excel the results are given in Table 27.

Dynamic calculations Standard Viking barge			
Component	Hand calculations	HydroD calculations	Formula
M	9,64e+06 kg	9,64e+06 kg	(Eq. 2.1)
I_{44}	6,48e+08 kgm^2	6,43e+08 kgm^2	(Eq. 2.27) Table 8
I_{55}	6,94e+08 kgm^2	5,79e+08 kgm^2	
A_{33} 1)	2,72e+07 kg	- 1)	Figure 12 (Eq. 2.20) and (Eq. 2.21) Table 8
A_{44} 1)	1,68e+08 kg*m^2		
A_{55} 1)	1,92e+10 kg*m^2		
K_{33}	247e+02 kN/m	250e+02 kN/m	(Eq. 2.34) Table 11
K_{44}	159e+04 kN	146e+04 kN	
K_{55}	179e+05 kN	168e+05 kN	
K_{35}	-138e+02 kN	-116e+02 kN	
$\omega_{n,33}$	0,82 rad/s	-	(Eq. 2.41)
$\omega_{n,44}$	1,39 rad/s		
$\omega_{n,55}$	0,83 rad/s		
$T_{n,33}$	7,66 s	7,63 s 2)	(Eq. 2.42)
$T_{n,44}$	4,51 s	5,95 s 2)	
$T_{n,55}$	7,58 s	6,45 s 2)	
Comment: The force and moments are calculated based on *(Eq. 2.37)(Eq. 2.34)* which led to the results represented in Table 12. The response, force and moments from the hand calculations and HydroD can be found in Appendix A. 1) The two-dimensional added mass coefficients are independent of the wave frequency, in reality and in computer programs the added mass depend of the frequency. Therefore the added mass from HydroD is not included in this table. 2) The deviation in natural periods is related to variable added mass. (as illustrated in Figure 43)			

Table 27 Dynamic calculations Standard Viking barge

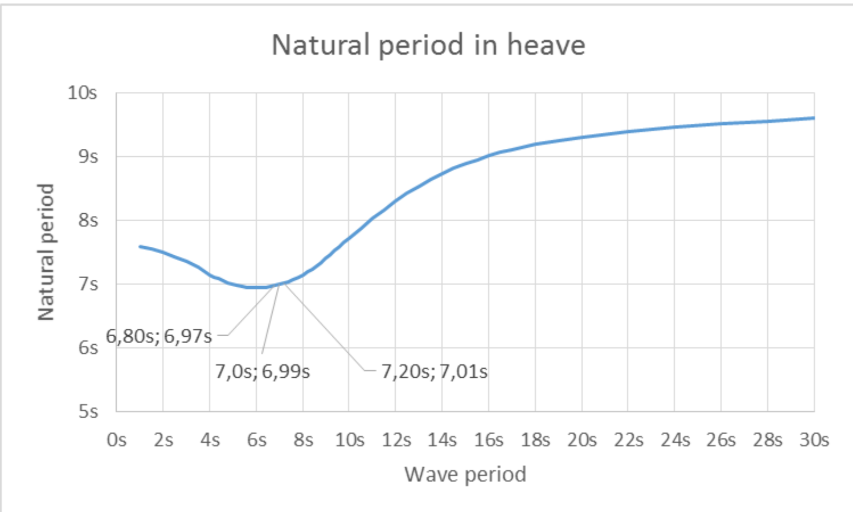


Figure 43 Natural period in heave with different wave periods.

The topsides moments and products of inertia has been calculated using a finely distributed weight database for the Huldra topside the results are given in Table 28.

Dynamic hand calculations topside		
Component	Calculated value	Formula
M	4,87e+06 kg	-
I_{xx}	6,14e+08 kgm^2	The moments and products of inertia are calculated by using (Eq. 2.28), (Eq. 2.29), (Eq. 2.30) and a detailed weight list.
I_{yy}	1,48e+09 kgm^2	
I_{zz}	1,72e+09 kgm^2	
I_{xy}	1,51e+07 kgm^2	
I_{xz}	5,38e+07 kgm^2	
I_{yz}	-9,21e+07 kgm^2	

Table 28 Dynamic hand calculations topside

The equation of motion and HydroD has been used to calculate the RAO curves for the barge, for all the 6 DOF and headings from 0 to 180 deg since the barge is symmetric about the centreline but have different fore and aft geometry. The RAO curves for heave is illustrated in Figure 44, the rest of the RAO curves can be found in Appendix C(C3 and C4).

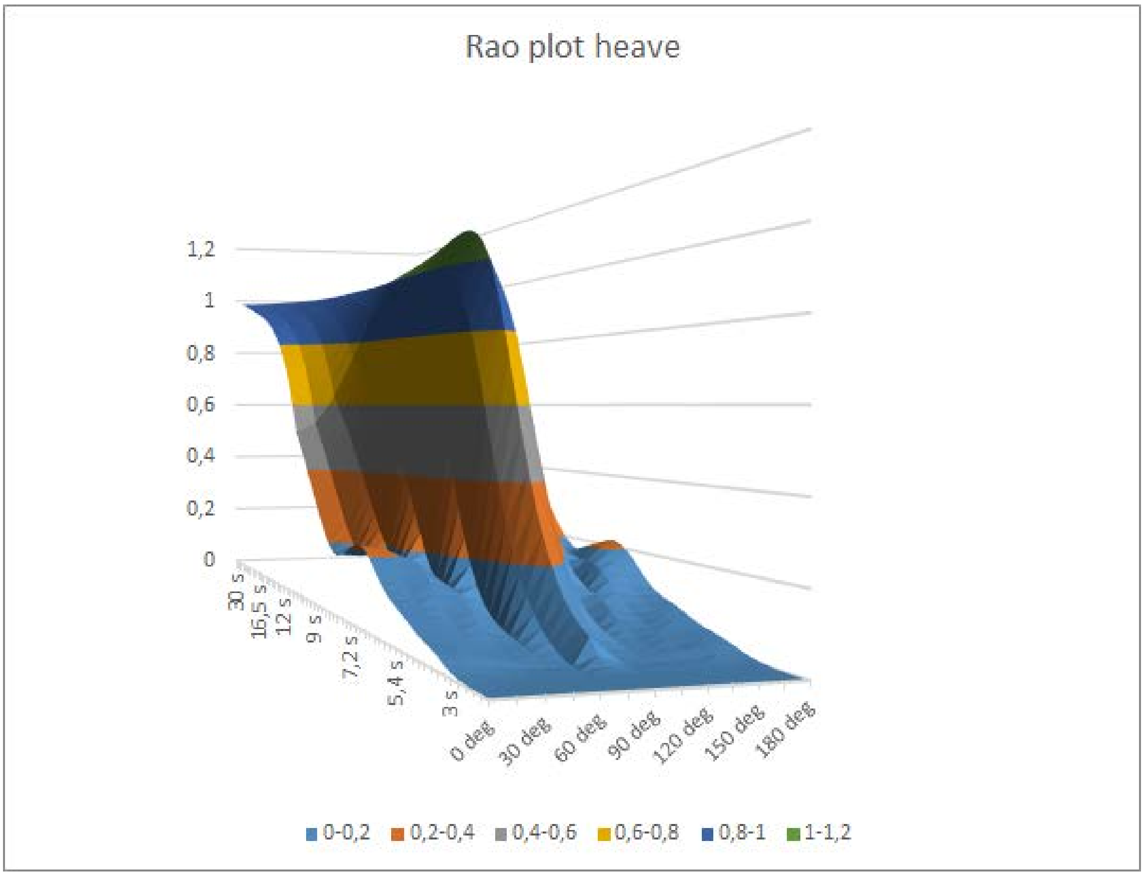


Figure 44 RAO curve heave motion

5.3 SIMA analysis

5.3.1 Static analysis

Static calculations are done in Excel to calculate the forces which are introduced into the wires (takes tension) and fenders (takes compression) to achieve the equilibrium position the results are given in Table 29.

Fenders	STAMOD	Hand calculations
Fender_Z_B11_1	2,73e+04 kN	2,72e+04 kN
Fender_Z_B11_2	2,73e+04 kN	2,72e+04 kN
Fender_Z_B12_1	3,44e+04 kN	3,44e+04 kN
Fender_Z_B12_2	3,44e+04 kN	3,44e+04 kN
Fender_Z_B21_1	4,06e+04 kN	4,06e+04 kN
Fender_Z_B21_2	4,06e+04 kN	4,06e+04 kN
Fender_Z_B22_1	5,14e+04 kN	5,14e+04 kN
Fender_Z_B22_2	5,14e+04 kN	5,14e+04 kN

Wires	STAMOD	Hand calculations
W_B11	4,79e+04 kN	4,79e+04 kN
W_B12	6,06e+04 kN	6,06e+04 kN
W_B21	7,15e+04 kN	7,15e+04 kN
W_B22	9,04e+04 kN	9,04e+04 kN

Table 29 Forces in wires and fenders

In addition the de-ballasting is calculated to get even draft and no trim of the two barges.

5.3.2 Dynamic analysis (time domain)

For the time domain analysis several (10) realisations of 3 hours is done where the extremes values from each simulations is estimated as the most probable maximum (MPM) of the extreme value distribution. The MPM value is found on 4 different points representing the 4 stabbing cone, and the maximum value for these 4 points is kept to calculate the extreme value (P90). If the P90 extreme value is equal or less than the criteria given in Table 32 it is a safe to do the marine operation for the given sea state. By using this approach the limiting H_S for a given T_P is found. The result is illustrated in Figure 45 and Table 33.

Two different load conditions (illustrated Table 30 and Table 31) have been analysed, where the maximum velocity and acceleration for the four points representing the stabbing cones have been evaluated with respect to the limiting criteria (illustrated in Table 32). In addition the motion of the topside have been evaluated with respect to the limiting criteria (illustrated in Table 32) for the docking stage.

Load condition 1 (docking stage)	
Barges centre to centre	60 m
Topside elevation	27 m
Boom angle	51,3°
Stabbing cone elevation	22 m
Results	Figure 45 , Table 33 and Appendix D (D3)

Table 30 Details load condition 1 (docking stage)

Load condition 2 (initial mating stage)	
Barges centre to centre	62,4 m
Topside elevation	26
Boom angle	48,5°
Stabbing cone elevation	21 m
Results	Figure 46, Figure 47, Table 34 and Appendix D (D4)

Table 31 Details load condition 2 (initial mating stage)

	Acceleration		Velocity		Displacement					
	Horizontal	Vertical	Horizontal	Vertical	X	Y	Z	RX (Transver	RY (Longitud	RZ (Plan rotation)
Req	0,4905	0,981	0,5	0,4	1,5	1,5	1	2	2	3

Table 32 Limiting criteria according to Table 21, Table 22 and Table 23, ref. [19]

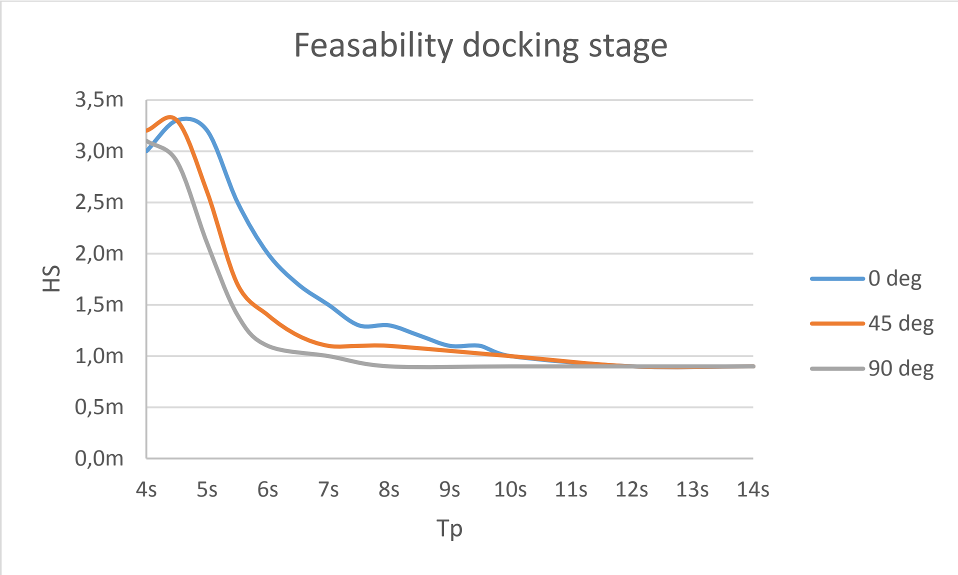


Figure 45 Limiting HS and TP (docking stage)

Direction	HS \ TP	4 s	6 s	8 s	10 s	12 s	14 s
Head Sea (0 deg)	0,9 m						
	1 m						
	1,3 m						
	2 m						
	3 m						
Quartering Sea (45 deg)	0,9 m						
	1,0 m						
	1,1 m						
	1,4 m						
	3,2 m						
Beam Sea (90 deg)	0,9 m						
	1,1 m						
	3,1 m						

Table 33 Limiting HS and TP (docking stage)

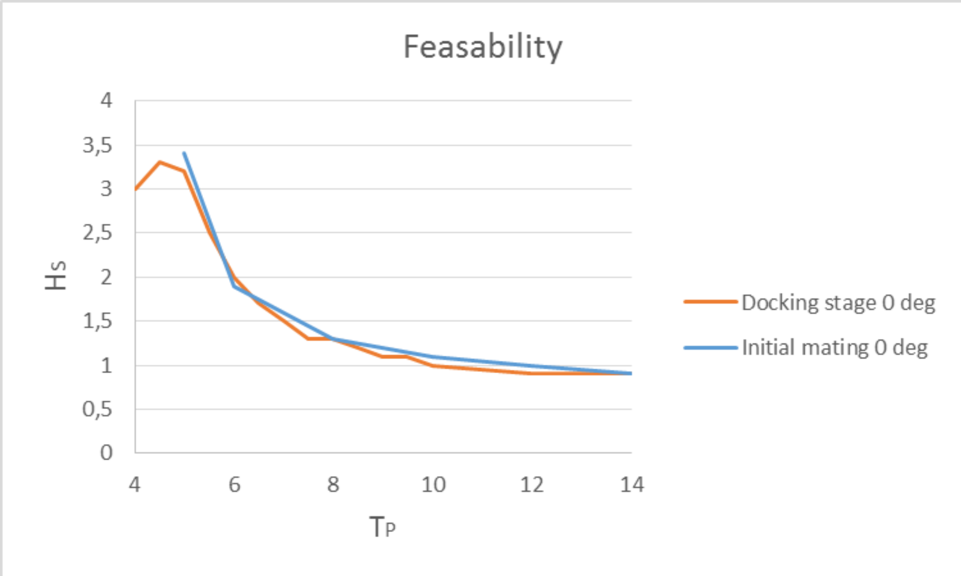


Figure 46 Limiting HS and TP (0 degrees, docking stage and initial mating stage)

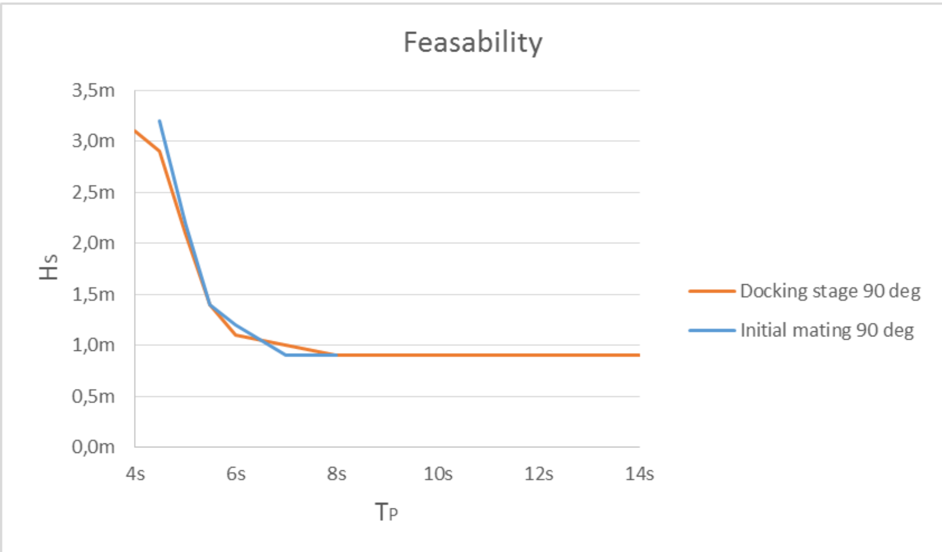


Figure 47 Limiting HS and TP (90 degrees, docking stage and initial mating stage)

Direction	HS \ TP	5 s	6 s	8 s	10 s	12 s	14 s
Head Sea (0 deg)	0,9 m						
	1,0 m						
	1,1 m						
	1,3 m						
	1,9 m						
	3,4 m						
Beam Sea (90 deg)	0,9 m						
	1,2 m						
	2,2 m						

Table 34 Limiting HS and TP (initial mating)

6 Discussion

6.1 Hand calculations

6.1.1 Strip theory and HydroD

The results from the hand calculations and HydroD are comparable (illustrated in Table 27 and Appendix A), this is a good verification of the model and the software. From the force and motion curves in Appendix A it is possible to see that waves that are relative short compared to the vessel have a small influence. This is reasonable because the sum of the wave elevation is close to zero. It is assume that the varying amplitude is due to the number of peaks and valleys can be equal or unequal. For the heave motion it is possible to see that for long waves ($>>L_B$) the vessel follows the wave, because then one wave will contribute to a surface elevation (illustrated in Table 35). For the rotational force and motion it can be seen that when the wave length is equal or greater than the length (L_B) or breadth (B_B) the wave contributes to a moment and rotational motion.

Wave length	Wave length [m]	Assumption	Wave period [s]
2 x Length of vessel	183	Linear waves (deep water)	10,8
1 x Length of vessel	91,4		7,65
1x Breadth of vessel	27,4		4,19

Table 35 Wave length and period

There is some deviation for the roll motion amplitude in the damping controlled region, there might be at least three reasons for this appearance:

- The hand calculated roll moment is greater than the roll moment calculated in HydroD.
- The strip theory is limited to relative small motions.
- The up righting moment is not included in the quasi static calculations, the up righting moment will make a moment in the opposite direction.

In addition there is a small difference on where the peak on the RAO curve can be found. A two dimensional constant added mass. This is applied for the hand calculations believed to explain most of the difference. While in HydroD the added mass is shape and frequency dependent.

6.1.2 Moments and products of inertia

The moments and products of inertia (Table 28) are found by assuming that each weight specified is a “particle” with a small mass and a given distance from the centre of gravity (COG). This is a good approximation because the moments of inertia about the origin (I_0) are relative small since the weight database is finely distributed. In addition the moment of inertia about the origin (I_0) will be relative small compared to the contribution from the parallel axis theorem when the distance from the COG increase as illustrated in (Eq. 2.29) and (Eq. 2.30).

6.2 Gumbel

The total wave system is assumed to be a summation of many independent components. The large number of wave components are assumed to have definite frequencies and random phase angles. ($\xi_a(t) = \xi_i \cos(\omega t + \theta)$ To implement a random phase angle a new seed number is introduced for each 3 hour time domain analysis.

The extreme value distribution will for increasing number of maxima approach a Gumbel distribution (according to ref. [13]), therefore it is assumed that 10 realisations also follows the Gumbel distribution.

In addition boot strapping and Monte Carlo simulation are done to give an estimate of the confidence. The Monte Carlo simulation is done by assuming that the MPM follows a calculated Gumbel distribution. Then random numbers from 0-1 with equal probability are generated. Then new MPM values are calculated from the cumulative distribution function. If the random generated numbers and the numbers from the simulation coincides (narrow band) confidence is achieved.

It can be seen from the bootstrapping that there is a relation between the standard deviation and the uncertainty (illustrated in Figure 48), this is because the scale parameter is a function of the standard deviation. 10 realisations are assumed to be sufficient when the standard deviation is a relative small value compared to the mean value which is the case for most of the results given in Appendix D (D3 and D4). But for the conditions where the standard deviation is greater it is recommended to do more realisations.

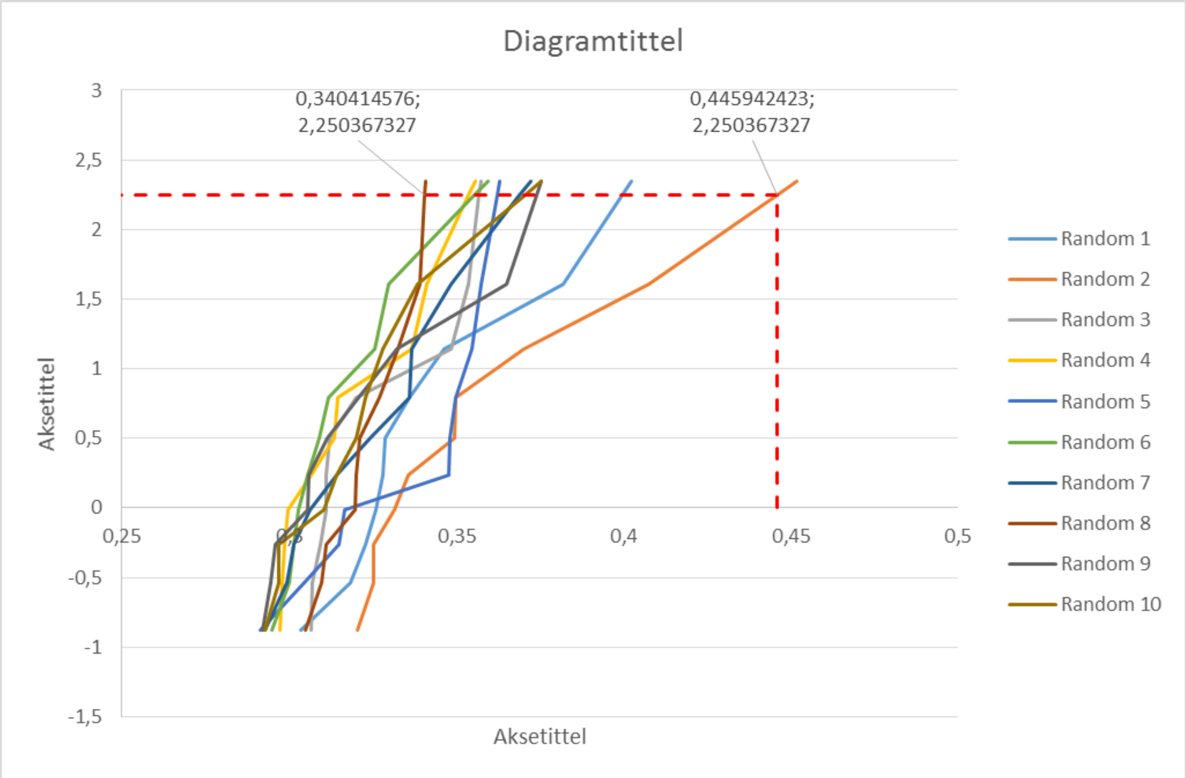
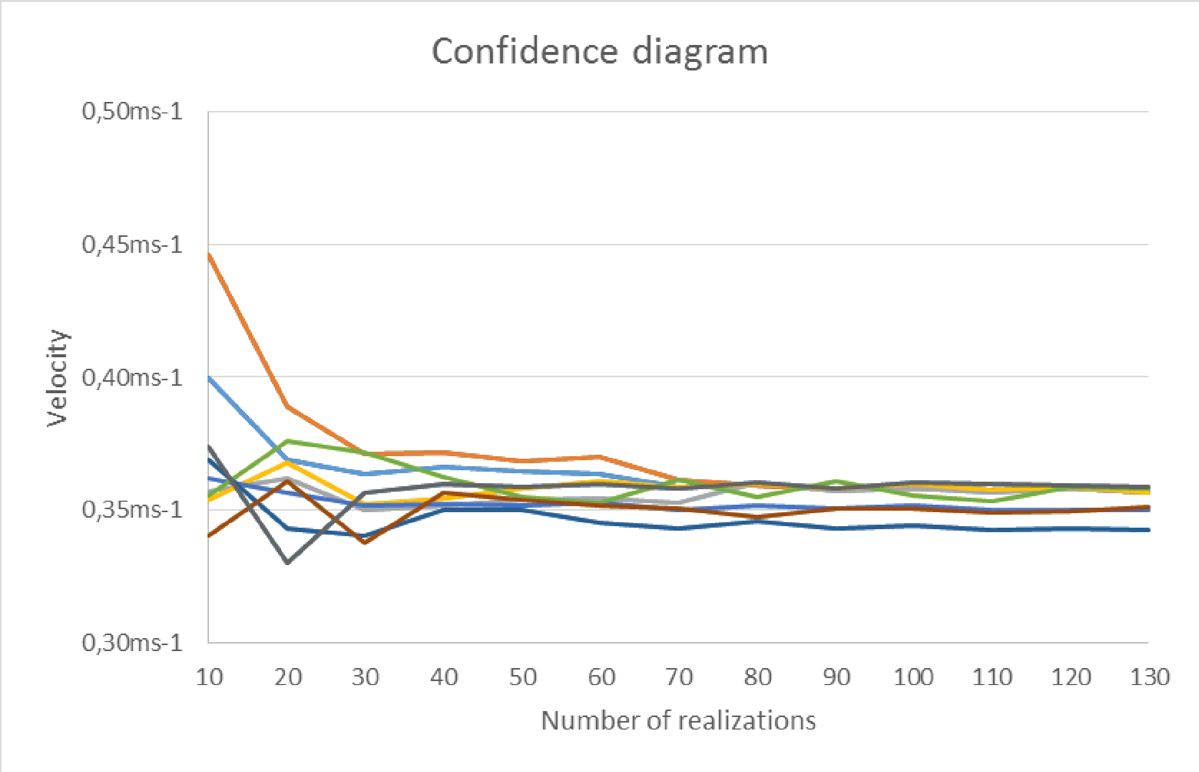


Figure 48 Bootstrapping of the z velocity, the stippled line represent P90 (TP 7,5, HS 1,3 dir 0 deg (s=0,03))

Better confidence is achieved by performing more realisations (>40). In other words the probability of overestimating (the orange line in the Figure 49) or underestimating (the grey, blue or brown line in the Figure 49) the extreme value decreases.



Analysis	#-LN(-LN(Fx)	Random 1	Random 2	Random 3	Random 4	Random 5	Random 6	Random 7	Random 8	Random 9	Random 10
10	2,25036733	0,39956571	0,44594242	0,35684289	0,35371764	0,36212879	0,35530372	0,36893067	0,34041458	0,37406547	0,37048744
20	2,25036733	0,36890031	0,38912267	0,36167653	0,36772954	0,35651049	0,37569111	0,34291056	0,36068539	0,33012182	0,34993869
30	2,25036733	0,36353034	0,37089938	0,34991519	0,35242446	0,35168913	0,37178923	0,34054864	0,33739191	0,35663017	0,3604761
40	2,25036733	0,36621755	0,37144314	0,35174716	0,35442514	0,35200709	0,36227555	0,35021748	0,35651291	0,35985042	0,36584586
50	2,25036733	0,36438494	0,36833752	0,35365108	0,35827473	0,35186401	0,35469731	0,3500651	0,35377172	0,3589141	0,36295223
60	2,25036733	0,36372509	0,36996369	0,3545958	0,36081953	0,35250467	0,35298394	0,34514323	0,35180595	0,35997653	0,36733329
70	2,25036733	0,35871968	0,36133438	0,3526323	0,35877822	0,35005076	0,36131818	0,34328122	0,35054553	0,35815992	0,36202223
80	2,25036733	0,35988566	0,35924878	0,36006166	0,35994408	0,35168405	0,35485592	0,34557072	0,34715394	0,36025583	0,36457754
90	2,25036733	0,3582758	0,35764347	0,35685128	0,35833322	0,35082467	0,36088993	0,34296461	0,35040876	0,35831818	0,36164094
100	2,25036733	0,35969998	0,35837225	0,35825561	0,35999582	0,35160316	0,35526679	0,34426214	0,35053648	0,36031259	0,35942604
110	2,25036733	0,35773205	0,35733057	0,35631938	0,35767146	0,3498046	0,35339151	0,34252314	0,3487602	0,35975514	0,35664056
120	2,25036733	0,35858509	0,35818199	0,35790493	0,35852423	0,35007628	0,35879763	0,34306764	0,3495781	0,35918668	0,36220807
130	2,25036733	0,35681428	0,35669552	0,35647846	0,3567452	0,34999143	0,35809407	0,34274385	0,35093212	0,3584786	0,36165876

Figure 49 Confidence achieved with different number of realisations (TP 7,5, HS 1,3 dir 0 deg)

6.3 Results from SIMA

In SIMA the model is coupled with fenders and wires to satisfy the assumption that the barges are free to move relative to each other. As mentioned earlier in (4.2.5) real waves in the ocean travel in many different directions. For this reason spreading (n=2 according to ref. [20]) is implemented in SIMA.

It is assumed that the impact force limitation can be expressed as a velocity and acceleration limitation because both terms contributes to impact force. This is a good simplification because the velocity and acceleration have different phase angles and will not occur simultaneously. Therefore it is reasonable to assume that there will not be a large correlation for the impact force based on acceleration and velocity.

Wind and current is neglected, wind and current contributes to forces which is trying to move the system in the given direction. Since the system is kept in position by tug boats it is assumed that the effect of wind and current can be handled in the limiting conditions presented in Table 33.

The limitations is based on the vertical velocity for T_P greater than 4,5s (Appendix D). This seems reasonable from looking at the heave curve in Appendix A. From T_P 4,5s the RAO curve for heave motion starts to build up as the waves get larger and become a surface elevation when the wave period increase (illustrated in Table 15). Since the RAO curve increase with increasing T_P it can be seen that the operation criteria (H_S) diminish with increasing T_P. It can be seen that the operation criteria flatten out when T_P is greater than 12 seconds the (illustrated in Figure 45, 0 degrees) same can be observed for RAO curve for the heave motion in Appendix A. In addition it can be seen that there is a dump around the natural period in heave which is around 7,5 s (illustrated in Figure 45).

There is a small difference between the results obtained from the docking stage and the initial mating stage (illustrated in Figure 46 and Figure 47), this is reasonable because it is the heave velocity which is the limiting criterion. The small difference gives a slightly better operation condition (illustrated in Figure 46), there might be at least two reasons for this appearance:

- The reason for this appearance can be related to that one analyse gives an overestimate and the other analyse gives an underestimate (illustrated in Figure 49). In addition the P90 value is slightly more conservative for the docking stage compared to the P90 value for the initial mating stage (ref. Appendix D, D3 and D4).
- A reduction in the pitch velocity. The pitch velocity contributes to local z velocity as illustrated in *(Eq. 6.1)*. Therefore the docking stage will be the most critical stage, and where it have been done most analysis.

$$\dot{z}_p = Arm * \dot{\phi} \qquad \text{(Eq. 6.1)}$$

A long natural period in heave will move the dump (illustrated in Figure 45, around T_P 7-8 sec, which is the natural period in heave) to the right leading to better operation conditions. A long natural period is achieved by increasing the mass and reducing the waterline area (e.g. semi-submersible). It is also possible to increase the waterline area to achieve a better operation conditions because then the stiffness controlled region of the RAO curve is pushed to the right. The stiffness controlled region is pushed to the right because relative short waves compared to the length of the vessel will not create a heave motion (illustrated in Figure 50).

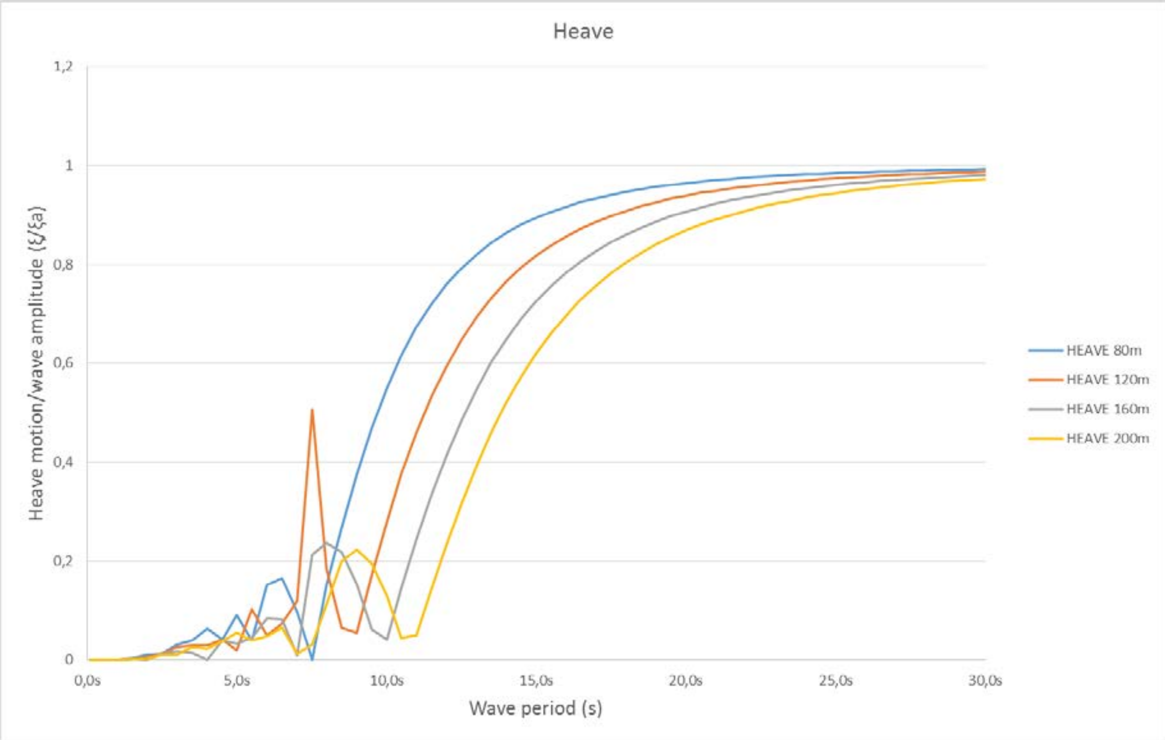


Figure 50 Illustrates the heave RAO function for 0 degrees for varying vessel length and fixed breadth (27,432 m)

Some combinations of TP and HS are rare. For that reason a joint model of H_S and T_P as the contour of constant probability density going through the above mentioned parameter combination. An example of such contour lines are shown in Figure 51 according to ref. [23]. The figure illustrates that a wave height above contour line is a rarity. Combinations of HS and TP has to be selected along a contour with return values that correspond to the requirement from table 3.3 in ref. [17].

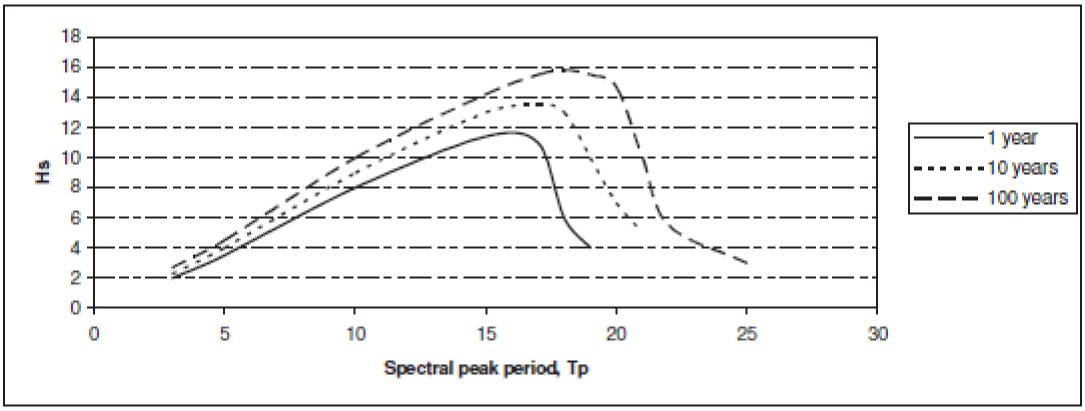


Figure 51 Example of contour line (joint probability HS and TP), ref. [23].

7 Conclusion

It has been found possible to make good estimates of RAO curves for heave and pitch motion by means of hand calculations (ref. Table 25, Table 27 and Appendix A). Further, a good correspondence between the hand calculations and the software calculations verify that the modelling in GeniE and HydroD is correct.

From the results from HydroD it is possible to see that the different bow and stern shape have a limited impact on the RAO curves. Only a small difference is observed from waves approaching from the head and the following directions (illustrated in Figure 16), the same apply to waves from bow and quartering (ref. Appendix C (C4)). This confirms that the barge is almost symmetrical about the longitudinal and the transverse direction, therefore only directions from 0^0 to 90^0 have been considered in the SIMA analysis.

In SIMA it is observed that the roll motion of the topside comes from individual heave of barges. In addition it has been observed that individual roll of the barges does not affect the movement of the topside.

In this master thesis the feasibility of the Versatruss system has been considered, and the installation limitations have been investigated in SIMA. It is assumed that the installation limitations due to impact force can be represented with a velocity and acceleration limitation. Several time domain analysis are preformed to find the limiting H_S and T_P. For the time domain analysis the JONSWAP and PM spectrum are used since these spectrums are most frequently used to describe wave systems in the North Sea ref. [17]. Since this is a feasibility study the peak parameter has been calculated from equation *(Eq. 4.15)* as recommended in ref. [15]. The critical significant wave height have been calculated for the chosen peak periods (T_P). As a result the installation limitations can be characterized by a limiting H_S and T_P (Figure 52 and Table 36). It can be seen that for increasing peak periods the H_S diminish, which is reasonable because then the vessel tends to follows the wave.

The limiting criterion is heave velocity (Eq. *7.1*) for large waves relative to the L_B (0 deg) or B_B (90 deg), therefore it can be observed that the limiting criteria diminish for increasing wave heading (0^0-90^0). This is reasonable because large waves creates a surface elevation which contributes to heave force. In addition it is reasonable that the limiting criteria diminish for increasing wave heading since the barges are slender (B<<L). For short waves the response is controlled by forced motion and rapid pitch/roll motion, therefore the limiting criterion is horizontal acceleration.

$$\dot{z} = \omega_n \cos(\omega t - \theta) \qquad \text{(Eq. 7.1)}$$

During the load transfer operation the topside is lowered down and the barges is moved to the sides. Additional simulation have been done and it has been observed that there is no significant difference between the different load conditions (illustrated in Figure 46 and Figure 47).

For the analysis a new and random seed is specified for each realisation in order to be sure that the wave generation have a random phase angles for the wave components. Then a Gumbel distribution is used to find the P90 extreme value. By using bootstrapping with Monte Carlo simulation it has been discovered that 10 realisations is not sufficient, because there is a probability of overestimating or underestimating the P90 value (illustrated in Figure 49). But nevertheless 10 realisations gives a good estimate of what the actual P90 value should be since the standard deviation is small (illustrated in Figure 49).

It is important that the weather criterion is lower than what the installation limitations suggests. Since a 3 hour time domain analysis is used to find limiting H_S and T_P values, the limitation values for operations lasting longer than 3 hours can be approximated with the alpha factor. A load transfer operation will require a weather window of 3-6 hours. In addition a meteorologist at site that has continuous access to weather information and is familiar with the local phenomena's is required in order to use the alpha factor (illustrated in Appendix E). The requirement which is specified in Figure 45 and Table 33 is a realistic condition in the North Sea for a summer installation in the months from May to August.

Since the results are based on JONSWAP and PM spectrums which are most frequently used to describe wave systems in the North Sea, the results will be applicable for several places in the North Sea. From a marine operational point of view the Versatruss system is feasible for a calm North Sea condition (illustrated in Figure 52). It is reasonable to believe that the installation limitations can be improved by increasing the dimensions of the barges as illustrated in Figure 50. If the Versatruss system is planned for a marine installation of a topside the system has to be checked with specified environmental parameters from the applicable field.

Transport and installation of a topside on the Norwegian continental shelf will require a weather window of 3 days in order to account for a round-trip. The Versatruss system requires a calm North Sea condition, therefore it is recommended that the transportation to the field is done on one large barge. By using one large barge the installation limitations for the transportation and waiting on good weather stage gets enhanced and the weather window for the Versatruss system is limited to the load transfer operation, which is beneficial for the installation limitations (ref. the alpha factor Appendix E). In addition this reduces the risk of getting caught by bad weather, which can cause a total loss. Chevron decided to transport the Versatruss system across the Gulf of Mexico fully assembled, to be towed in a catamaran formation. While in tow on open waters, the Versatruss System collapsed and became a total loss according to ref. [39].

Float over with the Versatruss system looks promising because it seems that it is a feasible technology for the North Sea with respect to the installation limitations. In addition the Versatruss system requires low CAPEX compared to other installation methods. But there is still several areas that must be taken into account in order to call it a proven technology for the North Sea.

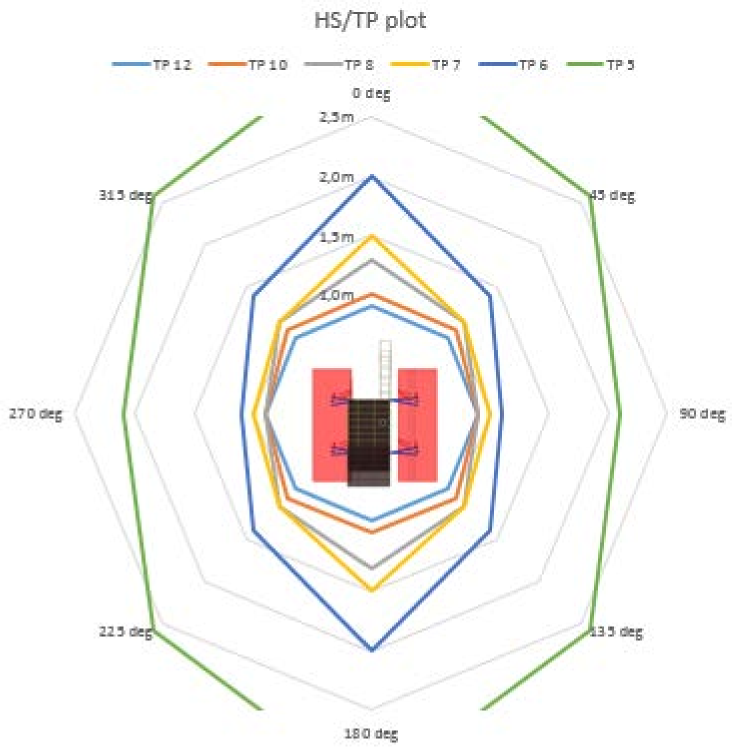


Figure 52 Feasible combinations of HS and TP

0/180 degrees		45/135/225/315 degrees		90/270 degrees	
TP	HS	TP	HS	TP	HS
4	3	4	3,2	4	3,1
4,5	3,3	4,5	3,3	4,5	2,9
5	3,2	5	2,6	5	2,1
5,5	2,5	5,5	1,7	5,5	1,4
6	2	6	1,4	6	1,1
6,5	1,7	6,5	1,2	-	
7	1,5	7	1,1	7	1
7,5	1,3	7,5	1,1	-	-
8	1,3	8	1,1	8	0,9
8,5	1,2	-	-	-	-
9	1,1	-	-	-	-
9,5	1,1	-	-	-	-
10,00	1	10	1	10	0,9
12,00	0,9	12	0,9	12	0,9
14,00	0,9	14	0,9	14	0,9

Table 36 Feasible combinations of HS and TP (-, means that the given TP has not been investigated)

7.1 Further work

- The Versatruss lifting system works by applying tension to winches and thereby forcing the boom tips to move upwards. This results in significant compressive forces between the connecting members of the lifted module. The connecting member have to be specially designed to withstand these compression forces according to ref. [6]. In addition structural reinforcement of the deck plate is needed where the lifting booms is placed.

- Handling difficulties due to boom length. If the boom angle ranges from 25 to 75 degrees, the Versatruss would require a boom length of approximately 85% greater than the vertical travel distance which result in handling difficulties according to ref. [6].

- Potential hazards should also be investigated to prevent potential accidents. There has been one accident when Chevron chose to use the Versatruss float-over system in Lake Maracaibo, Venezsuala. Chevron decided to transport the system across the Gulf of Mexico fully assembled on two barges, to be towed in a catamaran formation. While in tow on open waters, the Versatruss System collapsed and became a total loss according to ref. [39].

- Any new or modified design of a ship or equipment may be subjected to potential hazards and/or harmful effects. As they often are impossible to predict theoretically, model testing in waves is a well-established method. It is therefore recommended to do a model test of the Versatruss system.

- Several realisations should be done to achieve a better confidence as illustrated in Figure 49. In addition additional direction can be analysed (15º, 30º, 60º and 75º). Since this master thesis is a feasibility study, the JONSWAP spectrum has been specified with respect to DNV ref. [15]. If the Versatruss system is planned for a marine installation of a topside the system has to be checked with specified environmental parameters from the applicable field.

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[13]	DNV-OS-E301 Position Mooring October 2013
[14]	DNV-OS-H201 Load transfer operations April 2012
[15]	DNV-RP-H103 Modelling and analysis of marine operations April 2011
[16]	DNV-RP-H102 Marine operations during removal of offshore installations April 2004
[17]	DNV-OS-H101 Marine operations, General October 2011
[18]	NORSOK N002 Collection of metocean data (Rev 2, Oct 2010)
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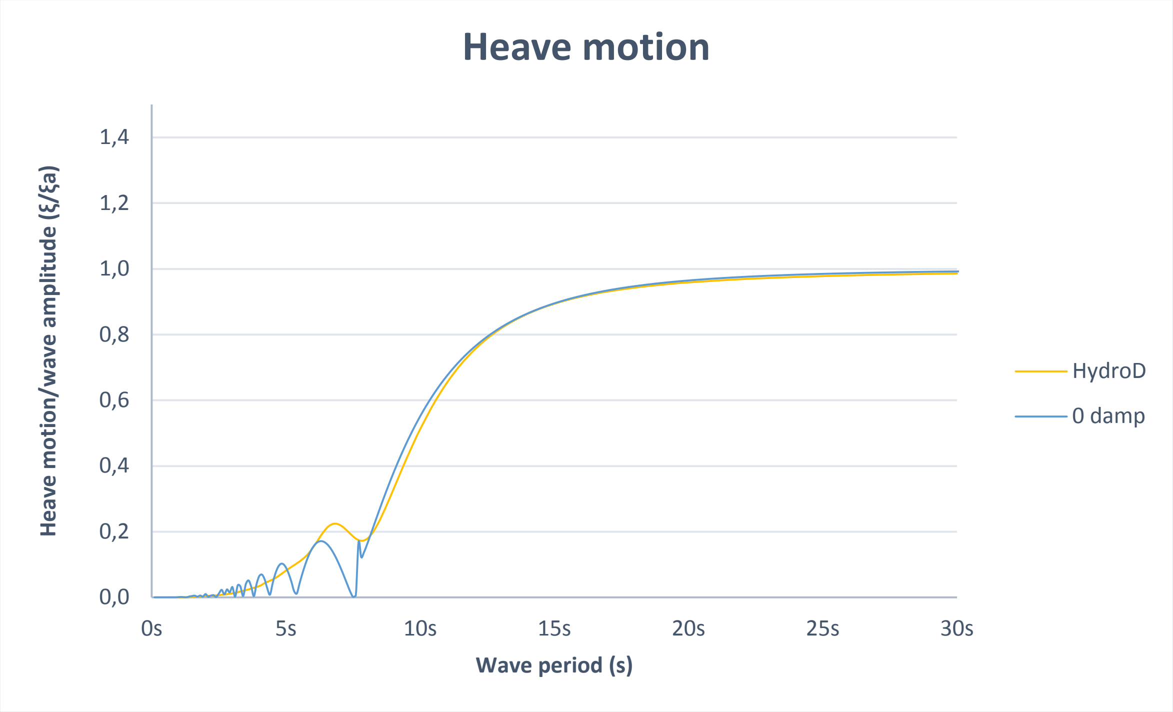
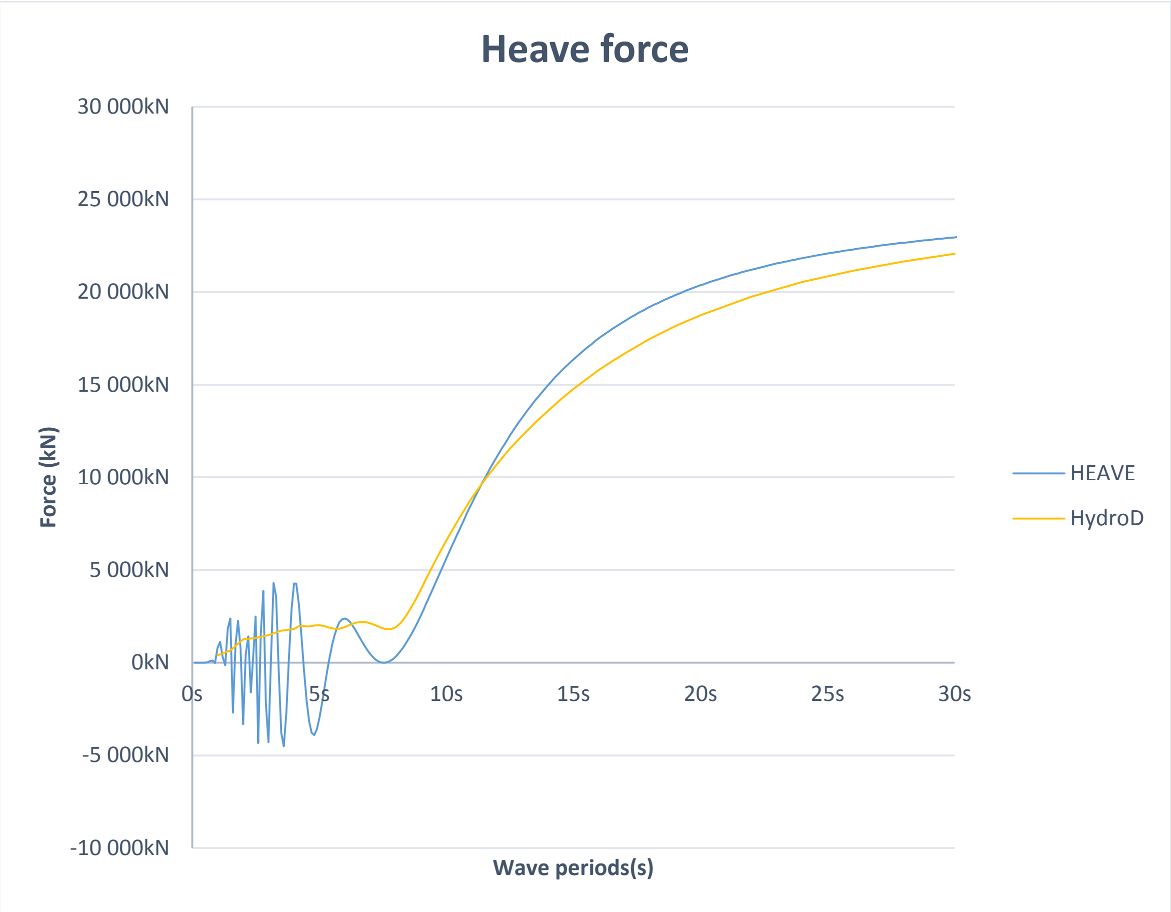
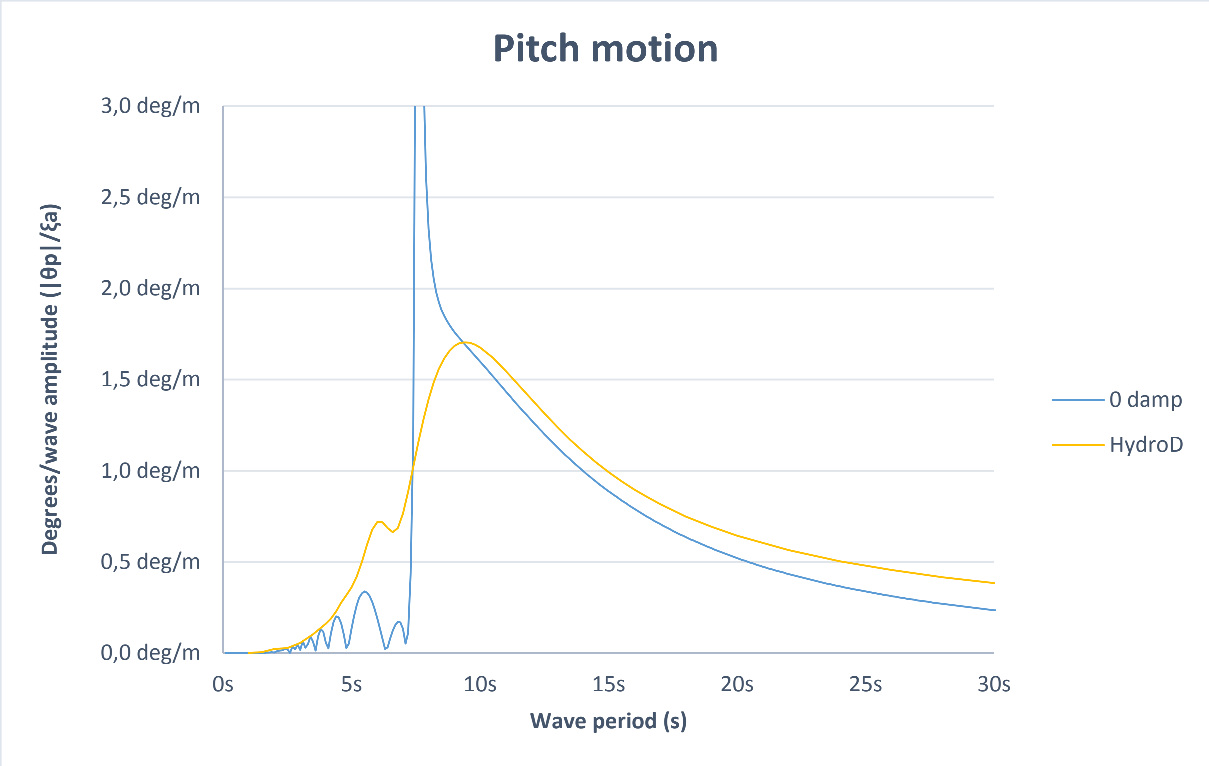
[42]	SIMO - Theory Manual Version 4.2 rev1
[43]	SIMO - General Description Version 4.2 rev 0

Appendix A Excel comparison (Hand calculations and HydroD)



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2,5 deg/m
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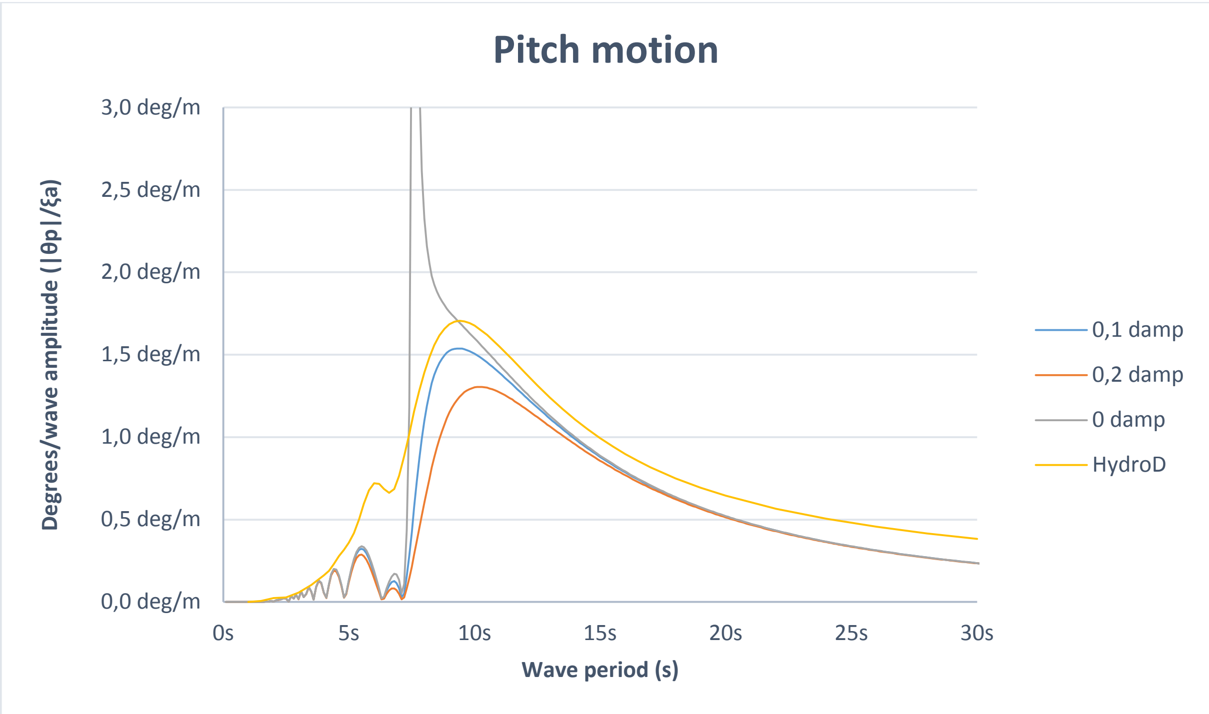
1,0 deg/m
0,5 deg/m
0,0 deg/m
Degrees/wave amplitude (|θp|/ξa)
0s
5s
10s
15s
20s
25s
30s
Wave period (s)
0 damp
HydroD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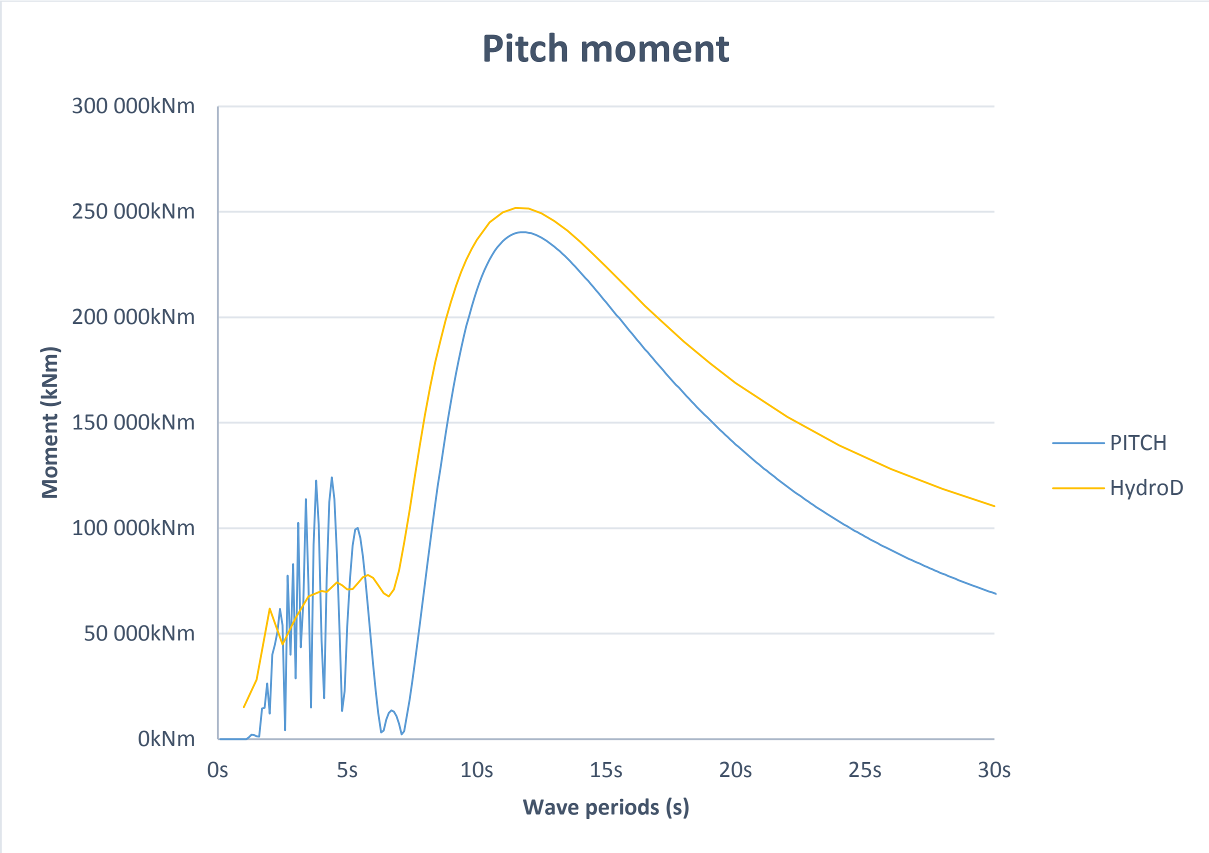
5s
10s
15s
20s
25s
30s
Wave period (s)
0,1 damp
0,2 damp
0 damp
HydroD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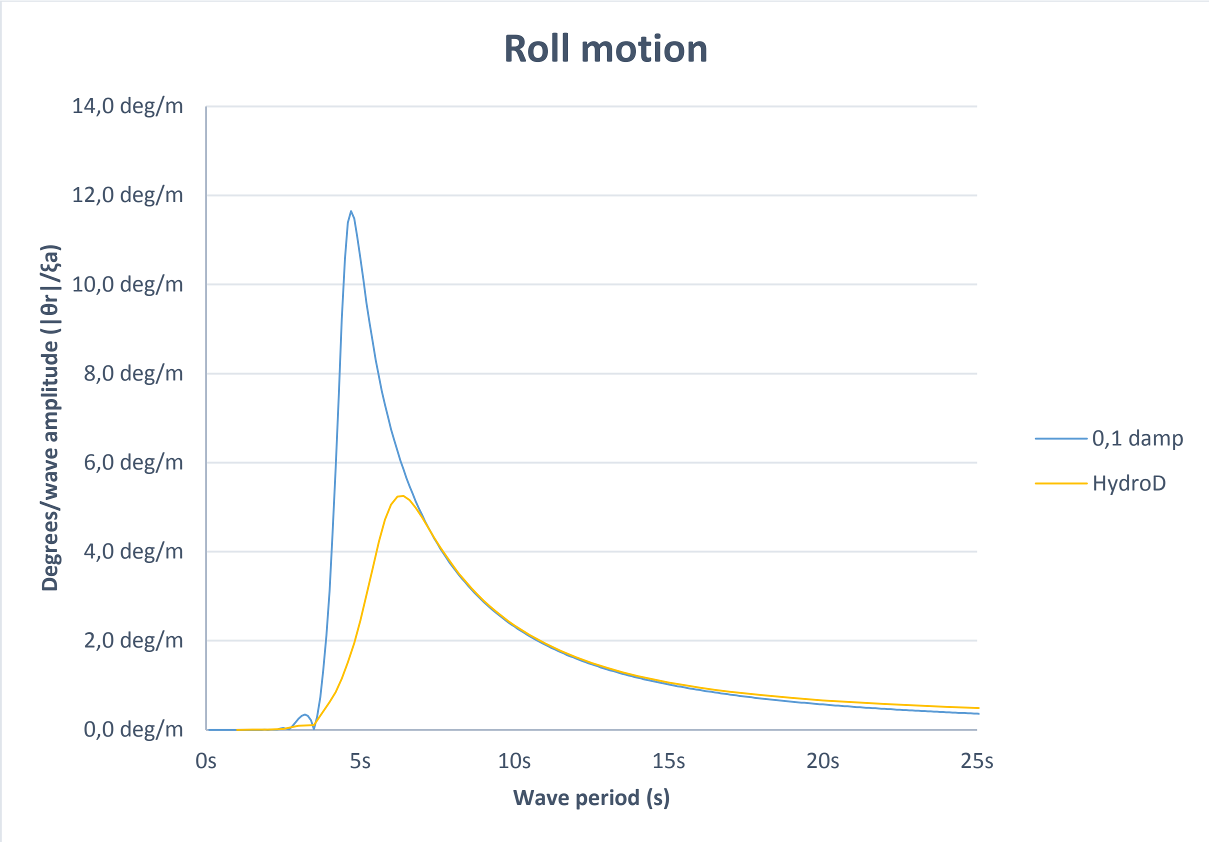
Wave periods (s)
PITCH
HydroD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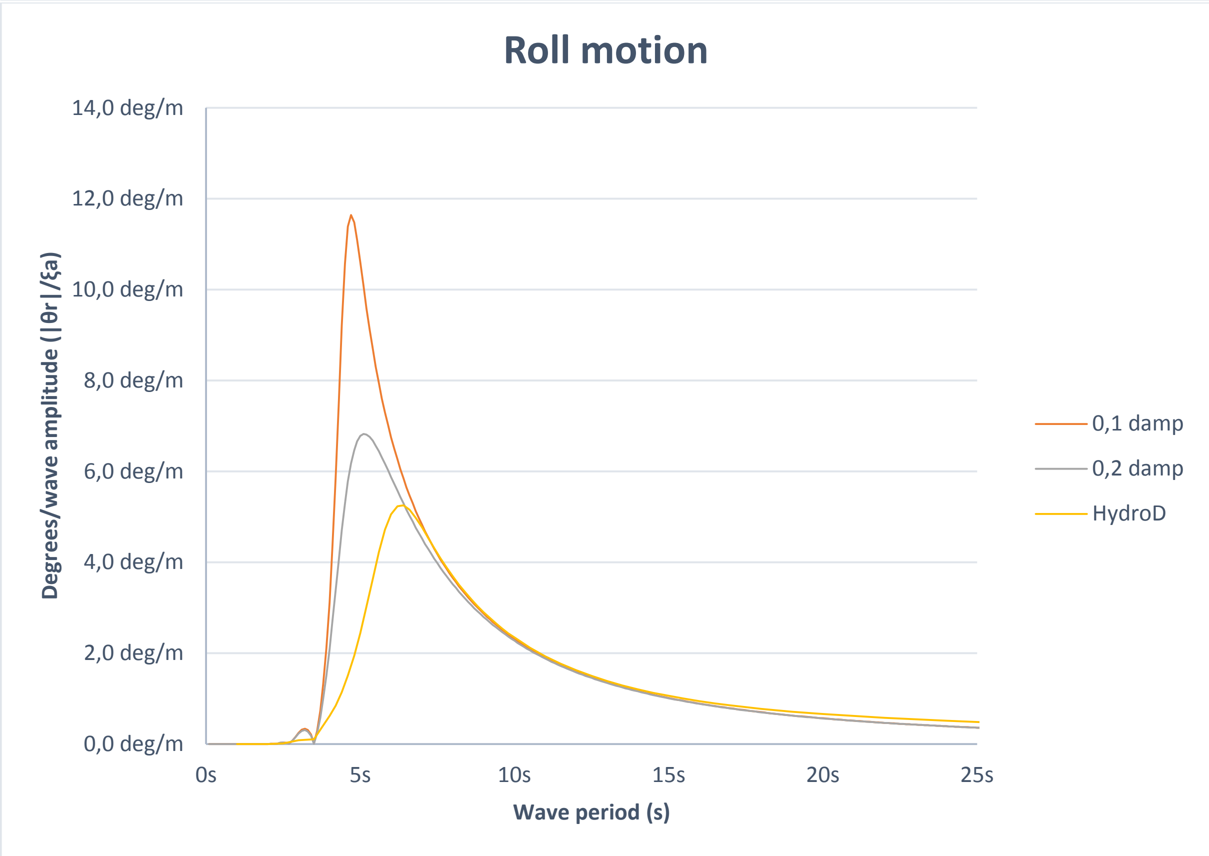
6,0 deg/m
4,0 deg/m
2,0 deg/m
0,0 deg/m
Degrees/wave amplitude (|θr|/ξa)
0s
5s
10s
15s
20s
25s
Wave period (s)
0,1 damp
HydroD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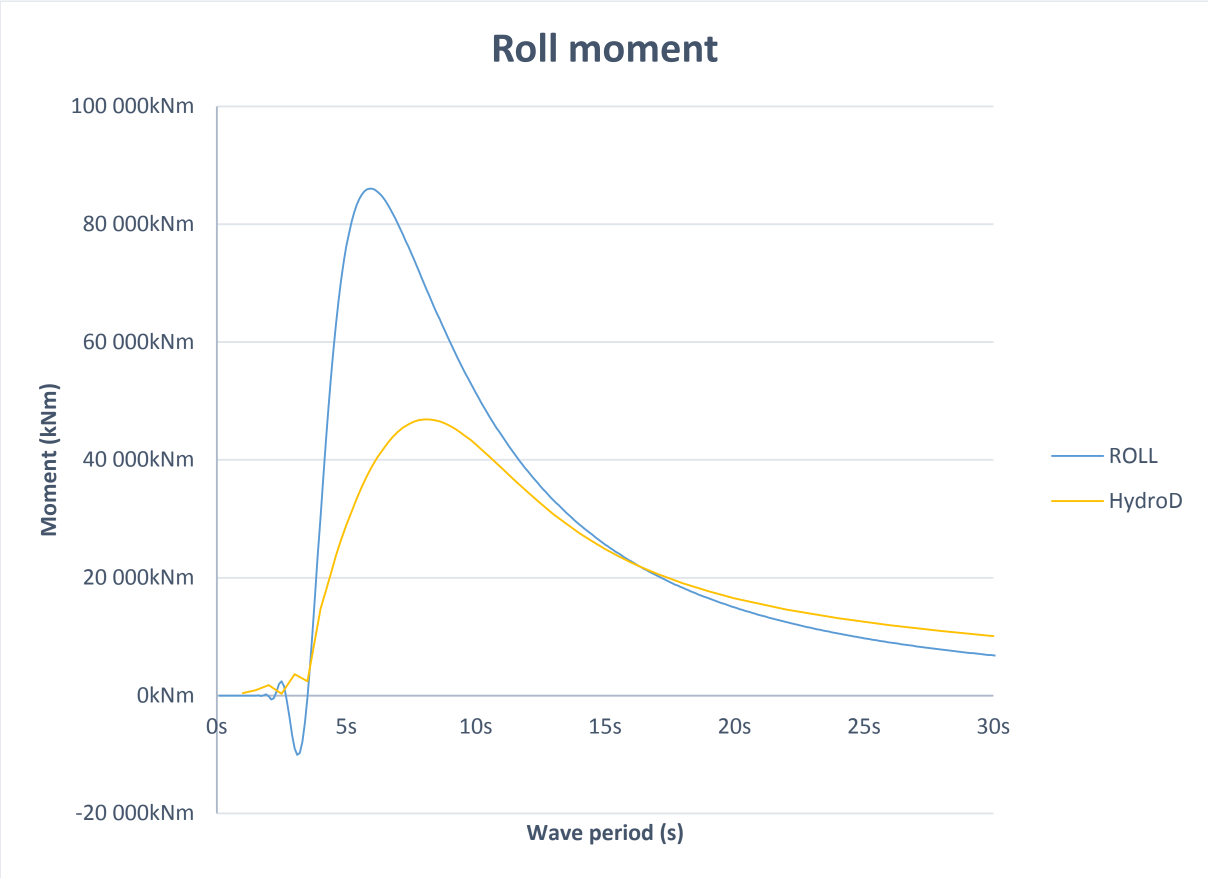
0,0 deg/m
Degrees/wave amplitude (|θr|/ξa)
0s
5s
10s
15s
20s
25s
Wave period (s)
0,1 damp
0,2 damp
HydroD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-20 000kNm
Moment (kNm)
0s
5s
10s
15s
20s
25s
30s
Wave period (s)
ROLL
HydroD

Appendix B Details barge, topside and jacket

B1 Details barge

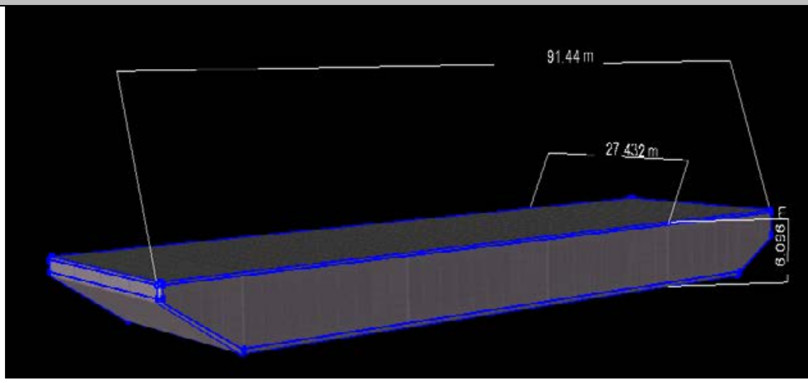
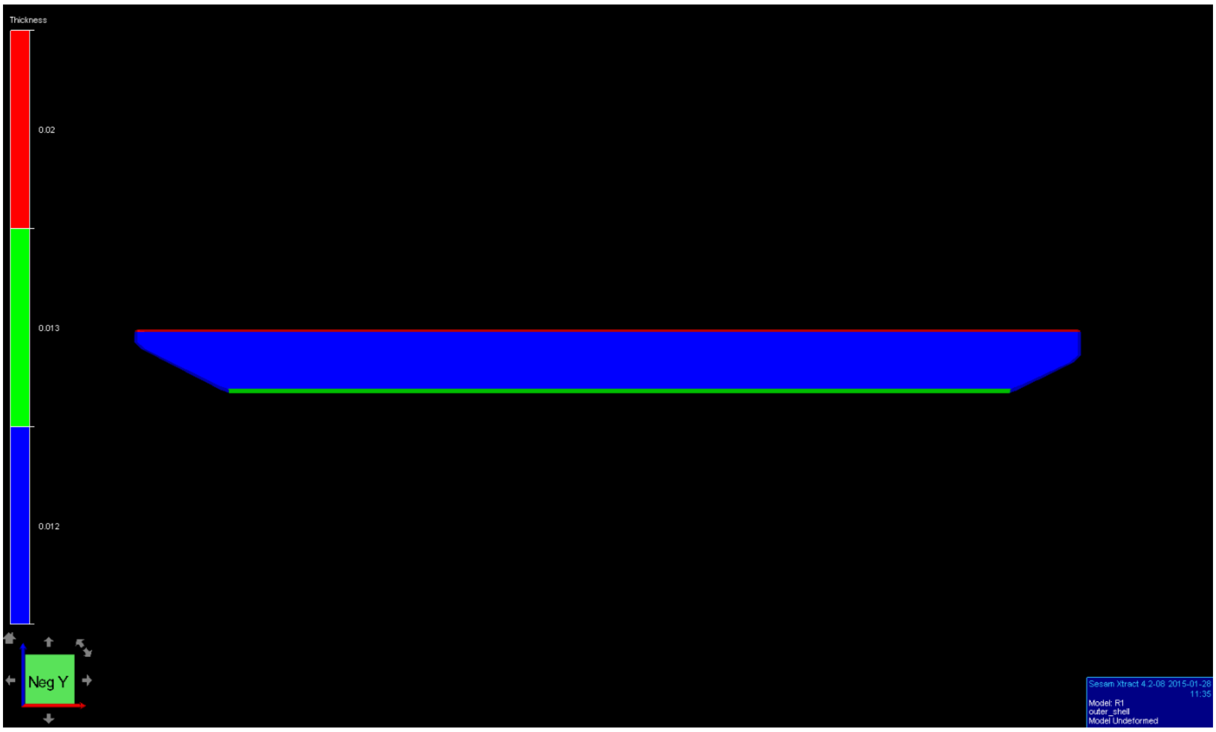
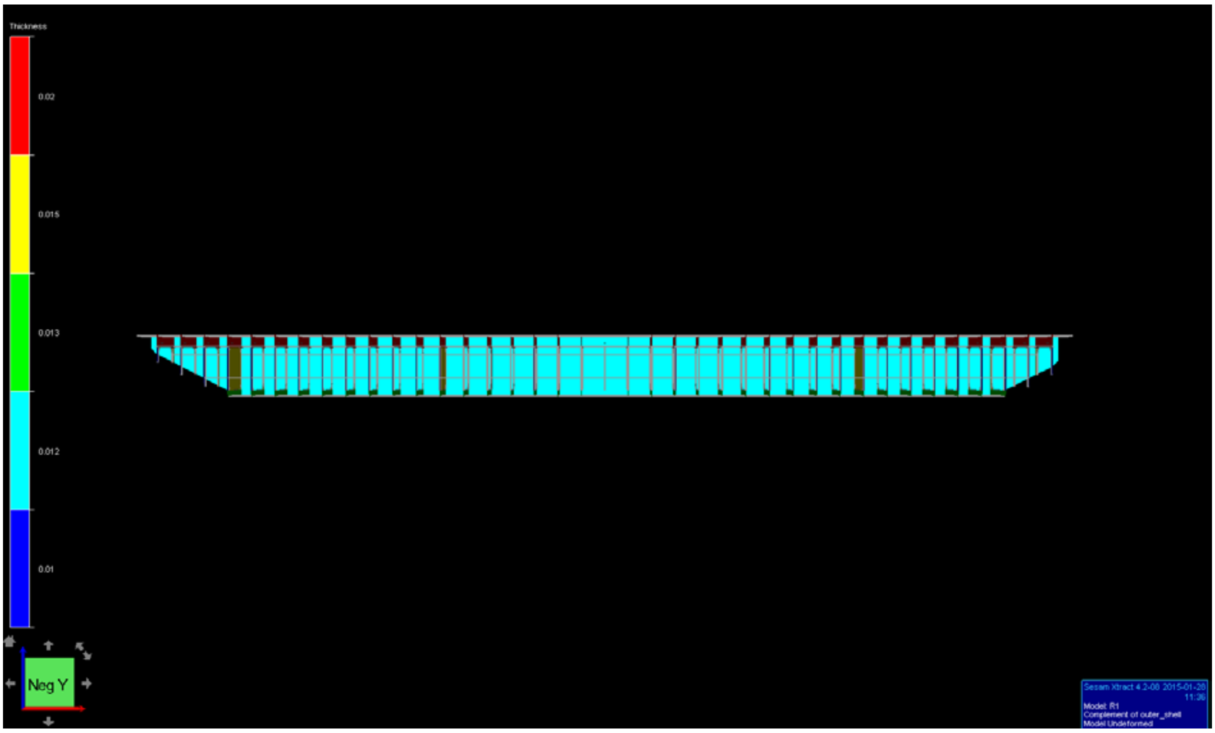
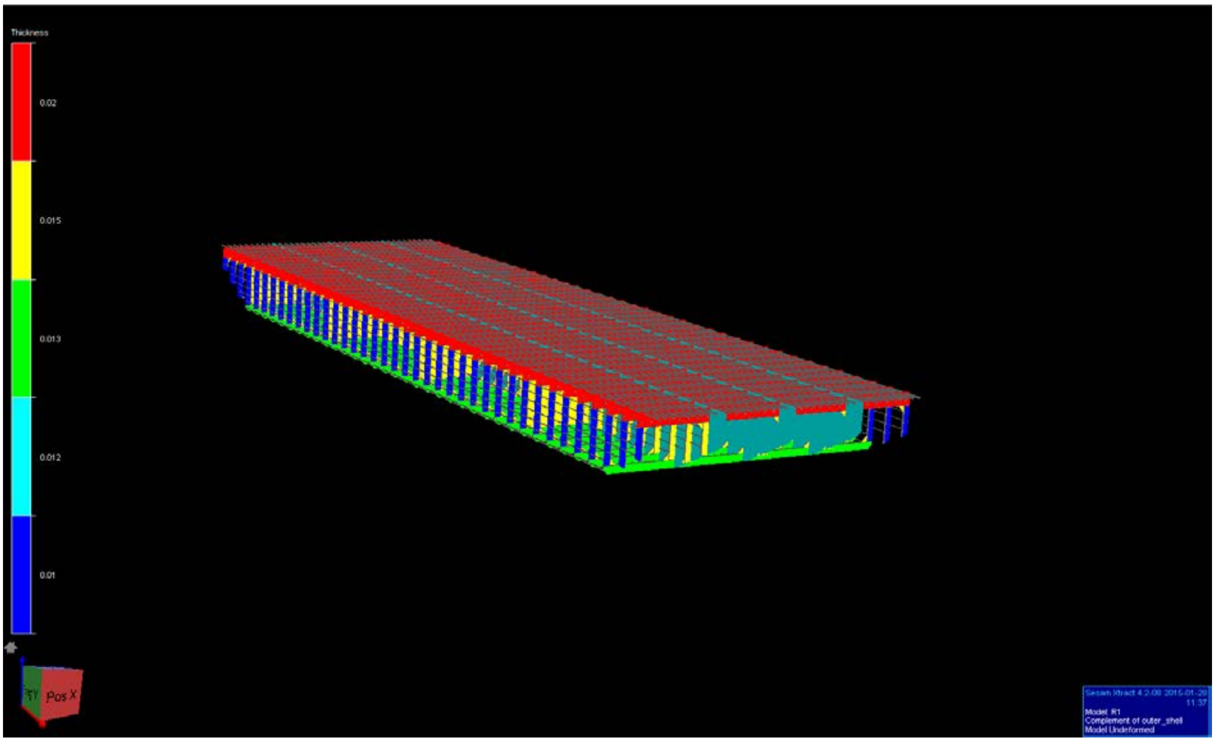
Standard Viking barge		
Barge	Value	
Length	91,44 m	
Length bow	9,244 m	
Length stern	6,858	
Breadth	27,432 m	
Depth	6,096 m	
Depth bow	4,896	
Depth stern	3,596	
Light weight (1)	1,850e+06 kg	
Ballast water	7,786e+06 kg (2)	
Draft	4,096	
Ixx		6,43E+08 kgm^2
Iyy		5,79E+09 kgm^2
Izz		6,38E+09 kgm^2
Ixy		2,00E+07 kgm^2
Ixz		-3,33E+07 kgm^2
Iyz		-2,07E+05 kgm^2
1) No fuel, passengers, cargo, water, and the like on board 2) Including the half weight of the topside (to get the correct draft)		

Figure 53 Standard Viking barge

Table 37 Details Barge




Thickness
0.02
0.015
0.013
0.012
0.01
Neg Y
Sesam Xtract 4.2-08 2015-01-28
11:36
Model: R1
Complement of outer_shell
Model Undeformed


Thickness
0.02
0.015
0.013
0.012
0.01
Pos X
Sesam Xtract 4.2-08 2015-01-28
11:37
Model: R1
Complement of outer_shell
Model Undeformed

B2 Details topside

Topside

Topside	Value
Elevation	25 m
Weight	4,872e+06 kg
Centre of gravity x	2,330 m
Centre of gravity y	5,919 m
Centre of gravity z	34,533 m
Ixx	6,14E+08 kgm^2
Iyy	1,48E+09 kgm^2
Izz	1,72E+09 kgm^2
Ixy	1,51E+07 kgm^2
Ixz	5,38E+07 kgm^2
Iyz	-9,21E+07 kgm^2

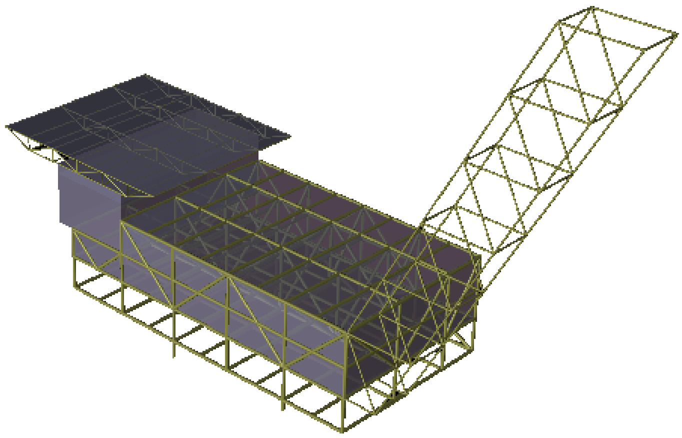


Figure 54 Huldra topside just for illustration

Area	Weight	Centre of gravity x	Centre of gravity y	Centre of gravity z
Vent Boom	1,374e+05 kg	29,94	-26,64	26,45
Helideck	7,971e+04 kg	-32,05	-3,70	14,71
LQ	1,720e+05 kg	-27,87	-1,87	8,21
WD	4,483e+06 kg	3,25	-5,48	6,80
Totals	4,872e+06 kg	2,33	-5,92	34,53

Cordinate system:

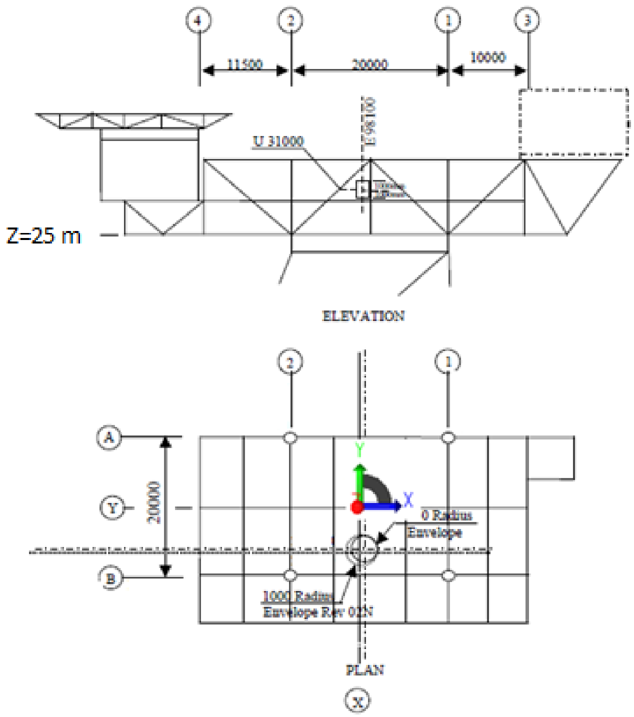


Figure 55 Detail drawing Huldra topside

Table 38 Details Topside.

B3 Details jacket

Jacket

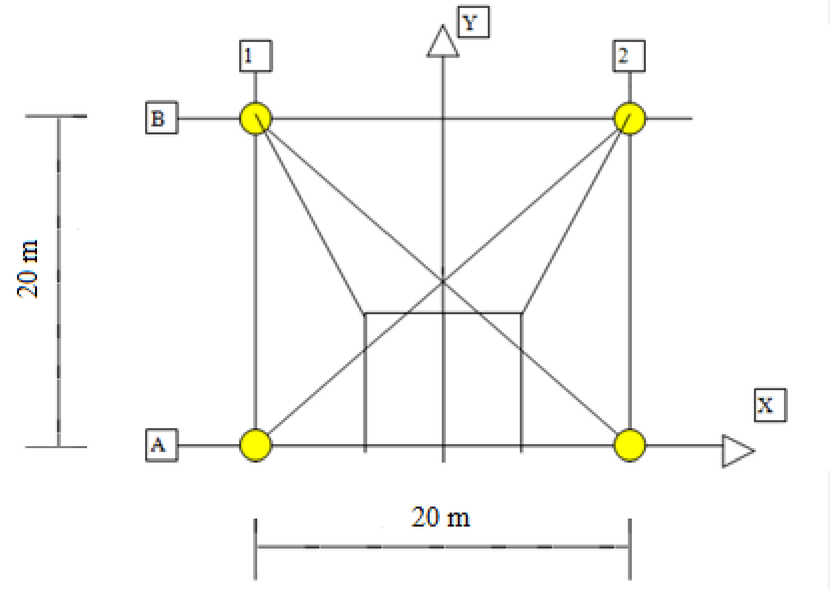


Figure 56 Jacket top dimensions

Jacket	Value
Total height	149 meter (154,51 m including mudmat skirts and topside stabbing pins)
Topside interference elevation (temporary)	20,0 m (*)
Topside interference elevation (permanent)	24,05 m
Top dimensions	20 by 20 (leg centre to centre distance)
Bottom dimensions	48 by 48 m (leg centre to centre distance)
(*) recommendation from specialists at Statoil. The jacket is launch installed before the topside, in the worst case the duration of the temporary stage can be greater than 180 days for this purpose the jacket has to survive the 100 yr wave. (according to table 3-3 acceptable return periods DNV OS H101)	

Table 39 Details Jacket.

Appendix C HydroD report

Location:

Name	Location1
Gravity [m/s^2]	9,80665
Depth [m]	120
Air Kinematic Viscosity [m^2/s]	0,00001462
Air Density [Kg/m^3]	1,226
Water Kinematic Viscosity [m^2/s]	0,00000119
Water Density [Kg/m^3]	1025
Border Infinity	Infinity

Condition:

Name	Condition1
DirectionSet1	DirectionSet1
FrequencySet1	FrequencySet1

Directions:

Name	DirectionSet1
Number of Headings	13

Frequencys:

Name	FrequencySet1
Period	Period
Number of Frequencies	59

Wadam runs:

Name	WadamRun2
Hydro Model	HydroModel2
Loading Condition	LoadingCondition1
Environment Data	Condition1
Use Sea State	false
Is Datacheck	false
Analysis Type	Global Response
Calculate Drift	false
Wave drift damping	false
Potential Matrix Solver	Direct
Max Matrix Dimension	5000
Singularity Type	Analytical
Integration Type	One node Gauss
Panel Dimension Type	Maximum diagonal
Remove Irregular Frequencies	false
Save Wamit Files	false
Stop Before Poten	false
Bypass Poten	false
Stop Before Force 1	false
Bypass Force 1	false
Stop Before Force 2	false
Bypass Force 2	false
Use Save/Restart	false
Print Type	Normal
Response File Type	SIF
Calculate Eigenvalues	true
Reference point x coordinate [m]	0
Reference point y coordinate [m]	0
Reference point z coordinate [m]	0
Load transfer in waterline method	No cutting
Second Frequencies	false
Difference Frequencies	false
Tolerance Waterline	5
Tolerance COG	5
Characteristic Length [m]	100
Use Roll Damping	false
Max Roll Angle Curve Size	0
Use Result Files Prefix	false
Automatically Overwrite Resultfiles	false
First Morison 3D Element	40000
First Anchor Element	50000
First Pressure Area Element	60000
First TLP Element	70000
First Morison 3D Section	40000
First Anchor Section	50000
First Pressure Area Section	60000
First TLP Section	70000
First Morison Section	80000

Wadam wizard:

Name	WadamWizard1
Model configuration	Panel model
Panel model configuration	Element model
Domain	Frequency
Include roll damping	false
Include load crossections	false
Include load transfer	false
Include compartments	true
Include pressure panels	false
Include offbody points	true
Include second order results	false
Include damping matrix	false
Include critical damping matrix	true
Include restoring matrix	false

Hydro models:

Name	HydroModel2
Boundary Condition	Floating
Is column stabilized	no

HydroModel2 Hydrostatic tab:

Column	Description	Unit
ZWL	Z-waterline	m
DISP	Volume of displacement	m^3
COB	Centre of buoyancy	m
COF	Centre of flotation	m
WPA	Water plane area	m^2
MX Z	Metacentre X-rotation Z-position	m
MY Z	Metacentre Y-rotation Z-position	m

ZWL	DISP	COB X	COB Y	COB Z	COF X	COF Y	WPA	MX Z	MY Z
m	m^3	m	m	m	m	m	m^2	m	m
-2,5	0						0		
-2	195	1,1	0	-2,05	1,11	0	2040	626,93	5049,49
-1,5	1246	1,13	0	-1,79	1,14	0	2146	106,11	876,1
-1	2333	1,14	0	-1,54	1,16	0	2200	57,57	504,12
-0,5	3447	1,15	0	-1,28	1,18	0	2255	39,72	367,02
0	4588	1,16	0	-1,03	1,2	0	2309	30,52	296,21
0,5	5756	1,17	0	-0,77	1,22	0	2364	24,97	253,3
1	6951	1,18	0	-0,51	1,21	0	2417	21,29	224,37
1,5	8169	1,16	0	-0,24	0,95	0	2456	18,6	200,43
2	9404	1,1	0	0,02	0,47	0	2482	16,57	180,06
2,5	10650	1,01	0	0,28	0,14	0	2500	15	162,78
3	11903	0,91	0	0,54	0	0	2508	13,75	147,31
3,5	13157	0,82	0	0,8	0	0	2508	12,75	133,59
4	14409	0,75	0	1,05	0	0	2461	6,26	61,54
(*) The bottom of the keel is speciefied at -2,096 m									

Mass model:

Name	MassModel1
File name	T2.FEM
Symmetry in statistics	No
Number of nodes	26630
Number of plates/shells	30563
Number of beam segments	12366
Number of solid elements	0
X-min [m]	-45,72
X-max [m]	45,72
Delta-X [m]	91,44
Y-min [m]	-13,716
Y-max [m]	13,716
Delta-Y [m]	27,432
Z-min [m]	-2,096
Z-max [m]	4
Delta-Z [m]	6,096
Mass Model Type	From file
Total mass [Kg]	9639110
Centre of gravity X [m]	1,10465
Centre of gravity Y [m]	1,38352E-05
Centre of gravity Z [m]	0,992172
Radius of gyration X (global system) [m]	8,16453
Radius of gyration Y (global system) [m]	24,4991
Radius of gyration Z (global system) [m]	25,7325
Specific product inertia radius XY (global system) [m]	-1,4398
Specific product inertia radius XZ (global system) [m]	1,85979
Specific product inertia radius YZ (global system) [m]	0,146593
Roll-pitch centrifugal moment(global system) [m^2]	-2,07303
Roll-yaw centrifugal moment (global system) [m^2]	3,45882
Pitch-yaw centrifugal moment (global system) [m^2]	0,0214896
Total mass-compartment mass in metacentre x-rot [Kg]	9639110
Centre of gravity X-compartment mass in metacentre x-rot [m]	1,10465
Centre of gravity Y-compartment mass in metacentre x-rot [m]	1,38352E-05
Centre of gravity Z-compartment mass in metacentre x-rot [m]	1,13198

Mass matrix:

X [Kg]	Y [Kg]	Z [Kg]
9639110	0	0
0	9639110	0
0	0	9639110

RX [Kg*m]	RY [Kg*m]	RZ [Kg*m]
0	-9714560	-133,359
9714560	0	10647900
133,359	-10647900	0

X [Kg*m]	Y [Kg*m]	Z [Kg*m]
0	9714560	133,359
-9714560	0	-10647900
-133,359	10647900	0

RX [Kg*m^2]	RY [Kg*m^2]	RZ [Kg*m^2]
642538000	-19982100	33339900
-19982100	5785450000	207141
33339900	207141	6382640000

Loading condition:

Name	LoadingCondition1
Z-waterline [m]	2
Heel [deg]	0
Trim [deg]	0
Displacement [m^3]	9404,01
Centre of buoyancy X [m]	1,10465
Centre of buoyancy Y [m]	1,3835E-05
Centre of buoyancy Z [m]	0,0173509
Flotation centre X [m]	0,466497
Flotation centre Y [m]	6,1787E-10
Flotation centre Z [m]	2
Waterline area [m^2]	2482,47
Metacentre X-rotation X [m]	1,10465
Metacentre X-rotation Y [m]	1,3835E-05
Metacentre X-rotation Z [m]	16,5672

Offbody points:

Name	OffbodyPoints1
Offbody Points Type	Grid
Grid X Min [m]	-50
Grid Y Min [m]	-18
Grid X Max [m]	50
Grid Y Max [m]	18
No Steps X	25
No Steps Y	25

Panel model:

Name	PanelModel2
File name	T1.FEM
Symmetry in statistics	No
Number of nodes	7394
Number of plates/shells	7400
Number of beam segments	0
Number of solid elements	0
X-min [m]	-45,72
X-max [m]	45,72
Delta-X [m]	91,44
Y-min [m]	-13,716
Y-max [m]	13,716
Delta-Y [m]	27,432
Z-min [m]	-2,096
Z-max [m]	4
Delta-Z [m]	6,096

Structure model:

Name	StructureModel2
File name	T2.FEM
Symmetry in statistics	No
Number of nodes	26630
Number of plates/shells	30563
Number of beam segments	12366
Number of solid elements	0
X-min [m]	-45,72
X-max [m]	45,72
Delta-X [m]	91,44
Y-min [m]	-13,716
Y-max [m]	13,716
Delta-Y [m]	27,432
Z-min [m]	-2,096
Z-max [m]	4
Delta-Z [m]	6,096

Compartments:

		X [m]			Y [m]			Z [m]			
LC number	Permeability	Min	Max	Delta	Min	Max	Delta	Min	Max	Delta	Vol [m^3]
2	Permeability1	-16,00	4,57	20,57	-6,86	0,00	6,86	-2,10	4,00	6,10	860,38
3	Permeability1	-16,00	4,57	20,57	-13,72	-6,86	6,86	-2,10	4,00	6,10	860,38
4	Permeability1	-16,00	4,57	20,57	0,00	6,86	6,86	-2,10	4,00	6,10	860,38
5	Permeability1	-16,00	4,57	20,57	6,86	13,72	6,85	-2,10	4,00	6,10	859,37
6	Permeability1	-36,58	-16,00	20,57	-6,86	0,00	6,86	-2,10	4,00	6,10	860,38
7	Permeability1	-36,58	-16,00	20,57	-13,72	-6,86	6,86	-2,10	4,00	6,10	860,38
8	Permeability1	-36,58	-16,00	20,57	0,00	6,86	6,86	-2,10	4,00	6,10	860,38
9	Permeability1	-36,58	-16,00	20,57	6,86	13,72	6,85	-2,10	4,00	6,10	859,37
10	Permeability1	-45,72	-36,58	9,14	6,86	13,72	6,85	-2,10	4,00	6,10	381,94
11	Permeability1	-45,72	-36,58	9,14	-6,86	0,00	6,86	-2,10	4,00	6,10	382,39
12	Permeability1	-45,72	-36,58	9,14	-13,72	-6,86	6,86	-2,10	4,00	6,10	382,39
13	Permeability1	-45,72	-36,58	9,14	0,00	6,86	6,86	-2,10	4,00	6,10	382,39
14	Permeability1	4,57	25,15	20,57	-6,86	0,00	6,86	-2,10	4,00	6,10	860,38
15	Permeability1	4,57	25,15	20,57	-13,72	-6,86	6,86	-2,10	4,00	6,10	860,38
16	Permeability1	4,57	25,15	20,57	0,00	6,86	6,86	-2,10	4,00	6,10	860,38
17	Permeability1	4,57	25,15	20,57	6,86	13,72	6,85	-2,10	4,00	6,10	859,37
18	Permeability1	25,15	36,58	11,43	6,86	13,72	6,85	-2,10	4,00	6,10	477,43
19	Permeability1	25,15	36,58	11,43	-13,72	-6,86	6,86	-2,10	4,00	6,10	477,99
20	Permeability1	36,58	45,72	9,14	-6,86	0,00	6,86	-2,10	4,00	6,10	382,39
21	Permeability1	36,58	45,72	9,14	0,00	6,86	6,86	-2,10	4,00	6,10	382,39
22	Permeability1	36,58	45,72	9,14	-13,72	-6,86	6,86	-2,10	4,00	6,10	382,39
23	Permeability1	36,58	45,72	9,14	6,86	13,72	6,85	-2,10	4,00	6,10	381,94

Name	CompartmentContents
Number of Compartment Contents	22

Compartment content:

Name	Intact fluid	Damage fluid	Flooded	Filling Fraction	Compartment
Cm_LC2_C	Water		false	FillingFraction0	Cm_LC2
Cm_LC3_C	Water		false	FillingFraction1	Cm_LC3
Cm_LC4_C	Water		false	FillingFraction0	Cm_LC4
Cm_LC5_C	Water		false	FillingFraction1	Cm_LC5
Cm_LC6_C	Water		false	FillingFraction1	Cm_LC6
Cm_LC7_C	Water		false	FillingFraction0	Cm_LC7
Cm_LC8_C	Water		false	FillingFraction1	Cm_LC8
Cm_LC9_C	Water		false	FillingFraction0	Cm_LC9
Cm_LC10_C	Water		false	FillingFraction1	Cm_LC10
Cm_LC11_C	Water		false	FillingFraction0_442	Cm_LC11
Cm_LC12_C	Water		false	FillingFraction1	Cm_LC12
Cm_LC13_C	Water		false	FillingFraction0	Cm_LC13
Cm_LC14_C	Water		false	FillingFraction1	Cm_LC14
Cm_LC15_C	Water		false	FillingFraction0_306	Cm_LC15
Cm_LC16_C	Water		false	FillingFraction1	Cm_LC16
Cm_LC17_C	Water		false	FillingFraction0_347	Cm_LC17
Cm_LC18_C	Water		false	FillingFraction1	Cm_LC18
Cm_LC19_C	Water		false	FillingFraction1	Cm_LC19
Cm_LC20_C	Water		false	FillingFraction0	Cm_LC20
Cm_LC21_C	Water		false	FillingFraction0	Cm_LC21
Cm_LC22_C	Water		false	FillingFraction1	Cm_LC22
Cm_LC23_C	Water		false	FillingFraction1	Cm_LC23

Critical damping matrix:

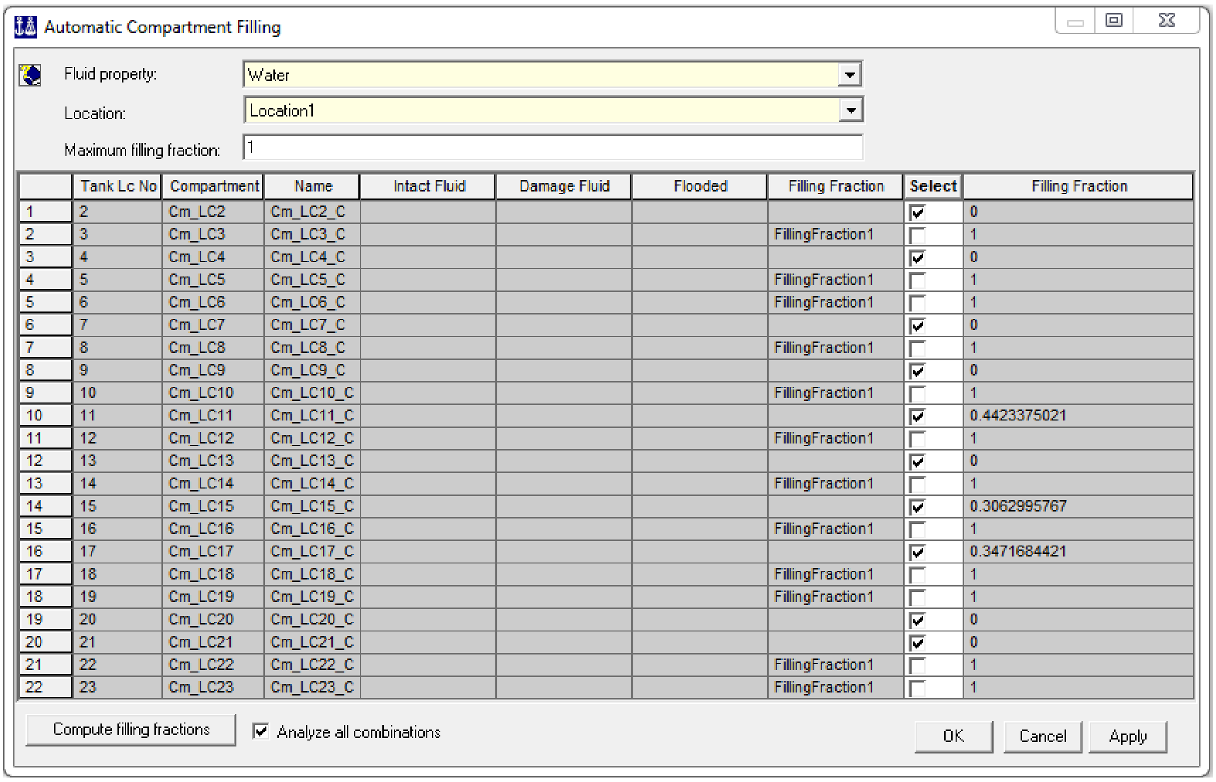
Name	Cr XX	Cr YY	Cr ZZ	Cr RX	Cr RY	Cr RZ
CrDampingMatix1	0	0	0	0,1	0	0

Fluids:

Name	Density [Kg/m^3]
Water	1025

C1 Stability results from HydroD

Ballast condition



Automatic Compartment Filling

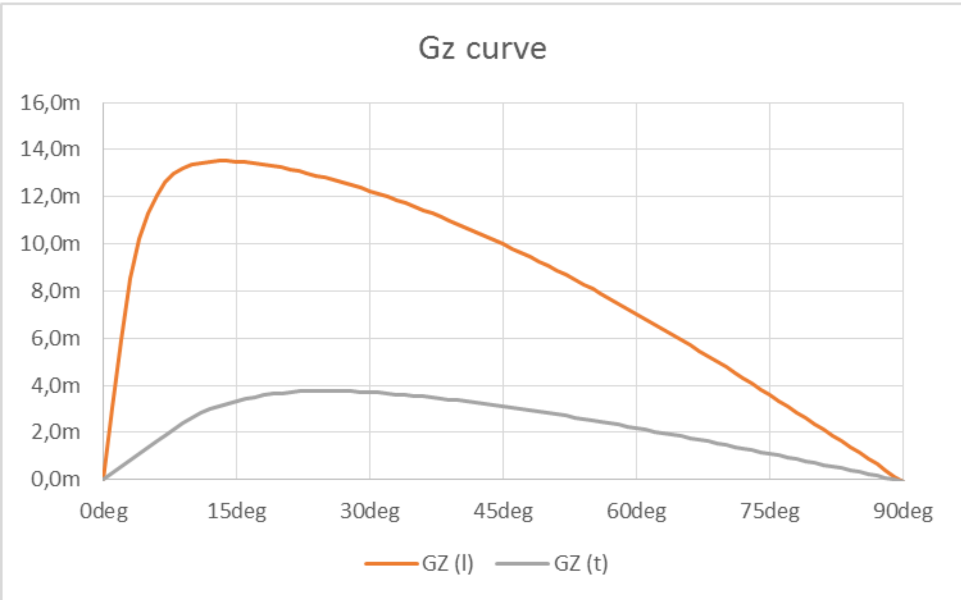
Fluid property: Water

Location: Location1

Maximum filling fraction: 1

	Tank Lc No	Compartment	Name	Intact Fluid	Damage Fluid	Flooded	Filling Fraction	Select	Filling Fraction
1	2	Cm_LC2	Cm_LC2_C					✓	0
2	3	Cm_LC3	Cm_LC3_C				FillingFraction1		1
3	4	Cm_LC4	Cm_LC4_C					✓	0
4	5	Cm_LC5	Cm_LC5_C				FillingFraction1		1
5	6	Cm_LC6	Cm_LC6_C				FillingFraction1		1
6	7	Cm_LC7	Cm_LC7_C					✓	0
7	8	Cm_LC8	Cm_LC8_C				FillingFraction1		1
8	9	Cm_LC9	Cm_LC9_C					✓	0
9	10	Cm_LC10	Cm_LC10_C				FillingFraction1		1
10	11	Cm_LC11	Cm_LC11_C					✓	0.4423375021
11	12	Cm_LC12	Cm_LC12_C				FillingFraction1		1
12	13	Cm_LC13	Cm_LC13_C					✓	0
13	14	Cm_LC14	Cm_LC14_C				FillingFraction1		1
14	15	Cm_LC15	Cm_LC15_C					✓	0.3062995767
15	16	Cm_LC16	Cm_LC16_C				FillingFraction1		1
16	17	Cm_LC17	Cm_LC17_C					✓	0.3471684421
17	18	Cm_LC18	Cm_LC18_C				FillingFraction1		1
18	19	Cm_LC19	Cm_LC19_C				FillingFraction1		1
19	20	Cm_LC20	Cm_LC20_C					✓	0
20	21	Cm_LC21	Cm_LC21_C					✓	0
21	22	Cm_LC22	Cm_LC22_C				FillingFraction1		1
22	23	Cm_LC23	Cm_LC23_C				FillingFraction1		1

Compute filling fractions ✓ Analyze all combinations OK Cancel Apply



C2 Hydrodynamic results from HydroD

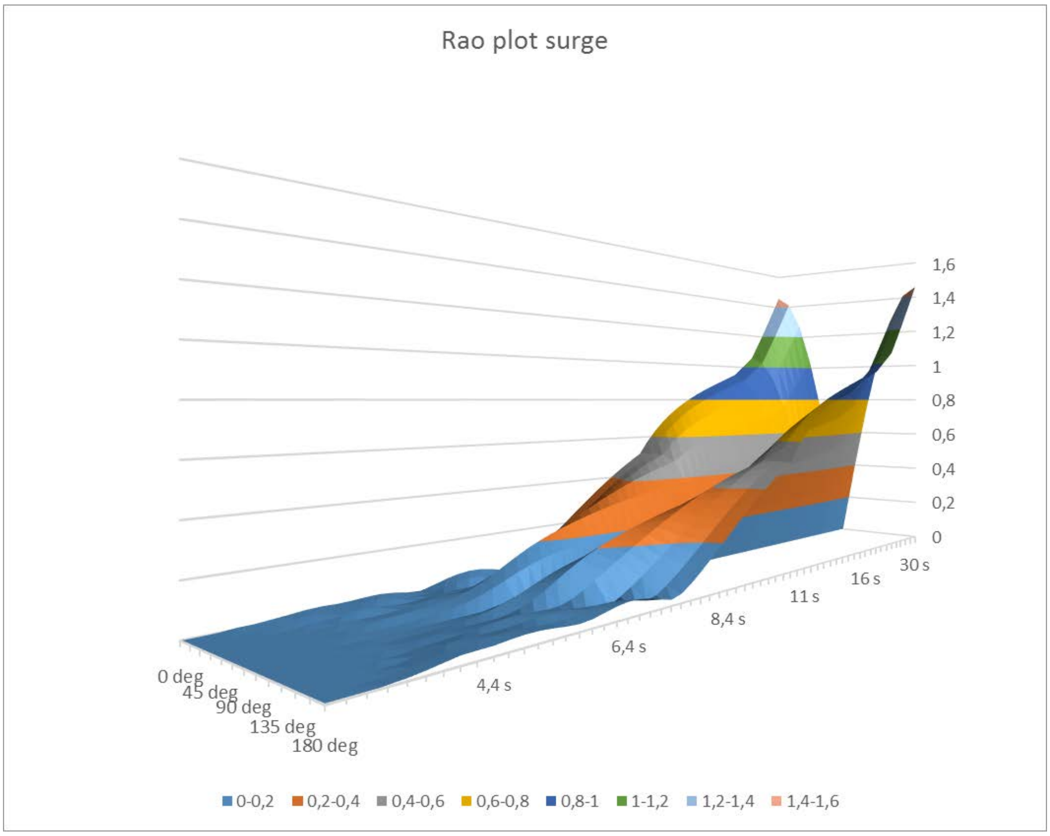
MASS PROPERTIES AND STRUCTURAL DATA:	
MASS OF THE STRUCTURE	9.63911E+06 [M]
CENTRE OF GRAVITY XG	1.10465E+00 [L]
CENTRE OF GRAVITY YG	1.38419E-05 [L]
CENTRE OF GRAVITY ZG	9.92171E-01 [L]
ROLL RADIUS OF GYRATION XYRAD	2.07430E+00 [L**2]
PITCH RADIUS OF GYRATION XZRAD	-3.45881E+00 [L**2]
YAW RADIUS OF GYRATION YZRAD	-2.15196E-02 [L**2]

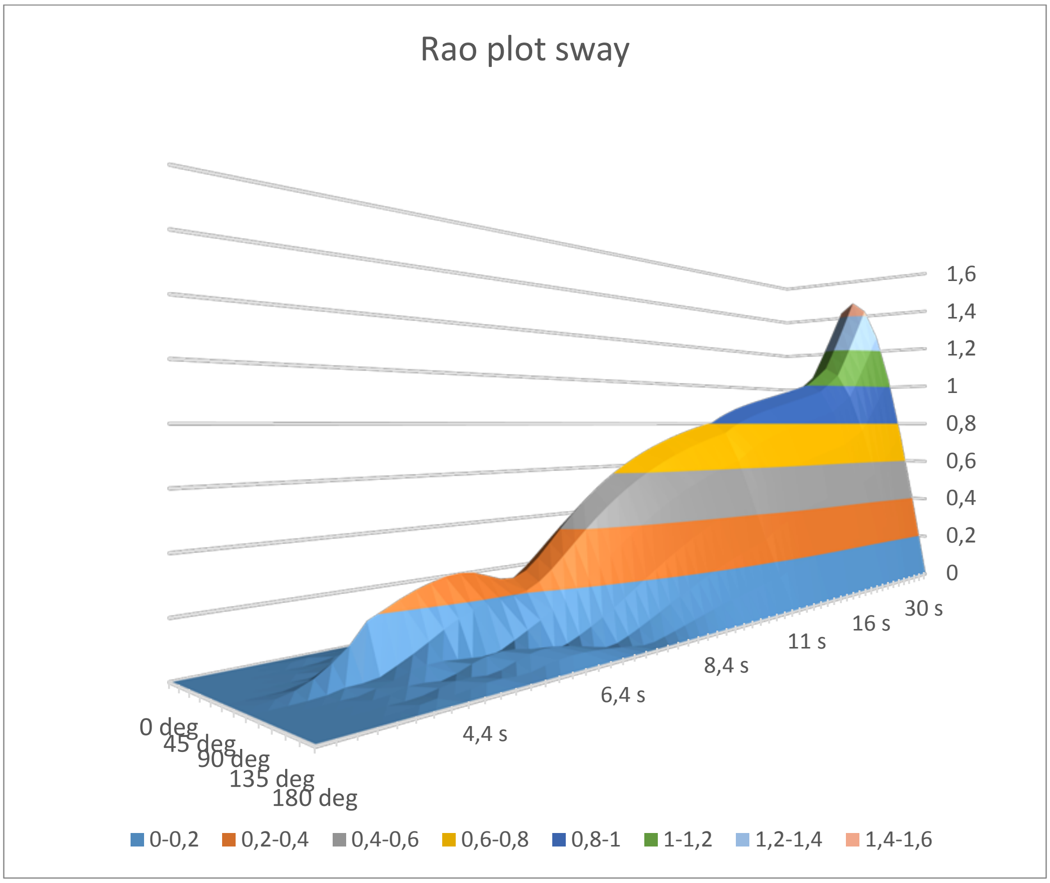
HYDROSTATIC DATA:	
DISPLACED VOLUME	9.40400E+03 [L**3]
MASS OF DISPLACED VOLUME	9.63910E+06 [M]
WATER PLANE AREA	2.48247E+03 [L**2]
CENTRE OF BUOYANCY XCB	1.10471E+00 [L]
CENTRE OF BUOYANCY YCB	-6.59466E-07 [L]
CENTRE OF BUOYANCY ZCB	1.73378E-02 [L]
TRANSVERSE METACENTRIC HEIGHT GM4	1.54353E+01 [L]
LONGITUDINAL METACENTRIC HEIGHT GM5	1.78149E+02 [L]
HEAVE-HEAVE RESTORING COEFFICIENT C33	2.49534E+07 [M/T**2]
HEAVE-ROLL RESTORING COEFFICIENT C34	-3.85338E+00 [M*L/T**2]
HEAVE-PITCH RESTORING COEFFICIENT C35	-1.16408E+07 [M*L/T**2]
ROLL-ROLL RESTORING COEFFICIENT C44	1.45905E+09 [M*L**2/T**2]
PITCH-PITCH RESTORING COEFFICIENT C55	1.68399E+10 [M*L**2/T**2]
ROLL-PITCH RESTORING COEFFICIENT C45	1.60443E+02 [M*L**2/T**2]
ROLL-YAW RESTORING COEFFICIENT C46	-4.81600E+03 [M*L**2/T**2]
PITCH-YAW RESTORING COEFFICIENT C56	1.37078E+03 [M*L**2/T**2]

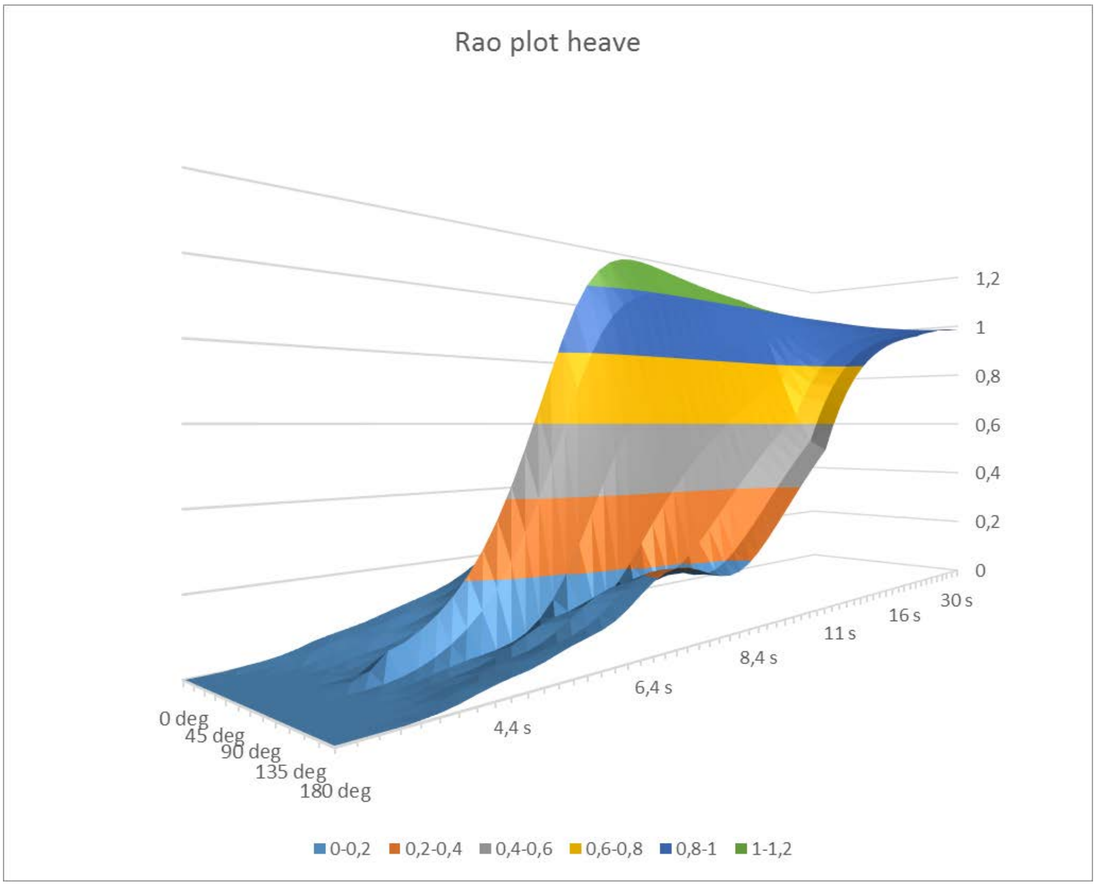
ENVIRONMENTAL DATA:	
WATER DEPTH	1.20000E+02 [L]
NUMBER OF WAVE LENGTHS	59
NUMBER OF HEADING ANGLES	13
WAVE PERIOD	1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.2, 4.4, 4.6, 4.8, 5.0, 5.2, 5.4, 5.6, 5.8, 6.0, 6.2, 6.4, 6.6, 6.8, 7.0, 7.2, 7.4, 7.6, 7.8, 8.0, 8.2, 8.4, 8.6, 8.8, 9.0, 9.2, 9.4, 9.6, 9.8, 10.0, 10.5, 11.0, 11.5, 12.0, 12.5, 13.0, 13.5, 14.0, 14.5, 15.0, 15.5, 16.0, 16.5, 17.0, 18.0, 19.0, 20.0, 22.0, 24.0, 26.0, 28.0, 30.0
WAVE DIRECTIONS	0, 15, 30, 45, 60, 75, 90

EIGEN SOLUTIONS TO THE RIGID BODY MOTION (PERIOD =10S):	
SURGE, SWAY, YAW	-
HEAVE	7.7634
ROLL	6.3170
PITCH	7.4606

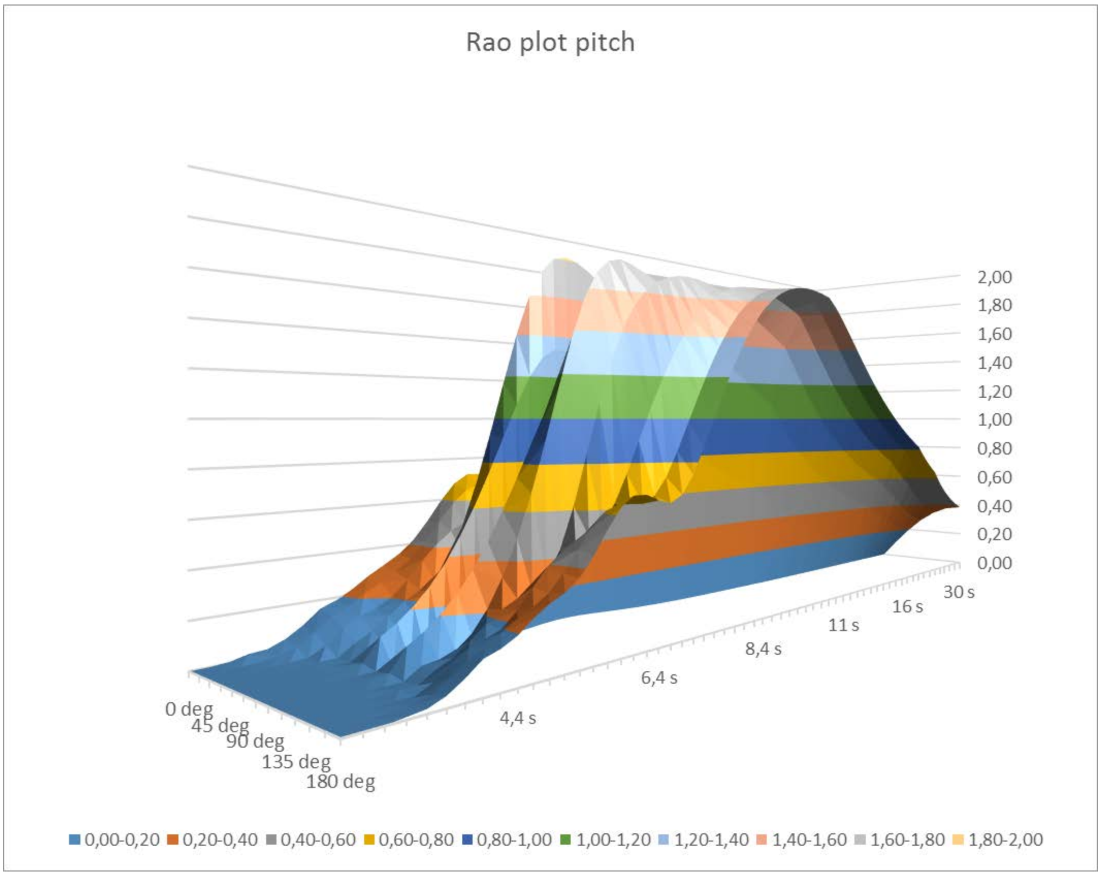
C3 RAO 3D plots from HydroD



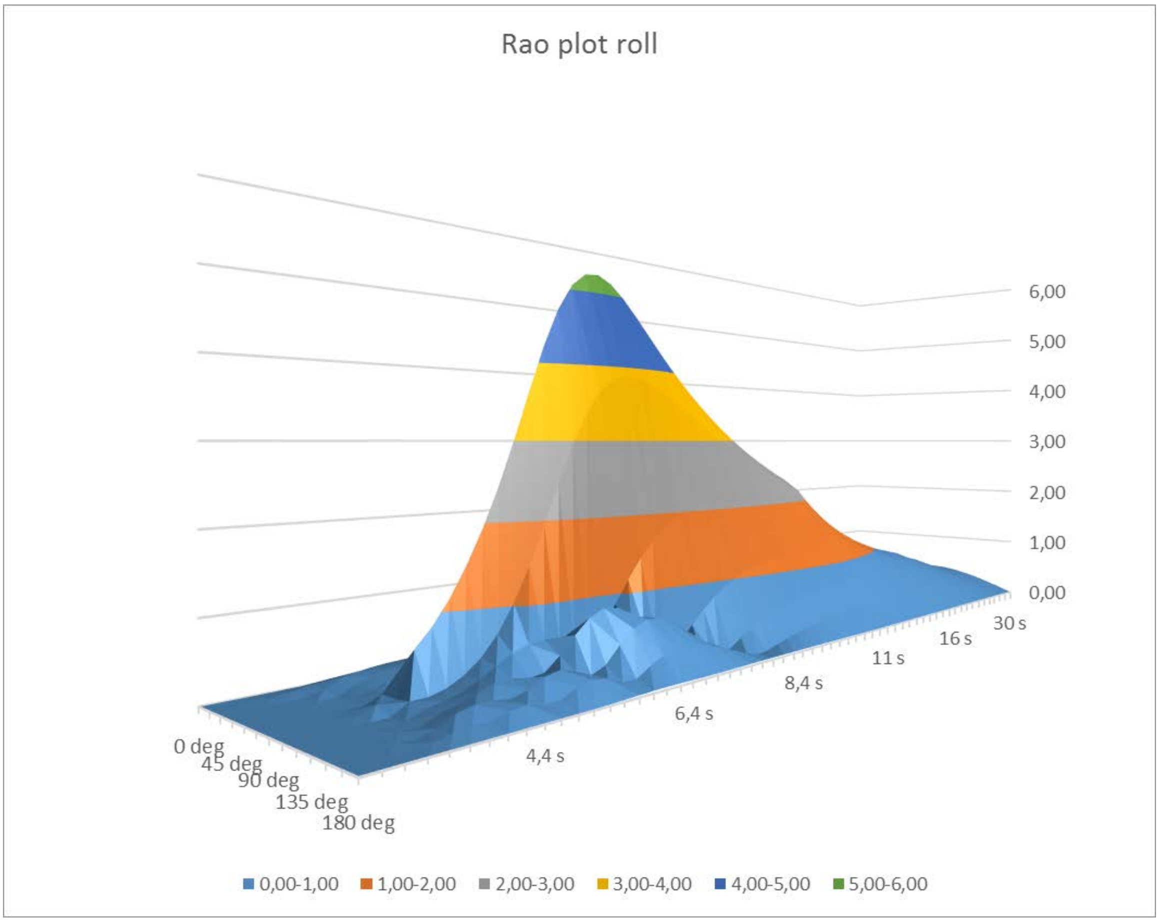


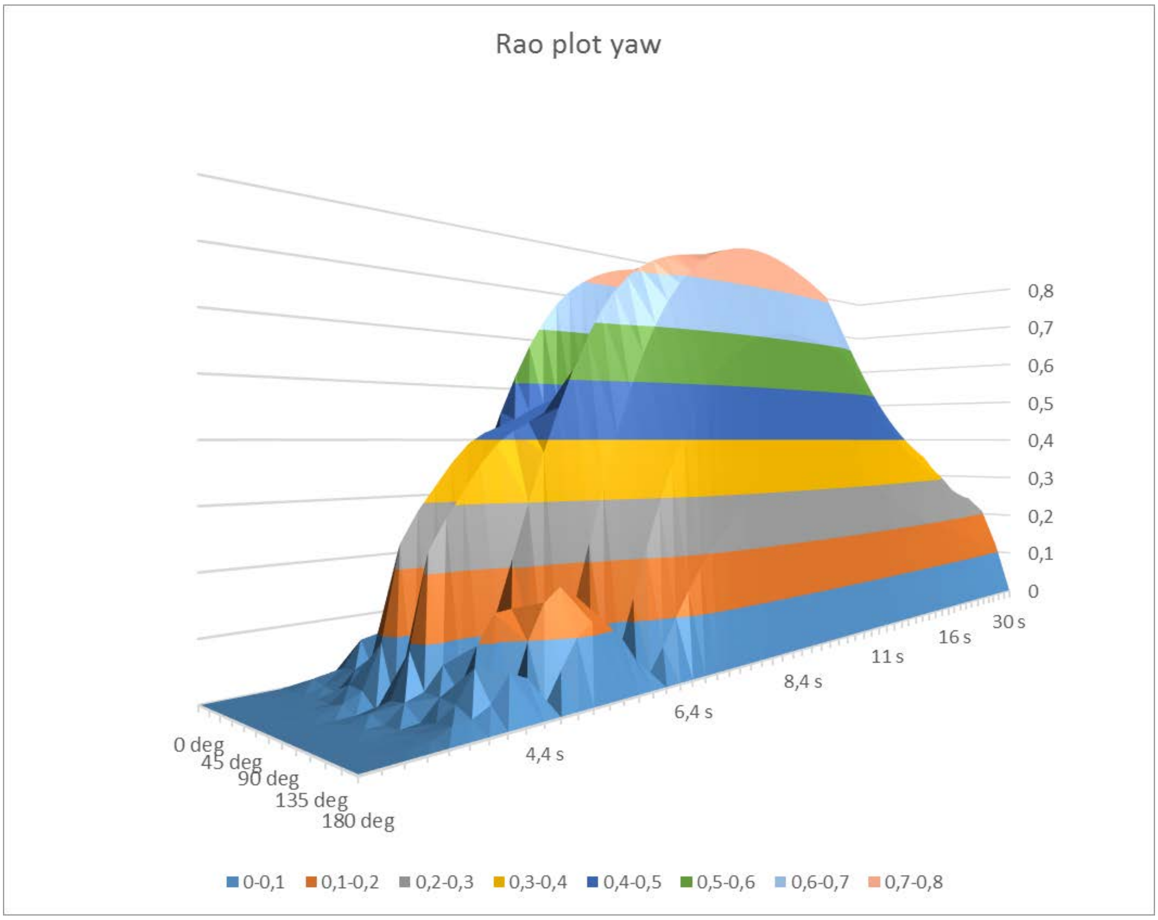


Rao plot heave
1,2
1
0,8
0,6
0,4
0,2
0
0 deg
45 deg
90 deg
135 deg
180 deg
4,4 s
6,4 s
8,4 s
11 s
16 s
30 s
0-0,2
0,2-0,4
0,4-0,6
0,6-0,8
0,8-1
1-1,2



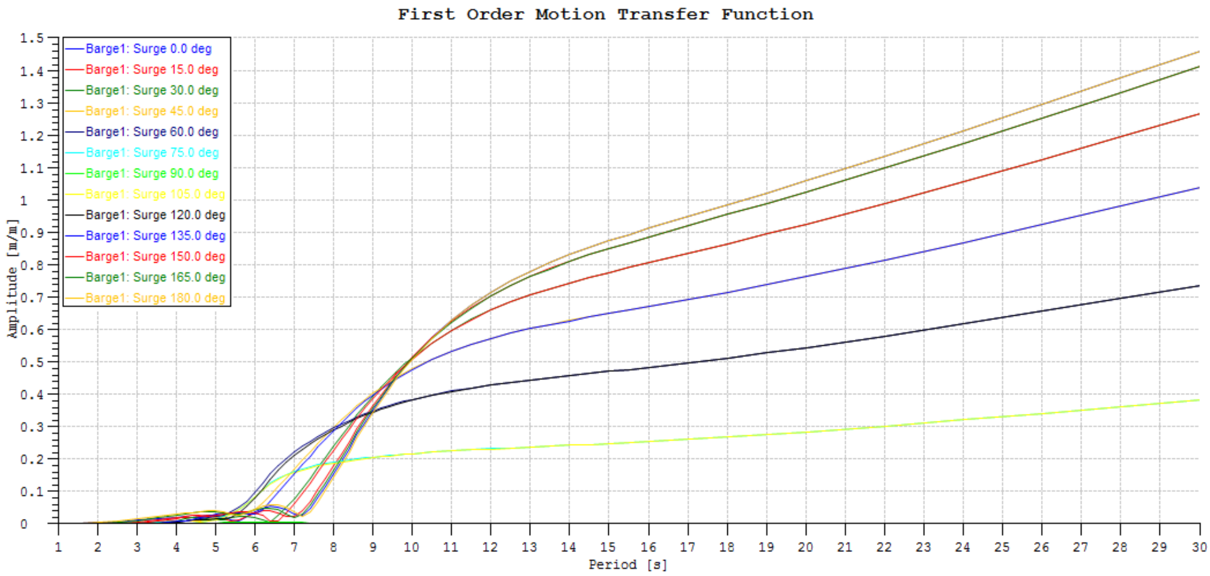
Rao plot pitch
2,00
1,80
1,60
1,40
1,20
1,00
0,80
0,60
0,40
0,20
0,00
0 deg
45 deg
90 deg
135 deg
180 deg
4,4 s
6,4 s
8,4 s
11 s
16 s
30 s
0,00-0,20
0,20-0,40
0,40-0,60
0,60-0,80
0,80-1,00
1,00-1,20
1,20-1,40
1,40-1,60
1,60-1,80
1,80-2,00


Rao plot roll
6,00
5,00
4,00
3,00
2,00
1,00
0,00
30 s
16 s
11 s
8,4 s
6,4 s
4,4 s
0 deg
45 deg
90 deg
135 deg
180 deg
0,00-1,00
1,00-2,00
2,00-3,00
3,00-4,00
4,00-5,00
5,00-6,00

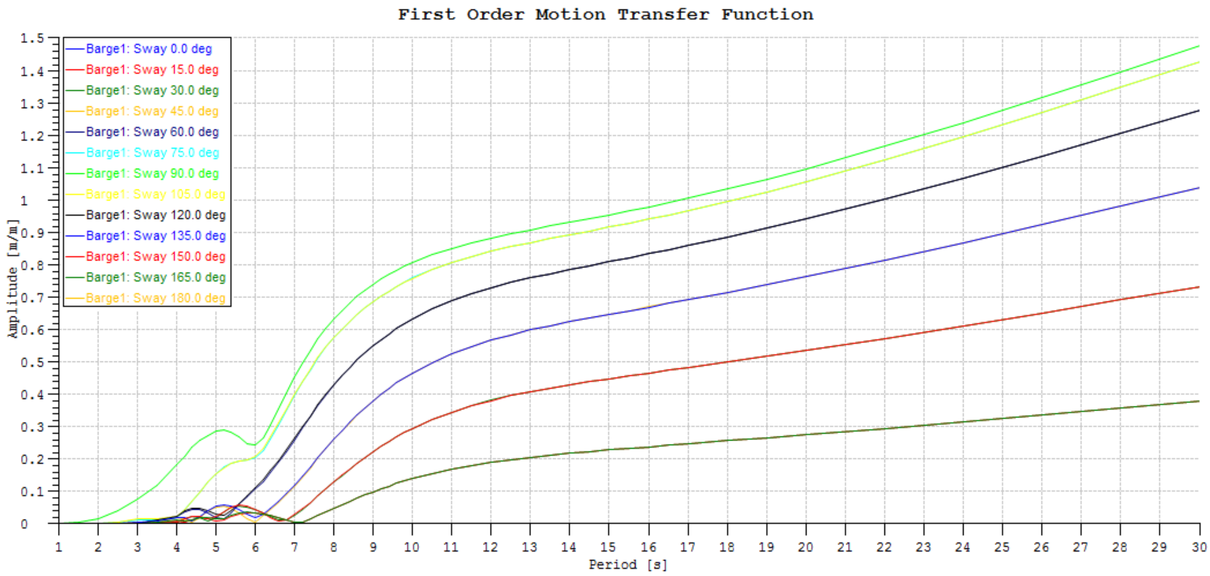

Rao plot yaw
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
30 s
16 s
11 s
8,4 s
6,4 s
4,4 s
0 deg
45 deg
90 deg
135 deg
180 deg
0-0,1
0,1-0,2
0,2-0,3
0,3-0,4
0,4-0,5
0,5-0,6
0,6-0,7
0,7-0,8

C4 RAO 2D plots from HydoD

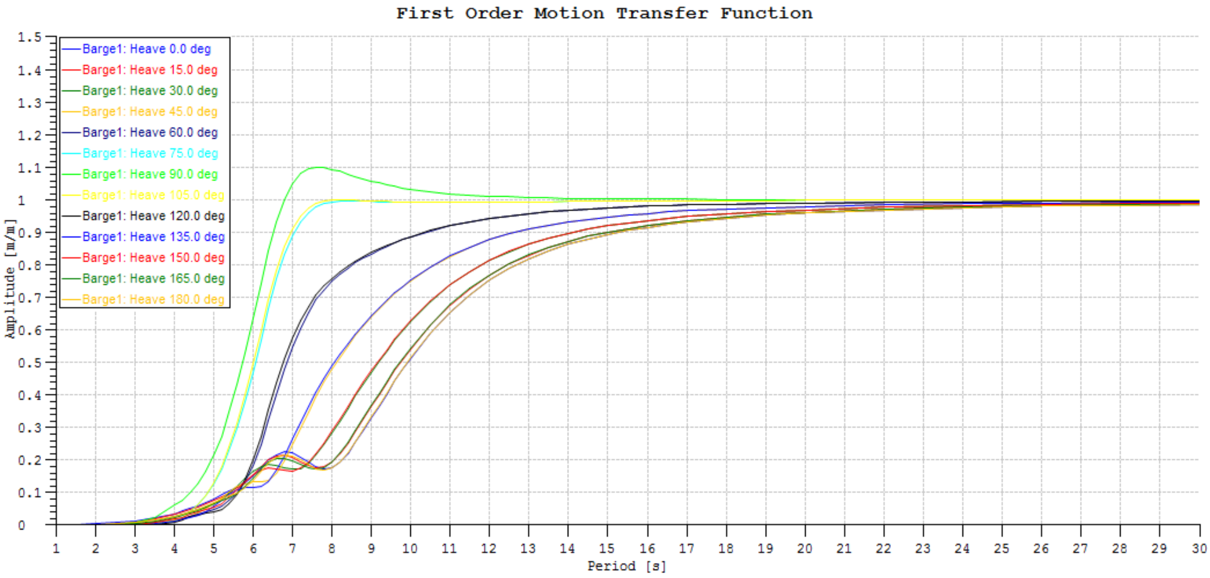
Surge motion:



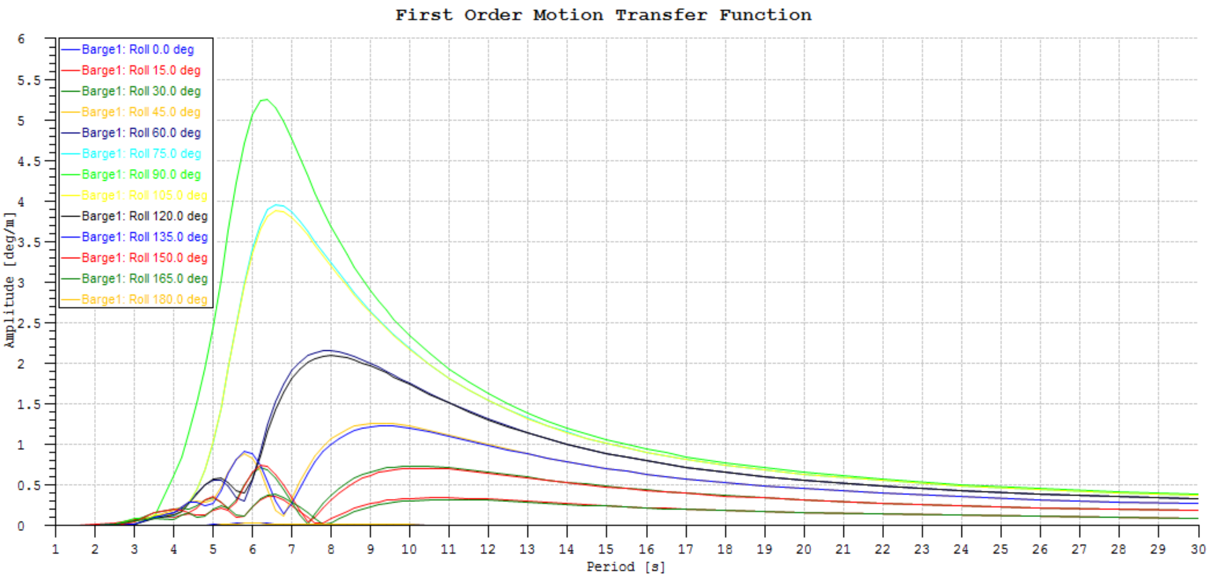
Sway motion



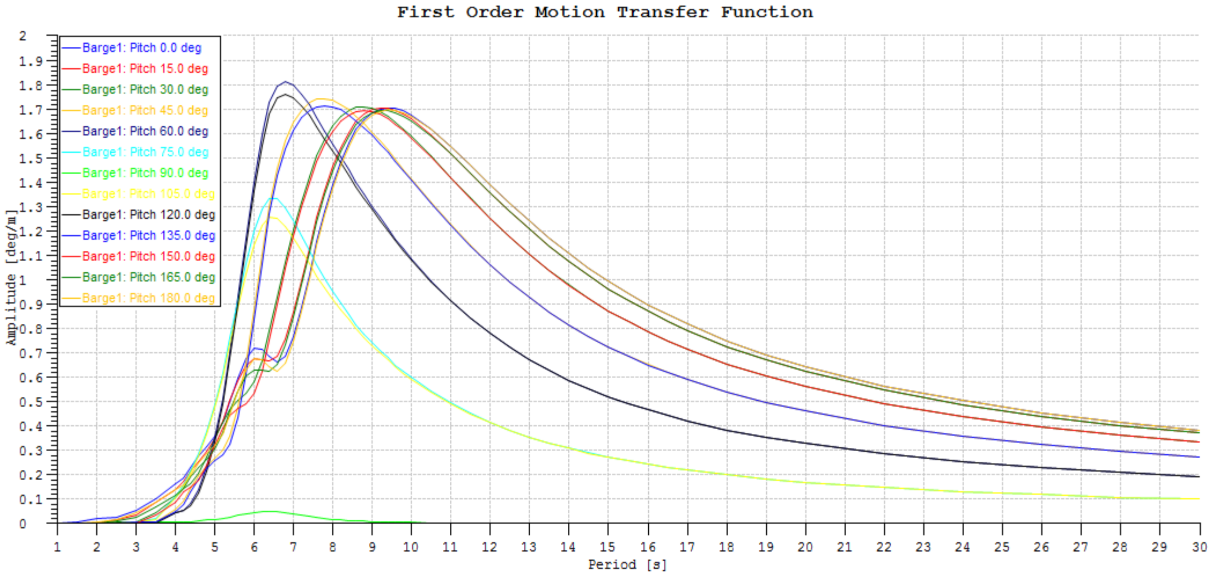
Heave motion:



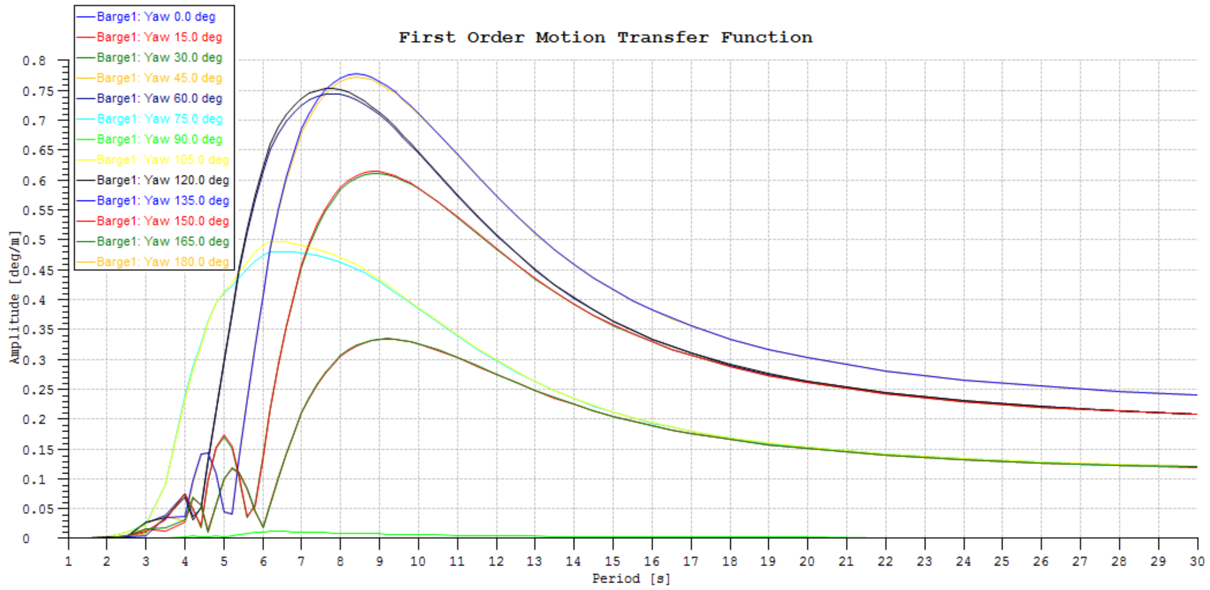
Roll motion:



Pitch motion:



Yaw motion:



Appendix D SIMA results

D1 Details barge:

Centre of Gravity:

X	Y	Z
1.105	0.000	-1.008

Mass coefficients:

Mass	Ixx	Iyx	Iyy	Izx	Izy	Izz
9.639e+06	6.425e+08	1.999e+07	5.786e+09	-3.334e+07	-2.074e+05	6.383e+09

Damping matrix:

	Surge	Sway	Heave	Roll	Pitch	Yaw
Surge	2.931e+05	0.000	0.000	0.000	0.000	0.000
Sway	0.000	3.148e+05	0.000	0.000	0.000	0.000
Heave	0.000	0.000	0.000	0.000	0.000	0.000
Roll	0.000	0.000	0.000	2.907e+04	0.000	0.000
Pitch	0.000	0.000	0.000	0.000	0.000	0.000
Yaw	0.000	0.000	0.000	0.000	0.000	2.045e+08

Stiffness Matrix:

	Surge	Sway	Heave	Roll	Pitch	Yaw
Surge	4.385e+03	0.000	0.000	0.000	0.000	0.000
Sway	0.000	4.709e+03	0.000	0.000	0.000	0.000
Heave	0.000	0.000	2.496e+07	0.000	-1.164e+07	0.000
Roll	0.000	0.000	0.000	1.471e+09	0.000	-1.144e+04
Pitch	0.000	0.000	-1.164e+07	0.000	1.695e+10	1.359e+03
Yaw	0.000	0.000	0.000	-1.144e+04	1.359e+03	3.059e+06

Added mass matrix (zero T=30s):

	Surge	Sway	Heave	Roll	Pitch	Yaw
Surge	7.077e+05	-1.958e-02	1.084e+05	-9.585	8.228e+07	277.855
Sway	0.494	3.808e+06	-9.956	-2.003e+07	-38.058	4.283e+06
Heave	1.080e+05	-8.564	4.920e+07	-95.854	-2.238e+07	201.310
Roll	-5.140	-1.999e+07	-87.620	8.059e+08	-388.151	-1.967e+07
Pitch	8.229e+07	-217.803	-2.238e+07	-537.723	1.854e+10	1.612e+04
Yaw	214.493	4.284e+06	78.307	-1.978e+07	1.648e+04	1.740e+09

Added mass matrix (infinite, T=0s):

	Surge	Sway	Heave	Roll	Pitch	Yaw
Surge	3.573e+05	26.196	8.582e+04	59.598	4.057e+07	-1.119e+03
Sway	0.000	1.096e+06	0.824	-4.950e+06	259.294	1.258e+06
Heave	9.369e+04	41.300	2.697e+07	-209.545	-2.123e+07	-1.589e+03
Roll	72.177	-5.412e+06	-593.948	6.823e+08	-620.251	-9.467e+06
Pitch	4.079e+07	2.176e+03	-2.187e+07	1.136e+03	1.246e+10	-1.259e+05
Yaw	0.000	1.278e+06	489.282	-7.865e+06	972.662	5.905e+08

D2 Details topside:

Position and mass

X	Y	Z	Rx	Ry	Rz	Gravity Included
-2.330	5.919	34.533	0.000	0.000	0.000	☑

Accumulated mass, volume and center of gravity (Calculated):

Acc Mass	Acc Volume	X	Y	Z
4.872e+06	0.000	0.000	0.000	0.000

Centre of Gravity:

X	Y	Z
0.000	0.000	0.000

Mass coefficients:

Mass	Ixx	Iyx	Iyy	Izx	Izy	Izz
4.872e+06	6.139e+08	1.513e+07	1.480e+09	5.376e+07	-9.213e+07	1.718e+09

D3 Docking stage

Name:	Dimension:
Height of topside	27 m
Distance between barges	60 m
Boom angle	51,3°

D3.1 Results from; Direction 0 degrees, Wave spreading (n=2, cos function)

TP	HS	Maximum Horizontal accelleration (XY)	Horizontal accelleration (P90)	Standard deviation
TP 4	3,00	0,48	0,43	0,09
TP 4,5	3,30	0,47	0,41	0,06

	HS	Maximum Vertical velocity (Z)	Vertical velocity (P90)	Standard deviation
TP 5	3,20	0,37	0,36	0,02
TP5,5	2,50	0,39	0,38	0,02
TP 6	2,00	0,37	0,37	0,02
TP 6,5	1,70	0,38	0,36	0,02
TP 7	1,50	0,38	0,37	0,02
TP 7,5	1,30	0,38	0,36	0,03
TP 8	1,30	0,38	0,37	0,02
TP 8,5	1,20	0,39	0,38	0,03
TP 9	1,10	0,38	0,38	0,02
TP 9,5	1,10	0,38	0,38	0,03
TP 10	1,00	0,38	0,36	0,02
TP 12	0,90	0,38	0,36	0,02
TP 14	0,90	0,38	0,37	0,02

	Acceleration		Velocity		Displacement					
	Horizontal	Vertical	Horizontal	Vertical	X	Y	Z	RX (Transver	RY (Longitud	RZ (Plan rotation)
Req	0,4905	0,981	0,5	0,4	1,5	1,5	1	2	2	3
TP 4	0,26	0,32	0,17	0,20	0,17	0,12	0,08	0,13	0,30	0,21
HS 3,0	0,26	0,31	0,17	0,19	0,25	0,16	0,07	0,10	0,29	0,24
Gamma 5	0,25	0,42	0,17	0,21	0,22	0,17	0,08	0,10	0,26	0,23
Dir 0	0,25	0,34	0,16	0,17	0,20	0,14	0,07	0,11	0,29	0,24
	0,48	0,47	0,19	0,21	0,21	0,16	0,08	0,09	0,30	0,24
	0,45	0,44	0,17	0,18	0,23	0,18	0,08	0,11	0,29	0,23
	0,26	0,31	0,16	0,17	0,22	0,14	0,07	0,11	0,27	0,23
	0,25	0,37	0,15	0,17	0,21	0,19	0,08	0,12	0,26	0,22
	0,39	0,42	0,17	0,20	0,21	0,13	0,08	0,09	0,28	0,26
	0,29	0,37	0,17	0,18	0,22	0,16	0,07	0,10	0,26	0,27
TP 4,5	0,36	0,42	0,24	0,28	0,40	0,23	0,14	0,19	0,55	0,35
HS 3,3	0,32	0,46	0,23	0,29	0,30	0,19	0,13	0,21	0,57	0,24
Gamma 5	0,30	0,37	0,22	0,24	0,30	0,20	0,13	0,19	0,50	0,27
Dir 0	0,40	0,42	0,20	0,27	0,30	0,23	0,13	0,19	0,47	0,34
	0,31	0,39	0,21	0,25	0,36	0,21	0,13	0,20	0,51	0,26
	0,29	0,40	0,21	0,25	0,31	0,19	0,13	0,18	0,48	0,29
	0,30	0,42	0,21	0,25	0,31	0,25	0,13	0,16	0,50	0,38
	0,31	0,38	0,23	0,26	0,32	0,23	0,14	0,22	0,53	0,26
	0,28	0,40	0,20	0,27	0,32	0,20	0,14	0,19	0,50	0,25
	0,47	0,47	0,22	0,28	0,32	0,22	0,14	0,20	0,50	0,30
TP 5	0,32	0,39	0,26	0,33	0,41	0,38	0,21	0,34	0,72	0,30
HS 3,2	0,34	0,44	0,27	0,36	0,41	0,36	0,19	0,29	0,82	0,42
Gamma 5	0,34	0,44	0,27	0,32	0,41	0,35	0,19	0,29	0,71	0,37
Dir 0	0,42	0,50	0,32	0,35	0,41	0,37	0,18	0,32	0,72	0,38
	0,32	0,48	0,25	0,34	0,44	0,48	0,20	0,32	0,84	0,32
	0,33	0,44	0,24	0,33	0,40	0,30	0,19	0,36	0,74	0,36
	0,41	0,49	0,27	0,37	0,45	0,34	0,20	0,29	0,73	0,32
	0,33	0,42	0,27	0,34	0,45	0,44	0,18	0,32	0,75	0,36
	0,31	0,40	0,25	0,34	0,41	0,34	0,21	0,29	0,71	0,36
	0,32	0,39	0,25	0,31	0,37	0,43	0,18	0,28	0,64	0,38
TP 5,5	0,29	0,38	0,25	0,37	0,40	0,42	0,20	0,39	0,83	0,37
HS 2,5	0,27	0,41	0,24	0,36	0,47	0,43	0,24	0,34	0,93	0,44
Gamma 5	0,27	0,36	0,24	0,33	0,40	0,37	0,21	0,38	0,87	0,36
Dir 0	0,28	0,41	0,24	0,36	0,47	0,40	0,22	0,34	0,86	0,44
	0,33	0,42	0,29	0,35	0,45	0,37	0,22	0,37	0,91	0,39
	0,32	0,48	0,26	0,38	0,45	0,39	0,22	0,34	0,93	0,32
	0,29	0,40	0,24	0,36	0,44	0,42	0,19	0,41	0,81	0,34
	0,27	0,37	0,24	0,34	0,45	0,38	0,19	0,32	0,96	0,47
	0,28	0,38	0,25	0,34	0,36	0,38	0,23	0,38	0,79	0,42
	0,28	0,38	0,27	0,39	0,47	0,37	0,23	0,40	0,94	0,34
TP 6	0,25	0,34	0,23	0,34	0,45	0,46	0,23	0,43	1,01	0,34
HS 2,0	0,26	0,38	0,23	0,34	0,47	0,41	0,24	0,43	0,94	0,35
Gamma 2,389	0,24	0,39	0,22	0,35	0,44	0,43	0,23	0,50	0,95	0,28
Dir 0	0,24	0,35	0,22	0,34	0,43	0,41	0,22	0,43	0,87	0,37
	0,23	0,36	0,22	0,35	0,45	0,42	0,23	0,46	1,04	0,30
	0,23	0,34	0,21	0,32	0,43	0,40	0,24	0,48	0,95	0,28
	0,25	0,37	0,22	0,37	0,42	0,37	0,27	0,40	0,95	0,28
	0,24	0,32	0,23	0,36	0,41	0,41	0,22	0,51	0,94	0,39
	0,24	0,37	0,22	0,36	0,43	0,39	0,26	0,48	1,07	0,31
	0,22	0,35	0,21	0,34	0,41	0,38	0,24	0,47	0,97	0,27
TP 6,5	0,21	0,31	0,20	0,32	0,41	0,32	0,22	0,50	0,97	0,29
HS 1,7	0,21	0,33	0,22	0,36	0,49	0,32	0,26	0,53	1,15	0,24
Gamma 1,017	0,20	0,32	0,19	0,35	0,48	0,36	0,25	0,55	1,19	0,26
Dir 0	0,20	0,31	0,20	0,35	0,44	0,34	0,25	0,52	1,10	0,23
	0,20	0,33	0,19	0,32	0,45	0,33	0,22	0,53	0,99	0,25
	0,22	0,31	0,23	0,32	0,42	0,36	0,22	0,64	1,13	0,27
	0,19	0,38	0,19	0,38	0,45	0,35	0,29	0,64	1,09	0,27
	0,19	0,28	0,19	0,33	0,42	0,35	0,25	0,57	1,03	0,27
	0,19	0,30	0,20	0,32	0,43	0,36	0,25	0,59	1,10	0,29
	0,21	0,30	0,21	0,32	0,42	0,33	0,26	0,52	0,99	0,27
TP 7	0,20	0,28	0,22	0,34	0,43	0,33	0,28	0,62	1,14	0,23
HS 1,5	0,18	0,29	0,19	0,34	0,46	0,40	0,25	0,65	1,30	0,24
Gamma 1	0,18	0,30	0,17	0,34	0,44	0,35	0,30	0,58	1,14	0,27
Dir 0	0,19	0,33	0,19	0,37	0,43	0,32	0,24	0,61	1,02	0,34
	0,18	0,29	0,19	0,33	0,43	0,41	0,25	0,71	1,19	0,26
	0,17	0,28	0,17	0,30	0,44	0,33	0,25	0,59	1,15	0,22
	0,17	0,27	0,19	0,31	0,39	0,39	0,27	0,75	0,99	0,25
	0,19	0,31	0,17	0,38	0,49	0,30	0,26	0,58	1,20	0,24
	0,19	0,29	0,20	0,34	0,42	0,39	0,28	0,65	1,09	0,24
	0,17	0,29	0,17	0,35	0,43	0,32	0,23	0,53	1,13	0,23

TP 7,5	0,18	0,34	0,19	0,38	0,44	0,29	0,28	0,54	1,10	0,21
HS 1,3	0,15	0,29	0,16	0,33	0,44	0,35	0,28	0,55	1,23	0,21
Gamma 1	0,16	0,29	0,17	0,33	0,38	0,38	0,30	0,64	1,02	0,19
Dir 0	0,16	0,31	0,16	0,36	0,52	0,30	0,28	0,53	1,40	0,19
	0,15	0,28	0,16	0,32	0,41	0,30	0,28	0,60	1,12	0,26
	0,18	0,31	0,19	0,35	0,42	0,31	0,27	0,61	1,13	0,21
	0,16	0,28	0,17	0,32	0,43	0,31	0,27	0,55	1,10	0,20
	0,16	0,27	0,17	0,30	0,38	0,31	0,28	0,65	1,10	0,21
	0,14	0,26	0,15	0,29	0,39	0,30	0,26	0,57	1,10	0,21
	0,17	0,25	0,17	0,31	0,40	0,37	0,26	0,73	1,10	0,22
TP 8	0,14	0,30	0,16	0,34	0,40	0,35	0,35	0,59	1,32	0,20
HS 1,3	0,16	0,27	0,17	0,36	0,44	0,37	0,35	0,69	1,29	0,23
Gamma 1	0,16	0,32	0,17	0,38	0,49	0,32	0,30	0,63	1,35	0,21
Dir 0	0,17	0,30	0,17	0,36	0,46	0,31	0,33	0,71	1,34	0,23
	0,16	0,28	0,17	0,33	0,39	0,35	0,29	0,62	1,17	0,22
	0,15	0,28	0,16	0,35	0,42	0,33	0,37	0,64	1,25	0,22
	0,16	0,29	0,16	0,35	0,44	0,35	0,33	0,80	1,27	0,21
	0,15	0,28	0,17	0,34	0,41	0,34	0,34	0,65	1,17	0,20
	0,17	0,31	0,18	0,36	0,45	0,37	0,34	0,70	1,27	0,21
	0,15	0,29	0,16	0,35	0,46	0,32	0,34	0,63	1,25	0,27
TP 8,5	0,13	0,25	0,14	0,32	0,39	0,32	0,33	0,67	1,29	0,19
HS 1,2	0,14	0,26	0,15	0,37	0,38	0,32	0,38	0,74	1,41	0,19
Gamma 1	0,14	0,28	0,15	0,37	0,44	0,27	0,35	0,66	1,55	0,20
Dir 0	0,14	0,29	0,16	0,33	0,42	0,35	0,33	0,64	1,27	0,19
	0,13	0,25	0,15	0,35	0,39	0,32	0,36	0,61	1,32	0,20
	0,14	0,27	0,15	0,33	0,42	0,32	0,35	0,68	1,29	0,22
	0,14	0,26	0,16	0,33	0,44	0,35	0,36	0,64	1,32	0,17
	0,14	0,27	0,16	0,39	0,42	0,32	0,42	0,64	1,18	0,19
	0,13	0,26	0,14	0,30	0,39	0,29	0,34	0,61	1,20	0,18
	0,13	0,27	0,16	0,37	0,40	0,39	0,44	0,64	1,43	0,21
TP 9	0,14	0,28	0,16	0,38	0,37	0,32	0,43	0,66	1,53	0,16
HS 1,1	0,12	0,26	0,14	0,35	0,45	0,29	0,41	0,72	1,41	0,16
Gamma 1	0,12	0,27	0,14	0,34	0,41	0,33	0,40	0,75	1,38	0,16
Dir 0	0,12	0,29	0,13	0,38	0,42	0,27	0,44	0,67	1,50	0,17
	0,12	0,25	0,14	0,35	0,41	0,29	0,41	0,58	1,35	0,15
	0,12	0,28	0,15	0,35	0,40	0,34	0,39	0,69	1,34	0,16
	0,14	0,24	0,15	0,32	0,38	0,27	0,38	0,72	1,33	0,19
	0,12	0,29	0,14	0,36	0,37	0,29	0,38	0,66	1,36	0,17
	0,12	0,28	0,14	0,35	0,44	0,35	0,40	0,60	1,33	0,18
	0,12	0,24	0,13	0,32	0,38	0,29	0,38	0,65	1,31	0,16
TP 9,5	0,12	0,25	0,14	0,34	0,38	0,26	0,39	0,64	1,31	0,16
HS 1,1	0,12	0,23	0,13	0,33	0,34	0,25	0,40	0,69	1,29	0,16
Gamma 1	0,11	0,26	0,15	0,35	0,40	0,29	0,42	0,69	1,27	0,19
Dir 0	0,12	0,24	0,15	0,30	0,40	0,32	0,38	0,70	1,16	0,17
	0,11	0,25	0,12	0,38	0,37	0,27	0,42	0,75	1,40	0,17
	0,11	0,23	0,13	0,32	0,39	0,27	0,42	0,63	1,26	0,16
	0,12	0,26	0,13	0,37	0,39	0,27	0,45	0,69	1,25	0,16
	0,11	0,28	0,13	0,38	0,45	0,26	0,42	0,67	1,58	0,15
	0,11	0,25	0,14	0,34	0,39	0,33	0,43	0,68	1,31	0,18
	0,11	0,26	0,14	0,33	0,37	0,33	0,40	0,84	1,28	0,16
TP 10	0,11	0,25	0,14	0,35	0,35	0,28	0,47	0,68	1,23	0,16
HS 1,0	0,09	0,23	0,13	0,32	0,31	0,24	0,43	0,71	1,18	0,14
Gamma 1	0,11	0,23	0,14	0,33	0,29	0,28	0,42	0,67	1,19	0,14
Dir 0	0,11	0,25	0,14	0,38	0,34	0,28	0,47	0,63	1,16	0,16
	0,10	0,22	0,13	0,32	0,37	0,23	0,44	0,63	1,24	0,14
	0,10	0,23	0,13	0,34	0,38	0,24	0,42	0,63	1,22	0,13
	0,09	0,23	0,11	0,34	0,35	0,27	0,44	0,75	1,23	0,13
	0,10	0,22	0,14	0,33	0,33	0,24	0,49	0,71	1,20	0,14
	0,11	0,23	0,13	0,32	0,36	0,24	0,46	0,60	1,38	0,13
	0,10	0,24	0,13	0,33	0,35	0,24	0,48	0,60	1,07	0,14
TP 12	0,11	0,21	0,17	0,34	0,31	0,18	0,58	0,54	1,07	0,11
HS 0,9	0,08	0,21	0,13	0,32	0,32	0,19	0,56	0,55	1,15	0,10
Gamma 1	0,09	0,23	0,14	0,33	0,29	0,18	0,56	0,56	1,20	0,10
Dir 0	0,09	0,20	0,14	0,38	0,25	0,20	0,55	0,53	1,07	0,09
	0,09	0,19	0,13	0,32	0,28	0,20	0,50	0,56	1,00	0,11
	0,09	0,20	0,13	0,34	0,31	0,20	0,53	0,64	1,12	0,10
	0,08	0,21	0,14	0,34	0,33	0,20	0,55	0,60	1,16	0,10
	0,08	0,22	0,13	0,33	0,29	0,21	0,56	0,68	1,27	0,11
	0,08	0,19	0,13	0,32	0,35	0,22	0,52	0,60	1,14	0,10
	0,10	0,21	0,16	0,33	0,27	0,20	0,53	0,57	1,17	0,11

TP 14	0,08	0,20	0,16	0,36	0,31	0,18	0,61	0,59	1,06	0,09
HS 0,9	0,08	0,21	0,16	0,32	0,29	0,18	0,62	0,54	1,15	0,09
Gamma 1	0,09	0,21	0,15	0,33	0,31	0,18	0,65	0,53	1,11	0,07
Dir 0	0,08	0,19	0,15	0,38	0,31	0,18	0,65	0,57	1,04	0,08
	0,08	0,18	0,17	0,32	0,36	0,19	0,61	0,53	1,09	0,08
	0,09	0,20	0,18	0,34	0,36	0,20	0,69	0,53	1,21	0,08
	0,09	0,21	0,16	0,34	0,29	0,21	0,68	0,56	1,08	0,09
	0,08	0,16	0,14	0,32	0,34	0,24	0,58	0,69	0,95	0,11
	0,08	0,19	0,15	0,33	0,30	0,19	0,63	0,56	1,04	0,08
	0,08	0,18	0,17	0,38	0,29	0,17	0,72	0,60	1,00	0,08

D3.2 Results from; Direction 45 degrees, Wave spreading (n=2, cos function)

TP	HS	Maximum Horizontal accelleration (XY)	Horizontal accelleration (P90)	Standard deviation
TP 4	3,20	0,51	0,46	0,08
TP 4,5	3,30	0,47	0,42	0,05

TP	HS	Maximum Vertical velocity (Z)	Vertical velocity (P90)	Standard deviation
TP 5	2,60	0,40	0,40	0,03
TP5,5	1,70	0,37	0,37	0,02
TP 6	1,40	0,38	0,37	0,02
TP 6,5	1,20	0,37	0,36	0,02
TP 7	1,10	0,37	0,36	0,02
TP 7,5	1,10	0,39	0,38	0,02
TP 8	1,10	0,41	0,40	0,02
TP 10	1,00	0,42	0,40	0,03
TP 12	0,90	0,36	0,36	0,01
TP 14	0,90	0,38	0,39	0,02

	Acceleration		Velocity		Displacement					
	Horizontal	Vertical	Horizontal	Vertical	X	Y	Z	RX (Transver	RY (Longitud	RZ (Plan rotation)
Req	0,4905	0,981	0,5	0,4	1,5	1,5	1	2	2	3
TP 4	0,51	0,58	0,19	0,25	0,33	0,66	0,11	0,15	0,28	0,32
HS 3,2	0,28	0,55	0,18	0,22	0,31	0,74	0,11	0,15	0,33	0,40
Gamma 5	0,37	0,48	0,17	0,20	0,24	0,62	0,10	0,15	0,28	0,46
Dir 45	0,34	0,48	0,21	0,22	0,32	0,73	0,11	0,14	0,29	0,52
	0,32	0,43	0,19	0,22	0,27	0,72	0,11	0,14	0,29	0,39
	0,27	0,43	0,17	0,21	0,26	0,76	0,10	0,14	0,29	0,42
	0,29	0,59	0,19	0,23	0,24	0,64	0,10	0,15	0,28	0,39
	0,28	0,50	0,19	0,23	0,28	0,78	0,12	0,14	0,29	0,38
	0,48	0,44	0,18	0,20	0,28	0,83	0,10	0,13	0,29	0,32
	0,39	0,45	0,17	0,20	0,26	0,66	0,11	0,16	0,30	0,42
TP 4,5	0,34	0,47	0,25	0,30	0,44	0,70	0,21	0,24	0,53	0,46
HS 3,3	0,47	0,56	0,32	0,31	0,36	0,73	0,22	0,27	0,59	0,46
Gamma 5	0,41	0,52	0,27	0,36	0,38	0,70	0,21	0,28	0,65	0,41
Dir 45	0,32	0,48	0,23	0,31	0,32	0,79	0,21	0,25	0,49	0,40
	0,34	0,50	0,26	0,30	0,34	0,78	0,21	0,25	0,56	0,40
	0,35	0,55	0,25	0,34	0,34	0,90	0,21	0,29	0,51	0,59
	0,33	0,54	0,24	0,30	0,37	0,92	0,24	0,24	0,60	0,43
	0,34	0,53	0,25	0,33	0,37	0,78	0,20	0,30	0,49	0,43
	0,34	0,50	0,25	0,31	0,38	0,74	0,19	0,25	0,53	0,44
	0,39	0,53	0,29	0,33	0,34	0,80	0,22	0,25	0,49	0,52
TP 5	0,28	0,49	0,23	0,38	0,35	0,92	0,26	0,38	0,63	0,41
HS 2,6	0,32	0,40	0,27	0,33	0,41	0,85	0,26	0,37	0,63	0,40
Gamma 5	0,33	0,47	0,26	0,39	0,41	0,80	0,27	0,39	0,59	0,36
Dir 45	0,29	0,42	0,25	0,33	0,40	0,82	0,25	0,35	0,59	0,35
	0,27	0,41	0,24	0,36	0,38	0,78	0,26	0,44	0,75	0,42
	0,31	0,46	0,24	0,35	0,37	0,84	0,25	0,41	0,65	0,39
	0,32	0,47	0,25	0,38	0,36	0,92	0,28	0,40	0,61	0,54
	0,32	0,46	0,26	0,34	0,35	0,85	0,27	0,42	0,67	0,33
	0,28	0,46	0,24	0,39	0,47	0,97	0,24	0,35	0,75	0,44
	0,28	0,45	0,25	0,40	0,40	1,09	0,28	0,40	0,60	0,40
TP 5,5	0,23	0,37	0,20	0,34	0,35	0,80	0,27	0,41	0,69	0,29
HS 1,7	0,23	0,39	0,22	0,37	0,33	1,16	0,33	0,41	0,64	0,24
Gamma 2,457	0,24	0,40	0,22	0,35	0,36	0,87	0,27	0,42	0,75	0,27
Dir 45	0,24	0,41	0,21	0,36	0,36	0,74	0,29	0,40	0,76	0,32
	0,27	0,35	0,26	0,33	0,35	0,88	0,27	0,51	0,71	0,29
	0,25	0,41	0,23	0,35	0,40	0,80	0,30	0,45	0,71	0,29
	0,27	0,41	0,25	0,37	0,41	1,09	0,30	0,40	0,79	0,31
	0,24	0,35	0,24	0,33	0,33	0,89	0,30	0,39	0,67	0,25
	0,25	0,36	0,21	0,33	0,33	0,78	0,28	0,42	0,69	0,25
	0,23	0,33	0,21	0,32	0,36	1,19	0,27	0,39	0,79	0,29
TP 6	0,22	0,31	0,22	0,30	0,33	0,66	0,27	0,51	0,69	0,36
HS 1,4	0,24	0,33	0,24	0,33	0,29	0,98	0,30	0,51	0,65	0,31
Gamma 1	0,24	0,34	0,25	0,32	0,38	0,79	0,29	0,55	0,74	0,30
Dir 45	0,22	0,35	0,23	0,36	0,35	1,05	0,35	0,55	0,80	0,39
	0,21	0,34	0,21	0,33	0,34	0,82	0,28	0,53	0,73	0,43
	0,23	0,36	0,22	0,34	0,33	0,88	0,30	0,53	0,76	0,27
	0,23	0,39	0,22	0,38	0,39	0,83	0,31	0,54	0,79	0,32
	0,23	0,33	0,22	0,34	0,33	0,88	0,32	0,57	0,73	0,34
	0,21	0,34	0,21	0,33	0,37	0,87	0,31	0,48	0,89	0,33
	0,22	0,33	0,22	0,34	0,35	0,80	0,29	0,49	0,76	0,26
TP 6,5	0,23	0,35	0,25	0,37	0,27	0,77	0,30	0,68	0,66	0,35
HS 1,2	0,24	0,37	0,22	0,37	0,38	0,74	0,34	0,64	0,93	0,34
Gamma 1	0,22	0,33	0,24	0,33	0,29	0,83	0,29	0,73	0,66	0,31
Dir 45	0,20	0,31	0,22	0,32	0,31	0,75	0,27	0,64	0,68	0,30
	0,22	0,30	0,23	0,33	0,30	0,93	0,29	0,58	0,71	0,36
	0,24	0,32	0,24	0,34	0,31	0,77	0,31	0,73	0,68	0,42
	0,21	0,34	0,22	0,32	0,31	0,66	0,27	0,60	0,72	0,22
	0,22	0,32	0,23	0,35	0,32	0,81	0,28	0,65	0,75	0,32
	0,23	0,30	0,22	0,31	0,33	0,67	0,27	0,64	0,74	0,28
	0,26	0,34	0,26	0,34	0,33	0,94	0,31	0,63	0,80	0,28
TP 7	0,19	0,30	0,20	0,34	0,37	0,63	0,29	0,72	0,86	0,28
HS 1,1	0,21	0,31	0,24	0,32	0,33	0,63	0,32	0,77	0,79	0,28
Gamma 1	0,21	0,31	0,22	0,34	0,34	0,65	0,29	0,69	0,77	0,30
Dir 45	0,22	0,30	0,23	0,32	0,35	0,74	0,29	0,69	0,79	0,29
	0,23	0,34	0,26	0,36	0,29	0,68	0,33	0,72	0,73	0,27
	0,21	0,34	0,22	0,34	0,30	0,65	0,31	0,71	0,73	0,25
	0,21	0,36	0,22	0,37	0,34	0,79	0,34	0,73	0,85	0,28
	0,23	0,33	0,27	0,35	0,30	0,60	0,34	0,77	0,76	0,28
	0,21	0,30	0,21	0,32	0,29	0,75	0,31	0,74	0,75	0,26
	0,20	0,29	0,22	0,33	0,29	0,68	0,31	0,66	0,77	0,26

TP 7,5	0,22	0,33	0,24	0,37	0,30	0,83	0,33	0,78	0,78	0,31
HS 1,1	0,20	0,34	0,22	0,37	0,45	0,65	0,36	0,85	1,20	0,39
Gamma 1	0,22	0,30	0,24	0,32	0,36	0,73	0,31	0,86	0,90	0,27
Dir 45	0,22	0,30	0,26	0,32	0,30	0,60	0,31	1,00	0,82	0,31
	0,22	0,29	0,24	0,32	0,30	0,81	0,30	0,75	0,82	0,31
	0,19	0,35	0,22	0,36	0,31	0,72	0,33	0,95	0,80	0,26
	0,20	0,34	0,23	0,39	0,34	0,61	0,36	0,83	0,97	0,29
	0,19	0,34	0,22	0,37	0,35	0,64	0,34	0,92	0,86	0,25
	0,21	0,31	0,22	0,35	0,33	0,86	0,32	0,82	0,91	0,28
	0,20	0,31	0,22	0,34	0,29	0,65	0,32	0,83	0,75	0,25
TP 8	0,19	0,33	0,21	0,38	0,33	0,60	0,37	0,88	0,95	0,31
HS 1,1	0,22	0,33	0,25	0,38	0,31	0,89	0,36	0,96	1,00	0,36
Gamma 1	0,19	0,31	0,21	0,38	0,32	0,56	0,35	0,81	0,94	0,33
Dir 45	0,20	0,32	0,23	0,37	0,32	0,72	0,34	0,97	0,87	0,28
	0,20	0,30	0,22	0,34	0,35	0,75	0,35	0,93	0,99	0,33
	0,22	0,31	0,23	0,34	0,33	0,80	0,37	0,96	1,03	0,26
	0,20	0,30	0,23	0,35	0,38	0,75	0,34	1,02	0,95	0,29
	0,22	0,33	0,25	0,38	0,37	0,65	0,37	0,85	0,99	0,28
	0,21	0,33	0,25	0,41	0,34	0,79	0,39	0,98	0,99	0,27
	0,22	0,32	0,24	0,36	0,34	0,64	0,33	0,96	0,93	0,35
TP 10	0,15	0,25	0,18	0,37	0,25	0,48	0,45	1,00	0,97	0,19
HS 1,0	0,16	0,28	0,20	0,37	0,26	0,54	0,48	1,07	0,98	0,20
Gamma 1	0,16	0,28	0,20	0,35	0,29	0,57	0,45	1,17	0,87	0,25
Dir 45	0,15	0,27	0,19	0,33	0,32	0,50	0,39	0,99	1,10	0,22
	0,16	0,26	0,19	0,36	0,35	0,52	0,44	1,09	1,15	0,23
	0,16	0,30	0,20	0,41	0,30	0,50	0,46	1,12	1,01	0,21
	0,17	0,26	0,20	0,34	0,30	0,62	0,44	1,00	1,00	0,20
	0,17	0,28	0,20	0,42	0,31	0,54	0,51	1,04	1,03	0,18
	0,18	0,27	0,23	0,35	0,27	0,60	0,41	1,08	1,09	0,21
	0,15	0,26	0,19	0,33	0,26	0,48	0,41	1,18	0,90	0,21
TP 12	0,12	0,21	0,17	0,34	0,21	0,35	0,54	0,87	0,88	0,13
HS 0,9	0,12	0,22	0,15	0,36	0,22	0,37	0,52	0,93	0,90	0,11
Gamma 1	0,11	0,22	0,14	0,35	0,23	0,41	0,54	1,03	0,89	0,14
Dir 45	0,13	0,21	0,15	0,35	0,22	0,37	0,57	1,07	0,84	0,13
	0,11	0,20	0,15	0,32	0,22	0,34	0,53	0,86	0,89	0,12
	0,11	0,24	0,15	0,35	0,26	0,38	0,52	0,82	0,93	0,13
	0,12	0,23	0,16	0,35	0,24	0,43	0,53	1,12	0,83	0,16
	0,12	0,22	0,15	0,34	0,23	0,40	0,53	1,16	1,00	0,14
	0,11	0,22	0,17	0,33	0,23	0,33	0,48	0,96	0,87	0,13
	0,12	0,23	0,15	0,35	0,24	0,33	0,55	0,94	0,83	0,13
TP 14	0,10	0,20	0,18	0,36	0,24	0,32	0,60	0,94	0,82	0,12
HS 0,9	0,11	0,21	0,17	0,38	0,23	0,37	0,64	1,07	0,89	0,11
Gamma 1	0,11	0,19	0,17	0,36	0,23	0,33	0,60	0,89	0,80	0,11
Dir 45	0,11	0,22	0,17	0,38	0,25	0,32	0,62	0,83	0,89	0,11
	0,10	0,20	0,17	0,35	0,23	0,35	0,64	0,90	0,93	0,10
	0,10	0,22	0,18	0,38	0,26	0,33	0,71	0,83	0,90	0,10
	0,11	0,21	0,17	0,37	0,22	0,36	0,68	1,08	0,83	0,11
	0,10	0,21	0,16	0,36	0,25	0,33	0,65	0,94	0,84	0,10
	0,10	0,22	0,17	0,37	0,23	0,30	0,68	1,02	0,83	0,12
	0,10	0,21	0,16	0,33	0,24	0,29	0,60	0,93	0,77	0,10

D3.3 Results from; Direction 90 degrees, Wave spreading (n=2, cos function)

TP	HS	Maximum Horizontal accelleration (XY)	Horizontal accelleration (P90)	Standard deviation
TP 4	3,10	0,36	0,35	0,01
TP4,5	2,90	0,45	0,45	0,03

TP	HS	Maximum Vertical velocity (Z)	Vertical velocity (P90)	Standard deviation
TP 5	2,10	0,36	0,36	0,02
TP5,5	1,40	0,39	0,38	0,02
TP 6	1,10	0,38	0,38	0,02
TP 7	1,00	0,41	0,40	0,03
TP 8	0,90	0,42	0,39	0,03
TP 10	0,90	0,40	0,39	0,02
TP 12	0,90	0,37	0,37	0,01
TP 14	0,90	0,41	0,39	0,02

	Acceleration		Velocity		Displacement					
	Horizontal	Vertical	Horizontal	Vertical	X	Y	Z	RX (Transver	RY (Longitud	RZ (Plan rotation)
Req	0,4905	0,981	0,5	0,4	1,5	1,5	1	2	2	3
TP 4	0,32	0,44	0,20	0,20	0,26	0,97	0,12	0,14	0,29	0,50
HS 3,1	0,34	0,54	0,23	0,24	0,27	1,01	0,12	0,17	0,27	0,36
Gamma 5	0,33	0,47	0,22	0,21	0,29	0,93	0,12	0,18	0,27	0,46
Dir 90	0,33	0,50	0,22	0,22	0,32	1,00	0,12	0,18	0,27	0,39
	0,34	0,43	0,21	0,20	0,31	0,89	0,12	0,16	0,26	0,43
	0,34	0,52	0,22	0,24	0,32	0,86	0,12	0,17	0,25	0,42
	0,36	0,53	0,23	0,21	0,25	0,87	0,13	0,16	0,27	0,33
	0,35	0,40	0,21	0,21	0,26	1,20	0,12	0,19	0,28	0,33
	0,31	0,52	0,20	0,22	0,31	1,16	0,13	0,16	0,27	0,48
	0,33	0,47	0,21	0,20	0,35	1,08	0,12	0,15	0,30	0,38
TP 4,5	0,44	0,45	0,33	0,30	0,40	0,94	0,20	0,29	0,55	0,39
HS 2,9	0,41	0,47	0,29	0,30	0,33	0,87	0,22	0,31	0,47	0,43
Gamma 5	0,42	0,46	0,27	0,31	0,32	0,84	0,21	0,28	0,49	0,48
Dir 90	0,42	0,51	0,29	0,28	0,36	0,80	0,23	0,30	0,50	0,47
	0,43	0,49	0,30	0,33	0,38	0,90	0,22	0,27	0,53	0,40
	0,43	0,45	0,32	0,30	0,36	0,94	0,21	0,28	0,51	0,44
	0,45	0,51	0,32	0,32	0,33	0,88	0,23	0,27	0,49	0,37
	0,44	0,45	0,32	0,34	0,36	0,87	0,25	0,28	0,43	0,40
	0,37	0,47	0,27	0,34	0,45	0,82	0,20	0,28	0,51	0,50
	0,39	0,46	0,26	0,32	0,34	0,94	0,23	0,29	0,45	0,40
TP 5	0,27	0,38	0,23	0,33	0,34	0,83	0,29	0,35	0,55	0,39
HS 2,1	0,27	0,39	0,22	0,36	0,33	1,04	0,26	0,37	0,53	0,41
Gamma 5	0,28	0,39	0,24	0,35	0,36	1,10	0,28	0,42	0,64	0,34
Dir 90	0,29	0,44	0,23	0,33	0,38	1,07	0,27	0,37	0,58	0,44
	0,29	0,42	0,25	0,34	0,34	0,87	0,27	0,38	0,55	0,46
	0,28	0,50	0,24	0,36	0,33	1,19	0,28	0,38	0,64	0,46
	0,30	0,39	0,25	0,32	0,50	0,99	0,26	0,39	0,56	0,41
	0,34	0,36	0,29	0,31	0,41	0,86	0,25	0,38	0,58	0,40
	0,31	0,42	0,26	0,36	0,33	0,94	0,26	0,42	0,55	0,36
	0,30	0,41	0,24	0,32	0,35	0,86	0,26	0,37	0,50	0,47
TP 5,5	0,28	0,36	0,25	0,37	0,31	1,28	0,35	0,46	0,63	0,47
HS 1,4	0,24	0,36	0,23	0,34	0,31	1,21	0,33	0,43	0,59	0,26
Gamma 1,498	0,25	0,36	0,23	0,35	0,30	1,26	0,32	0,41	0,56	0,28
Dir 90	0,24	0,38	0,25	0,34	0,31	1,06	0,30	0,44	0,65	0,31
	0,26	0,38	0,22	0,34	0,31	1,11	0,31	0,45	0,59	0,29
	0,24	0,40	0,21	0,33	0,32	0,95	0,30	0,46	0,55	0,32
	0,26	0,40	0,24	0,36	0,30	1,29	0,33	0,41	0,59	0,30
	0,27	0,35	0,23	0,32	0,30	0,94	0,30	0,47	0,63	0,25
	0,23	0,41	0,22	0,39	0,36	1,18	0,34	0,48	0,67	0,27
	0,28	0,38	0,27	0,36	0,29	1,08	0,33	0,45	0,58	0,26
TP 6	0,22	0,34	0,24	0,30	0,26	0,98	0,29	0,60	0,54	0,29
HS 1,1	0,26	0,33	0,27	0,34	0,29	0,88	0,34	0,56	0,61	0,28
Gamma 1	0,23	0,37	0,24	0,37	0,26	0,85	0,35	0,57	0,55	0,27
Dir 90	0,23	0,36	0,26	0,34	0,27	0,93	0,32	0,58	0,58	0,30
	0,23	0,30	0,23	0,32	0,29	0,94	0,30	0,55	0,59	0,25
	0,22	0,36	0,21	0,35	0,27	1,03	0,32	0,53	0,55	0,28
	0,22	0,34	0,21	0,33	0,25	0,87	0,32	0,51	0,52	0,28
	0,26	0,34	0,25	0,36	0,25	0,86	0,31	0,57	0,58	0,24
	0,25	0,36	0,24	0,38	0,25	1,06	0,32	0,52	0,51	0,29
	0,23	0,36	0,23	0,31	0,27	0,80	0,30	0,65	0,59	0,22
TP 7	0,26	0,38	0,28	0,41	0,29	0,96	0,37	0,81	0,57	0,26
HS 1,0	0,23	0,34	0,26	0,36	0,34	0,94	0,32	0,75	0,78	0,35
Gamma 1	0,22	0,34	0,25	0,35	0,29	0,89	0,36	0,77	0,57	0,25
Dir 90	0,29	0,35	0,31	0,35	0,29	0,82	0,35	1,02	0,55	0,30
	0,25	0,33	0,26	0,32	0,31	0,91	0,31	1,00	0,70	0,28
	0,24	0,35	0,26	0,37	0,27	0,84	0,34	0,83	0,62	0,27
	0,24	0,33	0,25	0,37	0,29	0,78	0,35	0,79	0,69	0,29
	0,24	0,34	0,27	0,37	0,29	0,95	0,34	0,75	0,61	0,25
	0,23	0,35	0,24	0,38	0,26	1,06	0,40	0,83	0,62	0,29
	0,23	0,35	0,27	0,36	0,27	0,92	0,33	0,80	0,61	0,34
TP 8	0,24	0,32	0,26	0,35	0,23	0,76	0,32	1,15	0,59	0,27
HS 0,9	0,24	0,31	0,27	0,34	0,22	0,78	0,33	0,98	0,58	0,24
Gamma 1	0,23	0,29	0,25	0,33	0,22	0,70	0,33	0,96	0,60	0,23
Dir 90	0,24	0,29	0,28	0,33	0,22	0,71	0,31	1,02	0,53	0,23
	0,24	0,30	0,28	0,32	0,23	0,74	0,34	1,10	0,57	0,22
	0,22	0,32	0,25	0,33	0,25	0,72	0,33	1,04	0,57	0,23
	0,25	0,34	0,28	0,39	0,21	1,03	0,36	1,16	0,55	0,38
	0,28	0,37	0,31	0,42	0,26	0,76	0,39	1,06	0,59	0,24
	0,20	0,30	0,22	0,33	0,24	0,72	0,31	1,05	0,57	0,23
	0,26	0,28	0,30	0,32	0,22	0,69	0,31	1,07	0,55	0,25

TP 10	0,22	0,28	0,26	0,35	0,19	0,79	0,41	1,43	0,59	0,20
HS 0,9	0,19	0,26	0,23	0,35	0,20	0,69	0,40	1,32	0,56	0,18
Gamma 1	0,20	0,29	0,24	0,40	0,20	0,70	0,43	1,40	0,59	0,21
Dir 90	0,21	0,25	0,23	0,33	0,21	0,65	0,43	1,06	0,56	0,19
	0,18	0,28	0,20	0,39	0,22	0,65	0,41	1,17	0,67	0,21
	0,21	0,28	0,26	0,35	0,20	0,69	0,44	1,30	0,61	0,18
	0,18	0,27	0,21	0,33	0,19	0,64	0,38	1,23	0,67	0,21
	0,19	0,30	0,23	0,36	0,18	0,65	0,39	1,18	0,56	0,17
	0,18	0,26	0,22	0,36	0,19	0,67	0,47	1,19	0,57	0,16
	0,19	0,26	0,22	0,35	0,19	0,63	0,42	1,15	0,58	0,18
TP 12	0,15	0,22	0,19	0,34	0,17	0,50	0,52	1,06	0,55	0,13
HS 0,9	0,14	0,23	0,20	0,33	0,16	0,49	0,51	1,09	0,64	0,15
Gamma 1	0,15	0,22	0,19	0,35	0,16	0,52	0,53	1,09	0,62	0,15
Dir 90	0,17	0,24	0,21	0,36	0,18	0,61	0,49	1,21	0,58	0,13
	0,13	0,24	0,19	0,33	0,16	0,56	0,51	1,16	0,66	0,14
	0,14	0,24	0,18	0,36	0,16	0,51	0,53	1,24	0,57	0,14
	0,16	0,23	0,20	0,33	0,16	0,52	0,49	1,29	0,60	0,15
	0,15	0,24	0,19	0,34	0,16	0,59	0,51	1,24	0,53	0,14
	0,16	0,27	0,21	0,37	0,15	0,51	0,50	1,33	0,61	0,14
	0,15	0,26	0,19	0,36	0,16	0,47	0,53	1,19	0,59	0,14
TP 14	0,12	0,22	0,18	0,37	0,17	0,48	0,59	1,12	0,59	0,12
HS 0,9	0,11	0,21	0,18	0,36	0,17	0,41	0,61	1,12	0,56	0,11
Gamma 1	0,12	0,21	0,21	0,35	0,18	0,47	0,61	1,07	0,51	0,12
Dir 90	0,12	0,23	0,20	0,37	0,16	0,51	0,66	1,05	0,61	0,13
	0,13	0,22	0,18	0,41	0,20	0,47	0,75	1,12	0,60	0,12
	0,12	0,22	0,18	0,37	0,16	0,39	0,63	1,07	0,54	0,12
	0,12	0,23	0,19	0,35	0,17	0,43	0,58	1,12	0,60	0,10
	0,16	0,21	0,23	0,38	0,17	0,59	0,59	1,09	0,59	0,12
	0,15	0,24	0,22	0,37	0,16	0,45	0,61	1,17	0,57	0,11
	0,13	0,24	0,18	0,37	0,16	0,45	0,61	1,02	0,54	0,13

D4 Initial mating stage

D4.1 Results from; Direction 0 degrees, Wave spreading (n=2, cos function)

Name:	Dimension:
Height of topside	26 m
Distance between barges	62,4 m
Boom angle	48,5°

	HS	Maximum Vertical velocity (Z)	Vertical velocity (P90)	Standard deviation
TP 5	3,40	0,41	0,40	0,02
TP 6	1,9	0,37	0,37	0,02
TP 8	1,30	0,41	0,40	0,03
TP 10	1,10	0,40	0,40	0,02
TP 12	1,00	0,41	0,40	0,02
TP 14	0,90	0,38	0,37	0,02

	Acceleration		Velocity	
	X	Z	X	Z
Req	0,4905	0,981	0,5	0,4
TP 5	0,33	0,45	0,27	0,39
HS 3,4	0,35	0,44	0,28	0,37
Gamma 5	0,32	0,45	0,25	0,36
Dir 0	0,32	0,47	0,27	0,41
	0,33	0,45	0,26	0,34
	0,39	0,45	0,26	0,38
	0,34	0,40	0,27	0,33
	0,33	0,43	0,27	0,36
	0,32	0,43	0,25	0,37
	0,32	0,44	0,27	0,36
TP 6	0,21	0,38	0,20	0,36
HS 1,9	0,21	0,31	0,21	0,32
Gamma 2,105	0,21	0,36	0,20	0,37
Dir 0	0,21	0,34	0,19	0,35
	0,20	0,30	0,20	0,29
	0,22	0,34	0,20	0,33
	0,21	0,34	0,20	0,35
	0,21	0,33	0,20	0,34
	0,22	0,33	0,20	0,33
	0,25	0,36	0,23	0,36
TP 8	0,14	0,30	0,16	0,38
HS 1,3	0,13	0,28	0,15	0,34
Gamma 1	0,14	0,28	0,14	0,32
Dir 0	0,14	0,33	0,15	0,41
	0,13	0,32	0,14	0,41
	0,15	0,29	0,15	0,34
	0,16	0,28	0,16	0,35
	0,14	0,31	0,14	0,37
	0,16	0,27	0,18	0,35
	0,13	0,27	0,14	0,31
TP 10	0,10	0,28	0,12	0,40
HS 1,1	0,14	0,25	0,14	0,38
Gamma 1	0,11	0,23	0,13	0,32
Dir 0	0,11	0,27	0,15	0,37
	0,10	0,26	0,13	0,38
	0,10	0,24	0,14	0,36
	0,10	0,26	0,12	0,35
	0,10	0,26	0,13	0,39
	0,12	0,28	0,15	0,39
	0,11	0,25	0,15	0,37

TP 12	0,11	0,22	0,17	0,37
HS 1	0,10	0,22	0,14	0,37
Gamma 1	0,09	0,23	0,15	0,37
Dir 0	0,14	0,23	0,19	0,37
	0,13	0,25	0,18	0,41
	0,09	0,24	0,14	0,36
	0,10	0,23	0,16	0,38
	0,11	0,24	0,16	0,38
	0,09	0,21	0,17	0,33
	0,12	0,21	0,16	0,33
TP 14	0,09	0,19	0,16	0,35
HS 0,9	0,08	0,18	0,16	0,35
Gamma 1	0,08	0,19	0,16	0,33
Dir 0	0,12	0,19	0,18	0,34
	0,11	0,22	0,17	0,38
	0,08	0,2	0,16	0,35
	0,09	0,19	0,16	0,35
	0,1	0,21	0,16	0,35
	0,09	0,17	0,18	0,31
	0,11	0,17	0,16	0,31

D4.2 Results from; Direction 90 degrees, Wave spreading (n=2, cos function)

Name:	Dimension:
Height of topside	26 m
Distance between barges	62,4 m
Boom angle	48,5°

TP	HS	Maximum Horizontal accelleration (XY)	Horizontal accelleration (P90)	Standard deviation
TP4,5	3,20	0,49	0,49	0,03

	HS	Maximum Vertical velocity (Z)	Vertical velocity (P90)	Standard deviation
TP 5	2,20	0,39	0,38	0,02
TP5,5	1,40	0,41	0,39	0,03
TP 6	1,20	0,40	0,39	0,02
TP 7	0,90	0,36	0,36	0,03
TP 8	0,90	0,42	0,39	0,03

	Acceleration		Velocity	
	XY	Z	XY	Z
TP 4,5	0,45	0,55	0,33	0,32
HS 3,2	0,43	0,45	0,32	0,32
Gamma 5	0,41	0,50	0,32	0,36
Dir 90	0,47	0,47	0,34	0,30
	0,48	0,47	0,36	0,30
	0,49	0,48	0,34	0,30
	0,46	0,47	0,34	0,31
	0,48	0,49	0,31	0,34
	0,48	0,47	0,34	0,33
	0,43	0,53	0,33	0,42
TP 5	0,30	0,35	0,25	0,32
HS 2,2	0,34	0,42	0,27	0,35
Gamma 5	0,32	0,37	0,25	0,34
Dir 90	0,30	0,40	0,27	0,32
	0,30	0,40	0,24	0,36
	0,30	0,41	0,26	0,39
	0,32	0,45	0,25	0,36
	0,31	0,40	0,28	0,34
	0,31	0,41	0,24	0,36
	0,29	0,44	0,25	0,35
TP 5,5	0,23	0,39	0,22	0,36
HS 1,4	0,22	0,37	0,20	0,36
Gamma 1	0,25	0,36	0,23	0,31
Dir 90	0,22	0,38	0,20	0,37
	0,24	0,36	0,23	0,34
	0,24	0,38	0,21	0,41
	0,23	0,36	0,22	0,34
	0,22	0,38	0,22	0,34
	0,23	0,39	0,22	0,33
	0,24	0,37	0,22	0,36
TP 6	0,24	0,35	0,24	0,36
HS 1,2	0,26	0,35	0,26	0,36
Gamma 1	0,25	0,37	0,29	0,39
Dir 90	0,24	0,38	0,24	0,39
	0,23	0,38	0,26	0,40
	0,22	0,35	0,22	0,35
	0,23	0,35	0,24	0,36
	0,21	0,37	0,22	0,37
	0,24	0,36	0,25	0,35
	0,24	0,34	0,24	0,34

TP 7	0,22	0,32	0,26	0,36
HS 0,9	0,18	0,28	0,21	0,30
Gamma 1	0,19	0,30	0,22	0,31
Dir 90	0,20	0,28	0,23	0,31
	0,22	0,32	0,24	0,35
	0,22	0,29	0,23	0,30
	0,20	0,34	0,22	0,35
	0,21	0,34	0,22	0,35
	0,19	0,32	0,21	0,34
	0,21	0,27	0,24	0,29
TP 8	0,22	0,29	0,25	0,32
HS 0,9	0,24	0,29	0,26	0,31
Gamma 1	0,21	0,29	0,23	0,34
Dir 90	0,23	0,29	0,26	0,33
	0,23	0,33	0,26	0,36
	0,21	0,28	0,24	0,33
	0,24	0,38	0,28	0,42
	0,22	0,31	0,26	0,35
	0,19	0,29	0,22	0,34
	0,22	0,33	0,24	0,37

Appendix E Extract from DNV - OS - H101 , October 2011 P34 - p35

C. Weather Forecast

C 200 Weather forecast levels

201 Based on evaluations of the operational sensitivity to weather conditions and the operation reference period (TR), a categorisation of the operation into weather forecast levels A, B or C shall be made.

202 Level A - Weather forecast level A applies to major marine operations sensitive to environmental
conditions. Typical "level A" operations may be;
— mating operations,
— offshore float over,
— multi barge towing,
— GBS tow out operations,
— offshore installation operations, and
— jack-up rig moves.

Table 4-3 α-factor for waves, Level A with meteorologist at site

Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 12$	0.72	Linear Interpolation	0.84	Linear Interpolation	0.87	Linear Interpolation	0.88
$T_{POP} \leq 24$	0.69		0.80		0.84		0.86
$T_{POP} \leq 36$	0.68		0.78		0.80		0.84
$T_{POP} \leq 48$	0.66		0.75		0.78		0.81
$T_{POP} \leq 72$	0.61		0.69		0.75		0.79

Table 4-5 α-factor for waves, monitoring & Level A with meteorologist

Operational Period [h]	*Design Wave Height [m]*						
	$H_s = 1$	$1 < H_s < 2$	$H_s = 2$	$2 < H_s < 4$	$H_s = 4$	$4 < H_s < 6$	$H_s \geq 6$
$T_{POP} \leq 4$	0.9	Linear Inter-polation	0.95	Linear Inter-polation	1.0	Linear Inter-polation	1.0
$T_{POP} \leq 12$	0.78		0.91		0.95		0.96
$T_{POP} \leq 24$	0.72		0.84		0.87		0.90
$T_{POP} > 24$	According to Table 4-3						

Table 4-7 Weather forecast levels

Weather Forecast Level	*Meteorologist required on site?*	*Independent WF sources*	*Maximum WF interval*
A	Yes[1)]	2[2)]	12 hours[3)]
B	No[4)]	2[5)]	12 hours
C	No	1	12 hours

1) There should be a dedicated meteorologist, but it may be acceptable that he/she is not physically present at site. The meteorologist opinion regarding his preferable location should be duly considered. It is anyhow mandatory that the dedicated meteorologist has continuous access to weather information from the site and that he/she is familiar with any local phenomena that may influence the weather conditions. Note also that the meteorologist shall be on site in order to use alpha factors from Table 4-3 and Table 4-5.

2) It is assumed that the dedicated meteorologist (and other involved key personnel) will consider weather information/forecasts from several (all available) sources.

3) Based on sensitivity with regards to weather conditions smaller intervals may be required. However, see 305.

4) Meteorologist shall be conferred if the weather situation is unstable and/or close to the defined limit.

5) The most severe weather forecast to be used.

Independence between weather forecast sources is satisfied if there are organisational independence between the sources, i.e. it is acceptable to obtain the forecasts from a national and a local source (relevant for the actual area).