Global Response Analysis of Wind Turbine Installation Vessels in Semi-submerged Condition. A Modified Quasi-Static Approach

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Szczecin, February 2016

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Where I have consulted the published work of others, this is always clearly attributed.

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ABSTRACT

Wind Turbine Installation Vessels (WTIV) have a significant importance for the installation and maintenance of offshore wind farms. For a range of water depth, wind turbines will require a fixed foundation which can be installed with a jack up vessel. Jack up leg and jacking system design had been traditionally governed around consideration of the fully elevated condition, called also as survival condition.

Industry, nonetheless, had seen various leg and jacking system damages happening in transient phases (more often during semi-submerged condition) whether elevating or lowering legs for installation or maintenance duties at the required locations. The semi-submerged condition is a geometrical configuration where legs are attached to the seabed with a specific leg penetration and with the hull partially immersed. During this condition the exposure to wave loads, current loads, wind, and soil-leg interaction exposes the structure to high non-linear effects which worsen with large hull drifts, structure flexibility and dynamic effects.

Such conditions are not commonly covered by class societies or well acknowledged by designers. This transient phase is important for the vessel operation and depending on the environmental conditions it will be possible to become the governing design load case for some elements of the leg, jack up system, or other vessel components.

Knowing the global behave of the structure and the stress distribution during such conditions will allow the preparation of better designs, so analysis should be dedicated and delicately performed. To demonstrate the importance and risk associated, a study for the global response of WTIV in semi-submerged condition is performed characterizing the global behave of the structure and comparing it against the common design load case, the survival condition in extreme response.

A simplified structural model of a WTIV is used. Subsequently a CFD Hydrodynamic analysis coupled with a FE solver is performed to verify load increments during exposure to different sea states in the conditions mentioned. The analysis proposed is a Deterministic Linear Quasi-Static analysis where dynamic effects are modelled by modifying the FE model with additional inertial loads acting on the hull center.

Inertial wave loads acting on the body are determined by Potential Flow Theory solving the diffractive potential. Pressure distribution around the hull is calculated applying Panel Method with direct numerical integration over the surface. Additionally, Morison formulation is used to determine drag forces acting on the legs and later applied and solved on the FE model. Current profile is modelled as a constant of 5 m/s along the sea bed, used for drag linearization.

Different geometrical configurations of the semi-submerged condition are investigated by varying the water depth. The structure response is characterized: verifying the dynamic effects of the structure for the semi-submerged condition, comparing the structure response against the survival condition, varying the percentage of weight carried by the legs during the transient phase. Cases are evaluated and reported where hull displacements, base shear, vertical forces and overturning moment are reported for every case.

The study resulted in some interesting findings and discernments. It is uncovered that the semisubmersible condition represents a high risk operational condition that should be considered during the vessel design to reduce operational risk.

1 INTRODUCTION

This document has the purpose to present the research project performed regarding the Global Response Analysis of Wind Turbine Installation Units in semi-submerged condition. In this chapter, a description of the problem being studied as well as the main aim and scope of the study is given.

For a brief introduction to the subject, general information and other relevant for the study is presented in the Chapter 3.

1.1 The Problem

Since structural assessment of wind turbine installation vessels during semi-submerged condition are not commonly covered by class requirement or either well documented by designers, and considering that the industry had seen numerous leg and jacking system damages occurring in transient phases mainly during the semi-submerged condition, it is necessary to study the global response of such units to guarantee safety during operation and to understand and measure the risks that the industry may face.

Supposing a unit on a specific location for purposes of wind turbine equipment installation or other similar operation. As a transient phase, legs are supported on the seabed and the hull is in semi-jacked position, i.e. it remains partly submerged. There are two reasons why the unit is in such condition. One is related to temporary phase during jacking-up of unit and second it is related to units operation in limited soil bearing capacity condition.

This requires that when modeling, combined environmental and operational loads should be within adequate design limits, established for such operation.

Wave induced loads on the hull are expected to be dominating when considering the global response magnitudes, dependent also on the hull immersion level. This implies that special attention should be given for wave induced load calculation.

1.2 Objective

The aim of the analysis is to verify these design limits against safety of the Unit during the Semi-submerged condition and compared it against the common design load case for such vessels called, survival or elevated condition.

The general purpose of the project is to find the best way of analyzing the semi-jacked condition with application of a hydrodynamic software coupled with a FEM software. As secondary goal, the global characterization of the structure behave under environmental loading in such operational conditions is a matter of special concern. This is expected to be solved considering the output from the analysis compelling the various loads acting on the unit's structure (mainly in the hull and legs) such as:

- Total resultant base shear force and vertical loads in the global model and in each leg.
- Total overturning bending moment in the global model and in each leg.
- Hull motions RAO's.

1.3 Scope of Work

The study proposed in this document is a deterministic, modified linear quasi-static approach for global dynamic response characterization. For this type of analysis, assumptions have been taken for hydrodynamic load modelling, strength assessment and dynamic response characterization. The scope of each of this activities are mentioning below.

Modelling of Hydrodynamic loads is divided in Inertial and drag load calculations. In case of inertial load modelling for large bodies:

- Inertial forces are determined using Potential flow in combination with diffractive wave with direct numerical integration in frequency domain to determine the pressure distribution on the hull surface.
- First order velocity potential is used to determine the linear wave loads. I.e. non-linear wave is not considered in this study so higher harmonics to the first order are neglected.

In the case of the drag force modelling for small bodies:

- Drag forces are determined using Morison formulation solved with the wave kinematics determined with the diffractive potential. Drag coefficients are assumed for the leg cross section considered.
- Current loads are modeled considering a constant current velocity of 5 m/s for drag linearization of the Morison equation. No current profile is considered.

Modelling of large bodies with considerable drag effect.

- Under the presence of large bodies with non-negligible drag forces, inertial loads are calculated by Potential flow Theory and separately Morison formulation is used to determine drag forces on such bodies considering the characteristic length and wave kinematics from the diffractive potential. I.e. superposition of both effects is applied to determine the loads on such bodies to correct forces, damping and added mass matrices.

Strength calculation by FE method.

- A Quasi-static structural analysis is used to solve the FE model.
- To account the dynamic effects when significant (frequency encounter), P-Delta Effect and Ship drift due to environmental loading, Dynamic Amplification Factors (DAF) are used to determine the load increments when needed. Further explanation is found in the points 2.7 and chapter 4 of this section.
- Principal structural elements are modeled using 4-node shell elements. Longitudinal and transversal bulkheads, girders and hull shell are modeled in such way.
- Secondary structural elements are modeled with 2-node beam elements. Stiffeners and leg-columns are modeled in this way.
- Foundation models for soil-leg interaction are not considered. Instead, boundary conditions in legs are assumed to be pinned with a leg penetration of 5 m. Soil stiffness influence on dynamic response is determined varying the leg fixation coefficients.

2 THE STUDY OF OFFSHORE WIND TURBINE INSTALLATION VESSELS

2.1 Offshore Wind Turbine Industry

Relevant concepts for the understanding of the physical problem are explained in this chapter. It is presented a brief introduction to the offshore wind turbine industry as well as an explanation regarding to the type of turbines that can be installed and the vessels required for such activities.

Offshore industry represents nowadays one of the toughest activities that Engineers have been dealing with since early years of 1940. The activities of this industrial sector primarily comprise two industry variants known as offshore oil and gas industry and, the offshore wind energy industry.

Offshore industry began with the purpose of meet the increasing energy demand, for which it had been forced to grow faster and faster in the coming years. However this represents a beneficial point for companies due to the rising cost of energy worldwide.

With the develop of the industry, issues had been perceived the last century concerning the world contamination and climate changes accredited mainly to the oil and gas business. As a possible alternative to decrease such worsening, wind energy appears as a really feasible solution.

Today it is considered as one of the most well-known green energy sources, which is second only after to the hydroelectric generation. Besides onshore wind energy is well developed, the lack of open fields and their costs, and the need of certain weather conditions push the industry on the search of better conditions for green energy production.

Here is when offshore wind farms rise up with operations growing rapidly the last years in all over the world, but nowadays requirements for equipment are more demanding to guarantee a bigger generation capacity. This means that bigger ships and platforms for wind turbine installation and maintenance are required.

In the European context, the EU 2020 Goal indicates that the EU must get 20% of its energy from renewables, reduce its greenhouse emissions by 20% and its energy consumption by 20% by increase the energy efficiency.

Offshore wind operations will increase significantly up to the 2020 but safety during operation must be guarantee, where one of key issues is the in-service stability. A typical solution for this problem is to elevate the units above the water sea level.

Some equipment's designed specifically to perform such kind of task are the called Wind Turbine Installation Units (WTIU) and the thesis proposed in this document will study this type of equipment operating in certain conditions.

2.2 Wind Turbine Installation Units

In this section main concepts required for the understanding of the work presented are given. Explanation about equipment and their components, types of equipment's, design conditions, operational conditions and key aspects for wind turbine installation unit design are given.

2.2.1 Types of Offshore Wind Turbines

Offshore wind turbines are classified by the type of the foundation, which are fixed foundation and floating foundation. The main factor that determines which type of foundation is the depth of the sea bed where operations are interested to be developed. The different types of offshore wind foundations are shown in the figure 1.

For the fixed foundation, the most common type is the monopile which is costless and easier for installation, followed by tripod and jacket. Floating foundations are employed when water depths increase significantly making fixed foundation not feasible in the structural and economical point of view.

After foundation is located in de site of installation, the next stage corresponds to the assembling of the turbine. Depending of the foundation of the wind turbine either jack up or semi submerged wind turbine installation units (WTIU) can be used to perform such activity. Since the present document is focus on jack up installation units, further explanation is given just for this WTIU.

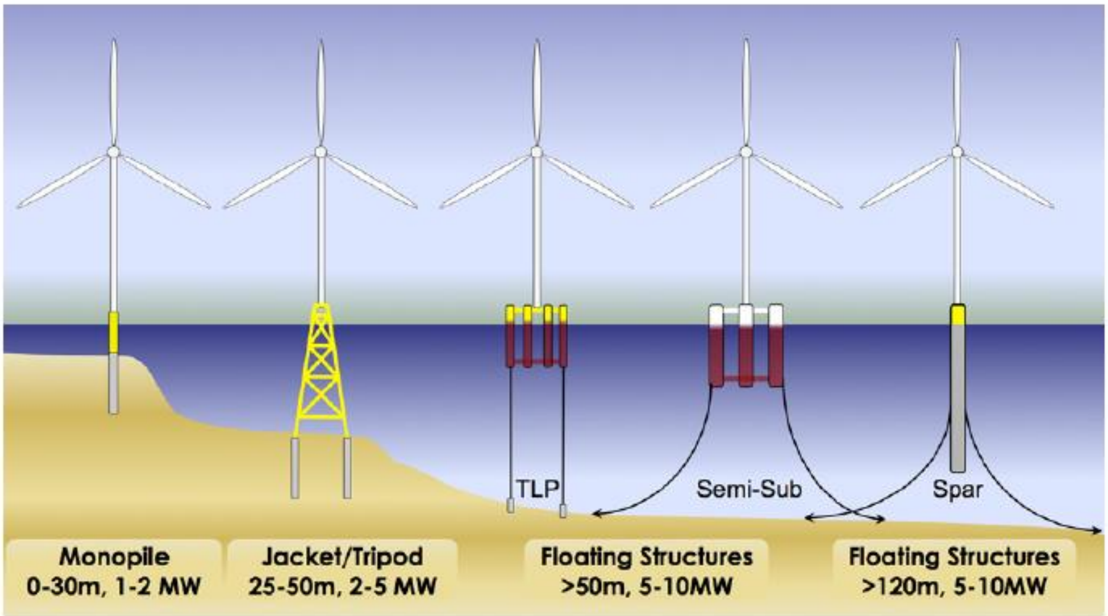


Figure 1. Types on Offshore Wind Turbines & application according to the water depth. http://www.rya.org.uk/SiteCollectionImages/environment/FloatingTurbineStructuresweb.jpg

2.2.2 Jack-Up Wind Turbine Installation Unit (WTIU)

A Jack up WTIU, is a self-elevating unit or jack-up vessel which dispose a hull with sufficient buoyancy to transport the unit (turbine) to the desired location, and that is bottom founded in its operation mode.

The unit reaches its operation mode by lowering the legs to the seabed and then jacking the hull to the required elevation. This type of vessel is used for the turbine installations where water depths are not bigger than 50 / 60 m.

The listed maximum operating water depth is a usually a nominal value as the actual limiting depth for each deployment will depend upon the installed leg length, the leg penetration in the sea bed, the minimum safe air gap and the required operating air gap. This can only be defined by the site-specific assessment for each location and the results of the assessment will determine whether installation and operation of the jack-up is feasible and whether any operating constraints or weather restrictions will apply which might affect the efficiency of the operation.

- The hull and its appendages: gives the buoyancy to the hull structure when other condition different than installing operational condition.
- Accommodation block and major deckhouses for vessel crew.
- Helideck and support structure for helicopter landing (optional)
- Main lifting equipment (Crane) and Crane pedestal for wind turbine component handling and installation.

Figure 2. Overview of a WTIU

http://www.swireblueocean.com/files/pdf/sbo_technical_specs_may_2013.pdf

The components of WTIU can be mainly listed as follows:

- Legs for structure vertical supporting during installing condition.
- Footings/spudcans: inverted cones mounted at the base of the legs which provide stability to lateral forces when WTIU is deployed into ocean-bed systems.
- Jacking system: system used to raise the entire Hull/barge above the water to a predetermined height leaving an "air gap" sufficient enough to guarantee waves, tidal and current loading acts only on the legs and not on hull

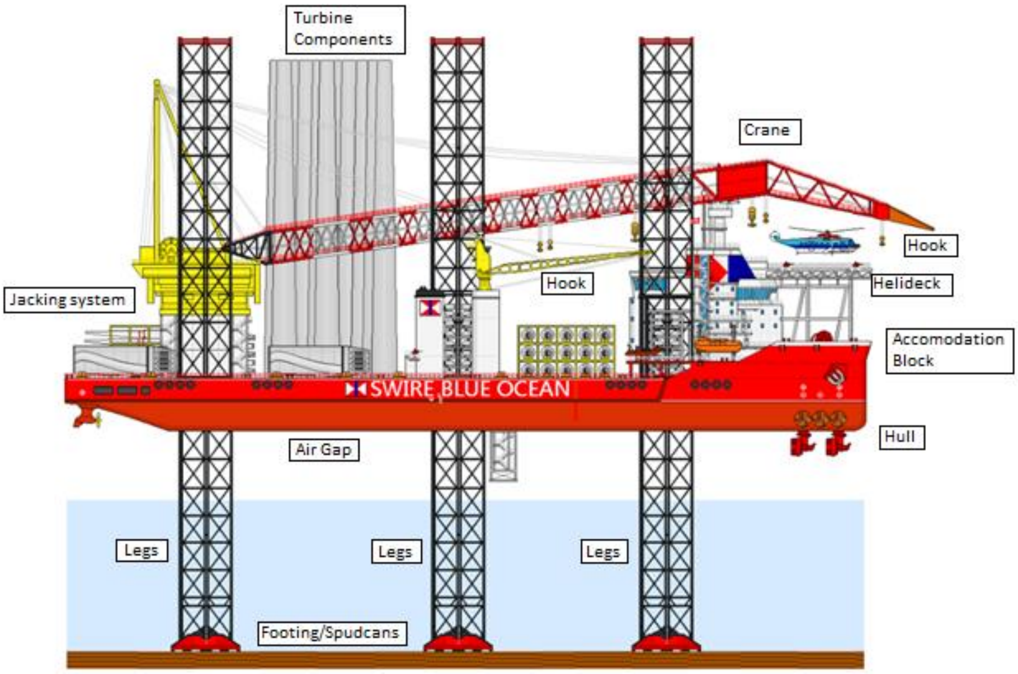


Figure 3. WTIU components

http://www.swireblueocean.com/files/pdf/sbo_technical_specs_may_2013.pdf

Figure 4. Wind Turbine Installation in Elevated Condition.

http://www.renewableuk.com/objects_store/offshore_wind_installation.jpg

2.2.3 Operational conditions of WTIU

Operating conditions are defined as the scenarios to which the WTIU may be exposed. Depending of the reference, the definition of these scenarios may vary so it is recommended when performing designing of such equipment, to consult how the operational conditions are defined.

The following concepts regarding to operational conditions of WTIU are taken directly from the *standard DNV OS-C104 standard.*

- *Installation condition: A condition during which a unit is lowering the legs and elevating the hull. This is also known as Jacking-up condition*
- *Operating conditions: Conditions wherein a unit is on location for purposes of drilling lifting, or other similar operations, and combined environmental and operational loadings are within the appropriate design limits established for such operations. The unit is supported on the seabed.*
- *Retrieval conditions: Conditions during which a unit is lowering the hull and elevating the legs.*
- *Semi-Jacked Condition: legs are supported on the seabed and the hull is in semi-jacked position, i.e. it remains partly submerged. This may happen during jacking-up of unit or when units operate in limited soil bearing capacity condition.*
- *Survival conditions: Conditions wherein a unit is on location subjected to the most severe environmental loadings for which the unit is designed. Drilling or similar operations may have been discontinued due to the severity of the environmental loadings. The unit is supported on the seabed.*
- *Transportation or transit conditions: All unit movements from one geographical location to another.*
- *Field move: A wet transit that would require no more than a 12-hour voyage to a location where the unit could be elevated, or to a protected location.*
- *Ocean transit: A wet transit that would require more than a 12-hour voyage to a location where the unit could be elevated, or to a protected location.*
- *Dry transit: A transit where the unit is transported on a heavy lift unit.*
- *Wet transit: A transit where the unit is floating during the move.*

The operation of the WTIU can be described following the sequence presented below. Once the unit arrives to the installation area, once equilibrium is reached in terms of hydrostatic, legs starts to descend until they reach the sea bottom. At this point the legs go over the sea bottom until a specific depth to guarantee the support of the unit is reached. Then vessel/platform will start to rise until minimum air gap is guarantee for the operation.

Figure 5. In-service WTIU

http://www.offshorewind.biz/tag/anholt/page/10/

http://www.kis-orca.eu/renewable-energy/wind-farms/installation-methods-practices#.VYldQfmqqko

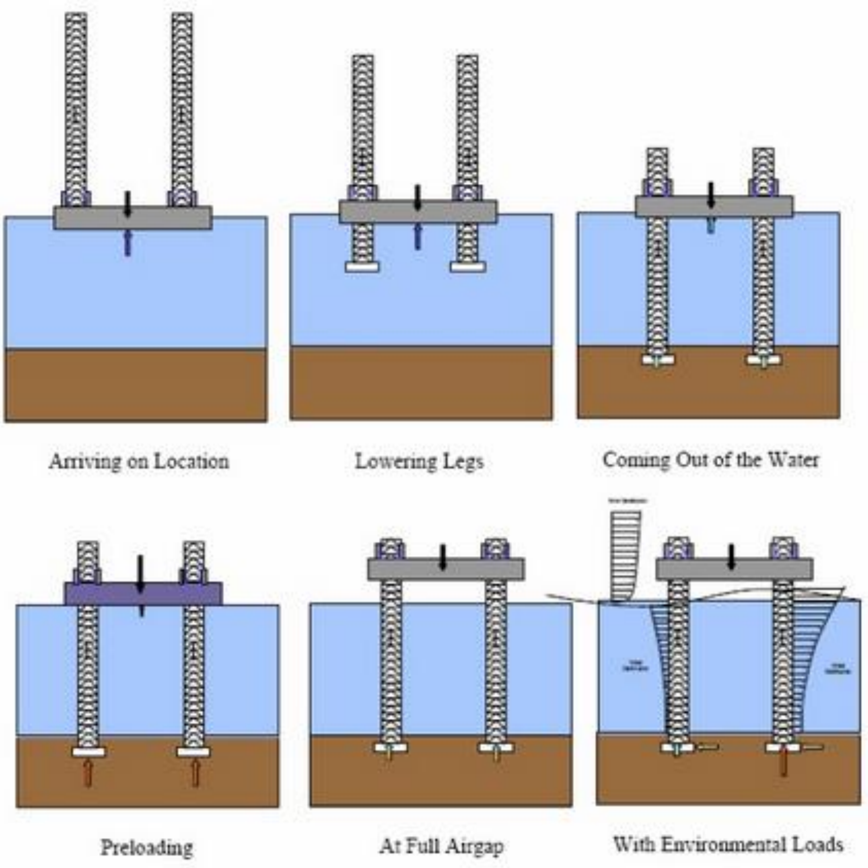


Figure 6. Operation of WTIU

http://www.modec.com/about/industry/oil_gas.html

2.3 The Global Response Analysis

A study aimed to determine how the various loads are distributed into the structure so motion and structural behave can be determined. Depending of the operational condition, load distribution will be different so special attention should be taken to identify the governing case for the design.

An accurate structural analysis must include realistic models of the wave loading, the geometrically non-linear behavior of the slender legs, and the complex non-linear response of the spudcan footings to combined loads. The lateral flexibility is also pending on the moment restraint at the connection between the leg footing and the soil foundations.

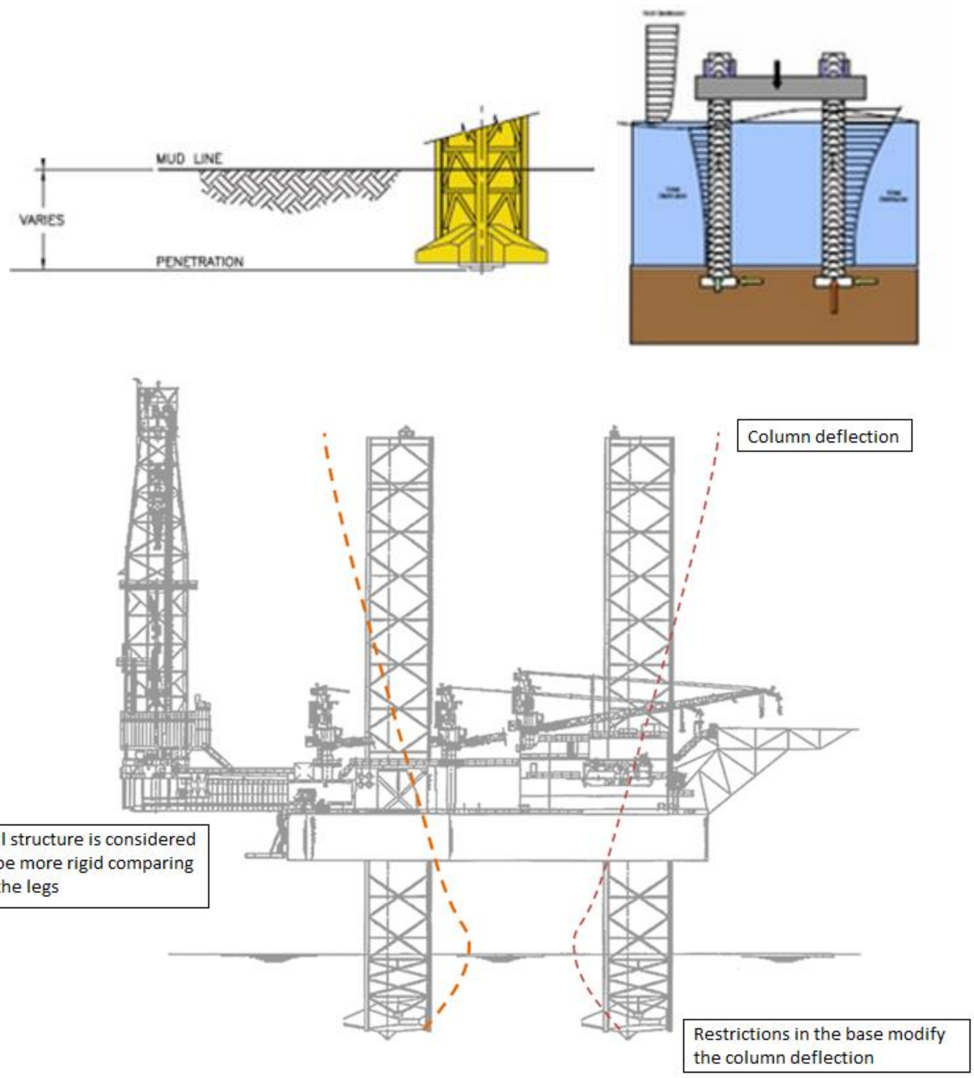


Figure 7. Environmental load effects during elevated condition. http://www.modec.com/about/industry/oil_gas.html and http://maritime-connector.com/wiki/offshore-industry/

Because jack-up rigs are flexible, dynamic effects are significant. A dynamic analysis is therefore required and, because of the numerous non-linear effects presented; this must be carried out by direct integration of the equations of motion in the time domain and/or frequency domain.

Since dynamic effects are significant and while the structure will typically be subjected to higher non-linear effects caused by large hull sway and more dynamic actions due to higher natural periods coinciding with or closer to the wave periods added to the flexibility of the structure, global response analysis is an important, dedicated and delicate task to perform.

We are interested in determine the global response of the structure for different operational conditions that are defined in the point 3.2.2. Main parameters of such type of analysis are:

- Displacement of spudcans
- Displacement of hull
- Moment in leg base
- Vertical and horizontal forces in legs
- Multibody hydrodynamic, interaction and motion

The application of a Global Response Analysis implies the usage of methodologies to perform the structural design. When the loads that are acting on the structure are defined, LRFD and WSD methods are the most common used in the industry in combination with Finite Element Methods (FEM). Now, methodologies for structural design are briefly explained below making reference to the document DNV – OS C104 and C201 and DNV-RP C104 and C205.

LRFD: Load Resistance design factor method also known as limit state design method (LSD), is a design methodology by which the target safety level is obtained as closely as possible by applying load and resistance factors to characteristic reference values of the basic variables defined as:

- Loads acting on the structure
- Resistance of the structure or resistance of materials in the structure.

Depending of the design considerations and regulations, limit states can be defined and considered in the study of WTIU. Some of them are listed below considering DNV RP-C104 standard.

- Ultimate Limit States (ULS) corresponding to the ultimate resistance for carrying loads
- Fatigue Limit States (FLS) related to the possibility of failure due to the effect of cyclic loading
- Accidental Limit States (ALS) corresponding to damage to components due to an accidental event or operational failure

WSD: means working stress design (WSD) method also known as the allowable stress method. This method is based in obtain the component safety level by checking the strength usage factors against permissible usage factors. Generally, the design of a structural system, its components and details should account the following principles:

- Resistance against relevant mechanical, physical and chemical deterioration is achieved
- Fabrication and construction comply with relevant, recognized techniques and practice
- Inspection, maintenance and repair are possible.

In the same way as the LRFD method, depending of the design considerations and regulations, loading cases can be defined and some of them might slightly differ from one reference to another. According to the DNV RP-C104, the load cases for this design methodology are:

- Functional loads
- Maximum combination of environmental loads and associated functional loads
- Accidental loads and associated functional loads
- Annual most probable value of environmental loads and associated functional loads after credible failures or after accidental events
- Annual most probable value of environmental loads and associated functional loads in a heeled condition

2.4 Loads Acting On WTIU

Loads acting on the platform can be classified depending of their source, time of application and effect on the structure (elastic or plastic behave of the structure). Following the DNV OS-C104 standard as a reference, loads acting on WTIU can be classified as:

- Permanent loads: loads that will not vary in magnitude, position, or direction during the period considered and include:

  - Lightweight' of the unit, including mass of permanently installed modules and equipment, such as accommodation, helicopter deck, drilling and production equipment
  - Permanent ballast
  - Hydrostatic pressures resulting from buoyancy
  - Pretension in respect to drilling and production systems (e.g. Risers, etc.).
- Variable functional loads Variable functional loads are loads that may vary in magnitude, position and direction during the period under consideration. This are the main source of fatigue damage on the structure and some examples of such loads may be:
  - Drilling, production, and combinations
  - Consumable re-supply procedures
  - Maintenance procedures
  - Possible mass re-distributions in extreme conditions
- Accidental loads: it's related to loads linked to accidents. In this way loads usually considered during design stage are:
  - Collision
  - Dropped objects (e.g. From crane handling)
  - Fire
  - Explosion
  - Unintended flooding during transit.
- Deformation loads: loads caused by inflicted deformations, such as temperature loads, built-in deformations, etc.
- Environmental loads: are loads which may vary in magnitude, position and direction during the period under consideration, and which are related to operations and normal use of the installation. These are one the most important group of loads for the design and this group is mainly characterized by
  - Hydrodynamic loads induced by waves and current.
  - Inertia forces.
  - Wind loads.
  - Earthquake.
  - Tidal effects.
  - Marine growth.

- Snow and ice.
- Combination of previous loads acting on supporting structures and lashing systems for rigid units of cargo, equipment or other structural components.

Supposing that risks regarding to accidents are low and enough fatigue life of the structure is given, the design of the structure may be governed by the combination of permanent and variable loads and environmental loads. Since environmental loads are hard to define since is a variable that cannot be controlled special considerations are taken to determine their effect on structures.

Some considerations are mentioned in the document DNV OS-C101 standard regarding to how environmental loads should be calculated. Some of the points that can be mentioned are the following.

> *"The design of mobile offshore units shall be based on the most severe environmental loads that the structure may experience during its design life. The applied environmental conditions shall be defined in the design basis or design brief, and stated in the unit's Operation Manual… The North Atlantic scatter diagram should be used in ULS, ALS and FLS for unrestricted worldwide operation…The analysis of the data shall be based on the longest possible time period for the relevant area. In the case of short time series the statistical uncertainty shall be accounted for when determining design values. Hindcasting may be used to extend measured time series, or to interpolate to places where measured data have not been collected. If hindcasting is used, the model shall be calibrated against measured data, to ensure that the hindcast results comply with available measured data."*

From all the environmental loads, hydrodynamic loads induced by wave and current as well as wave loads, wind loads and tidal effects are commonly hard tasks to perform so special attention should be considered when design is performed.

This means that special models and methodologies should be used for load estimation but it will depend on the references and credibility of the models used, how loads are characterized. For example, DNV OS-C101 and C205 present some considerations regarding to some parameters:

For hydrodynamic loads induced by waves and current

- Hydrodynamic loads shall be determined by analysis. When theoretical predictions are subjected to significant uncertainties, theoretical calculations shall be supported by model tests or full scale measurements of existing structures or by a combination of such tests and full scale measurements.
- Hydrodynamic model tests should be carried out to:
    - Confirm that no important hydrodynamic feature has been overlooked by varying the wave parameters (for new types of installations, environmental conditions, adjacent structure, etc.)
    - Theoretical calculations should be supported when available analytical methods are susceptible to large uncertainties.
    - Verify theoretical methods on a general basis.
    - Wind tunnel test should be carried out if wind loads are significant for overall stability, offset, motions or structural response.
- For wave loads on structures:
    - Wave theory or kinematics shall be selected according to recognized methods with due consideration of actual water depth and description of wave kinematics at the surface and the water column below.
    - Linearized wave theories, e.g. Airy, may be used when appropriate. In such circumstances the influence of finite amplitude waves shall be taken into consideration.
    - For slender structures (typically chords and bracings, tendons, risers) where the Morison equation is applicable, the wave loads should be estimated by selection of drag and inertia coefficients depending of the case considered.
    - In the case of large volume structures disturbing the free field wave kinematics, the presence of the adjacent structures may be considered by radiation and diffraction analyses for calculation of the wave kinematics, wave loads, excitation forces or pressure.

Further information is supplied in the documents mentioned before as it is the case for the calculation of inertia forces, forces due to wind, earthquake, tidal effects, marine growth, snow and ice.

After the loads are defined, global response analysis of the structure can be performed. Since it is interested that structure remain in an equilibrium condition without significant displacements, equilibrium studies are also performed for different operative conditions where the main interest is determine the minimum overturning moment on the legs of the WTIU.

2.5 Rules and standards for WTIU Design

In this section a brief overview of the relevant standards consulted for WTIU design are given. Moreover, it is considered as a main reference due to its recognition in the industry the DNV GL recommended practices and offshore standards, as well as other relevant documents.

2.5.1 DNV RP C104 - Self-Elevating Units

Presents recommendations for the strength analyses of main structures of self-elevating units. It refers to 2 safety formats of analysis: LRFD (Load and Resistance Factor Design method) and the WSD (Working Stress Design method).

2.5.2 DNV RP C205 - Environmental Conditions and Environmental Loads

Gives guidance for modelling, analysis and prediction of environmental conditions as well guidance for calculating environmental loads acting on structures. The loads are limited to those due to wind, wave and current. The RP is based on state of the art within modelling and analysis of environmental conditions and loads and technical developments in recent R&D projects, as well as design experience from recent and ongoing projects.

2.5.3 DNV OS C101- Design of Offshore Steel Structures, General (LRFD Method)

Provide principles, technical requirements and guidance for the structural design of offshore structures considering the LRFD method. The standard is applicable to all types of offshore structures of steel. The standard is applicable to the design of complete structures including substructures, topside structures, vessel hulls and foundations.

2.5.4 DNV OS C104 - Structural Design of Self-Elevating units (LRFD Method)

Provides principles, technical requirements and guidance for the design and construction of self-elevating units, which can also be applied to all types of self-elevating units constructed in steel. The study proposed in this document is based on the load and resistance factor design (LRFD).

2.5.5 DNV OS C201 - Structural Design of Offshore Units (WSD Method)

Provides principles, technical requirements and guidance for the structural design of offshore structures considering the WSD method. The standard is applicable to all types of offshore structures of steel. The standard is applicable to the design of complete structures including substructures, topside structures, vessel hulls and foundations. Examples of application are column-stabilized units, self-elevating units, tension leg platforms and/or deep draught floaters.

2.5.6 DNV OS C205 - Environmental Conditions and Environmental Loads

Gives guidance for modelling, analysis and prediction of environmental conditions as well guidance for calculating environmental loads acting on structures. The loads are limited to those due to wind, wave and current. The document is based on state of the art within modelling and analysis of environmental conditions and loads and technical developments in recent R&D projects, as well as design experience from recent and ongoing projects. The scope of the document is focused in determining the following loads: wind, waves, current and tides.

2.5.7 DNV OS J301 - Wind Turbine Installation Units

This standard provides principles, technical requirements and guidance for the design and construction of units built to satisfy the service notation “Wind Turbine Installation Unit”. This standard is in principle applicable to all types of wind turbine installation units including, but not limited to, the following variants: self-elevating units, column stabilized units. Additionally, Structural design covering marine operation sequences is not covered in this standard and shall be undertaken in accordance with the requirements stated in DNV-OS-H101 “Marine Operations, General” and DNV-OS-H102 “Marine Operations, Design and Fabrication”.

2.5.8 API RP 2A-WS - Planning, Designing, and Constructing Fixed Offshore Platforms- Working Stress Design

Serves as a guide for those who are concerned with the design and construction of new fixed offshore platforms and for the relocation of existing platforms used for the drilling, development, production, and storage of hydrocarbons in offshore areas. The scope of the document is focused on Planning, design criteria's, structural design, fatigue, foundation design, and accidental loads, fabrication, installation and inspection requirements.

2.6 Analysis Methods

Considering the document DNV RP C104 section 4.4, a series of recommended analysis are presented which can be used to characterize the response of self-elevated units in the elevated condition. A brief explanation of such methods is presented below.
The equations to be solved to perform a response analysis are:

Dynamic Equation

$$m\,\ddot{r} + c\,\dot{r} + k\,r = F \qquad \textbf{(1)}$$

$$F = c_d(v - \dot{r})|v - \dot{r}| + c_d\,a + c_m(a\,\ddot{r}) \qquad \textbf{(2)}$$

Linearized Dynamic Equation

$$(m + c_m)\ddot{r} + (c_l + c_{dl})\dot{r} + k_l r = F_l \qquad \textbf{(3)}$$

Where,

- m = mass of the structure
- c = global damping, c=c(r)
- k = stiffness, k=k(r)
- r = displacement of the structure
- $\dot{r}$ = velocity of the structure
- $\ddot{r}$ = acceleration of the structure
- a = acceleration of the fluid
- v = velocity of the fluid
- c_d = drag force coefficient
- c_f = froud krilov force coefficient

c_m = added mass

F_l $= c_{dl} + c_i\, a$

c_i $= c_f + c_m$

c_{dl} $= c_d(v-\dot{r})_{ref}$ for linearization by relative velocity

$= c_d\sqrt{(8/\pi)}\sigma_{v-\dot{r}}$ for linearization by standard deviation

$\sigma_{v-\dot{r}}$ $=\sqrt{\sigma_v{}^2 + \sigma_{\dot{r}}{}^2 - 2\sigma_{\dot{r}v}}$

σ_v =standard deviation of fluid velocity

σ_r =standard deviation of displacement of the structure.

c_l , k_l = linearized damping and stiffness.

Figure 8shows the methods hierarchy, where the ones located at the top offer better realistic results for the problems studied in terms of conservatism. I.e. method A will be less conservative than the methods B, C, D, E and F.

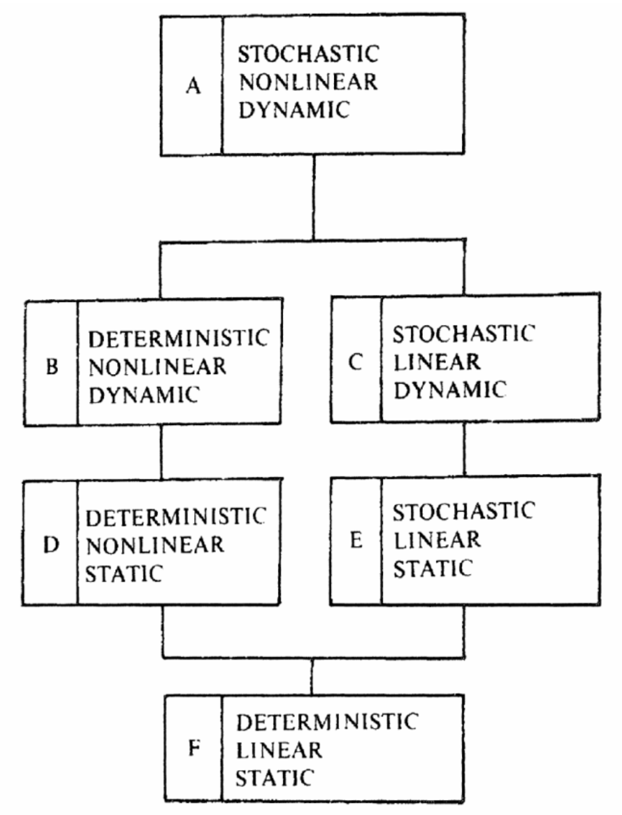


Figure 8. Methods for response analysis, DNV GL RP C104 Figure 4-4

2.6.1 Method A. Stochastic Non-Linear Dynamic Analysis

Method A is the most comprehensive of the methods. In principle it is possible to account for all of the special effects mentioned above. However, the method requires long computer times and preliminary calculations with simplified methods should be conducted in advance. The equations of motion may then be solved in the time domain by recognized methods as for instance the Newmark-β method.

2.6.2 Method B. Deterministic Non-Linear Dynamic Analysis

Method B is similar to method A except that only regular waves are considered. Fluid velocity and acceleration are determined from the most accurate wave theory, and the non-linear equations of equilibrium are solved by time integration. The method is well suited for extreme response analysis, but not for rigorous fatigue analysis.

2.6.3 Method C. Stochastic Linear Dynamic Analysis

Method C is based on a linearization of the equation of equilibrium where main feature is the linearization of the coefficient C_{dl} as presented before, by means of relative velocity or by means of standard deviation of the relative velocity which implies that an iterative procedure is required for the evaluation of the spectral density of the response.

2.6.4 Method D. Deterministic Non-Linear Static Analysis

Method D is equivalent to method B for very stiff platforms, for which dynamic effects are insignificant. The analysis is considerably simplified because the equation of equilibrium is reduced to:

$$k\,r = Fs \tag{4}$$

Where,

$$F_s = c_d v|v| + c_i a \tag{5}$$

However, jack-up platforms are in general so flexible that dynamic effects should not be neglected unless the effect is compensated by other conservative assumptions.

2.6.5 Method E. Stochastic Linear Static Analysis

Method E is equivalent to method C for very stiff platforms, for which dynamic effects are insignificant.

2.6.6 Method F. Deterministic Linear Static Analysis

Method F is the most simple of all methods, and in general a number of important effects are ignored. However, as discussed in connection with the other methods it is often possible to account for special effects by simple modifications. In many cases method F may be modified in such a way that the accuracy is not significantly reduced in comparison with method B. The main corrections will contain:

- A Dynamic amplification of the wave/current load, accounted by a horizontal “inertia” load in hull center. See points 4.4.3 to 4.4.6 of DNV RP C104 for calculation methods.
- Base shear and overturning moment amplification due to P-Δ effect (misalignment of vertical loads combined with hull displacements generating additional moments), including the nonlinear amplification factors “α”. The non-linear effect of large hull displacement can be accounted by a horizontal load in hull center, see point 4.4.7 of DNV RP C104 for calculation methods.

The main advantage of the method is that it is very easy to establish instantaneous load distributions, and it is possible to work with very large and detailed structural models.

2.6.7 Some Conclusions about Types of Analysis.

With the previous descriptions, it’s understood that a rigorous analysis will correspond to method A which can be used for special investigations, but expensive in terms of computational time.

Deterministic methods may be used for extreme response analysis. Dynamic effects and non-linear effects should be accounted for, but this may be done by approximate modifications of a linear/static analysis. On the other hand, stochastic methods should be used for fatigue analysis. Considering the information before, is established from now that the type of analysis proposed in this document for the survival and semi-jacked condition corresponds to the type E, Deterministic Linear Static Analysis.

This is decided since displacements and rotations are large but strains are expected to be small, so stress-strain relations are linear. Non-linear structural response should be consider for local analysis. Non-linear effects due to soil structure interaction can be quantified by considering soil non-linear models, but the structural response will continue to be evaluated as linear. A static analysis is considered since the dynamic effects can be quantified by means of Dynamic Amplification Factors obtained from a vibration and encounter frequency analysis.

The accuracy of the results won't be significantly reduced in comparison with method B since it had been proved that method E provides good approximation for large detailed structural models. This arguments are stablished in DNV offshore standards and recommended practices and can be found in DNV OS C-104 for further details.

2.7 Static and Dynamic Structural Response

In structures, the dynamic structural response will depend on the ratio between the excitation frequency and the structural natural frequency, I.e. in case of a vessel, the structural response will be conditioned by the incoming wave excitation. Due to this fact an Eigen frequency analysis should be performed to ascertain the range where resonance occurs and to quantify the dynamic effects on the structure. The eigenvalue problem is solved in this study applying the lanczos method.

Tree methods can be generally used to study the structures response under external loads and these are: Static Analysis, Quasi-Static Analysis and Dynamic Analysis. Each of them are strictly linked to the features of the loads acting on the body.

When loads are time independent, loads are called static. Contrary, a time dependent load will be called dynamic. Main difference is that static loads don't cause inertial effects since no accelerations and no strain deformation rates are produced on the body. When loads are time dependent, body accelerations are induced and so inertial forces become significant as well as strain rates. Nonetheless, if strain rates and inertial effects due to body acceleration are significantly small, the structure can be analyzed considering several static load cases where each of them represents a moment in the time-line. This method is called quasi-static analysis. An example of how the equation of motion is considered to be solved is shown below.

Let's consider a load "F" as a time dependent load acting on a body with "w" as the frequency linked to the incoming wave. If "w_n" is the structural natural frequency for 1 degree of freedom, and being "w/w_n" << 1, dynamic effects can be neglected and equation of motion can be solved at each time step with a Static Analysis. For the range where "w/w_n" > $\sqrt{2}$ the global damping of the structure generates a negative effect as known from vibration theory, so lightly damped system will have lower transmissibility than those with larger damping. I.e when "w/w_n" > $\sqrt{2}$ quasi-static analysis can be used to solve the equation of motion but forces determined will be bigger than the ones obtained due to the low transmissibility for that range of input frequencies.

$$\vec{F} = \overrightarrow{F_0}\sin(wt) \;\rightarrow\; t = 1 \quad \vec{F} = \vec{F}(1) = \overrightarrow{F_0}\sin(w) \;\rightarrow (m + c_m)\ddot{r} + (c_l + c_{dl})\dot{r} + k_l r = \vec{F}(1)$$
$$F = F_0\sin(wt) \;\rightarrow\; t = 2 \quad \vec{F} = \vec{F}(2) = \overrightarrow{F_0}\sin(2w) \;\rightarrow (m + c_m)\ddot{r} + (c_l + c_{dl})\dot{r} + k_l r = \vec{F}(2)$$
$$\textit{Each equation is Solved with Static Analysis}!$$

As commented before if dynamic effects are to be significant, a dynamic analysis should be prepared considering the input frequency. This leads to a situation where equation of motion must be solved by non-linear methods since large strain rates, deformations and inertial forces can't be neglected. In this case the motion equation to be solved is the following.

$$m\,\ddot{r} + c\,\dot{r} + k\,r = \vec{F} \tag{6}$$
$$\vec{F} = c_d(v - \dot{r})|v - \dot{r}| + c_d\,a + c_m(a\,\ddot{r}) \tag{7}$$

As main features of a dynamic response, it can be mentioned that inertial loads increases when the wave periods are close to structural natural frequencies. This generates significant accelerations which leads to large displacements and fast oscillations in time contrary when far from resonance. Is due to this fact that is necessary to perform a dynamic forced response analysis in the range where dynamic effects may be significant.

For the particular case of WTIU, in the elevated condition the lowest natural frequencies usually correspond to the longitudinal displacement (surge), transverse displacement (sway) and vertical rotation (yaw). When verifying the semi-submerged condition the same features can be found since the configuration is analogous. Meanwhile wave periods are usually small, these will be the motions excited by the incoming waves and so the main ones to be studied.

The ratio between the input period and the structural natural period (or equivalent ratio in terms of frequencies) is used to determine the load increments where dynamic effects are significant. This is done determining the called Dynamic Amplification Factor (DAF) which represents the factor by which displacements are amplified due to the fact that the external forcing is dynamic and not static, i.e. by knowing the magnitude of the static displacement and the input frequency, one can determine the dynamic effect of the structure for harmonic forces.

The DAF is calculated with the ratio between the dynamic deflection with the static deflection at a given frequency. Regarding to how much the response is amplified, it will depend on how close we are to the natural frequency (w/w_n close to 1 leads to maximum DAF values) and on the damping ratio of the structure.

From DNV RP-C104 4.4.4, a well-known formulation is given for the calculation of the DAF and the damping ratio as shown below.

$$DAF = \frac{1}{\sqrt{\left[\left[1-\left(\frac{T_0}{T}\right)^2\right]\right]^2+\left(2\xi\frac{T_0}{T}\right)^2}} \quad \textbf{(8)}$$

$$\xi = \frac{c}{c_r} = \frac{c}{2\sqrt{m\,k}} \quad \textbf{(9)}$$

Where

T_o = structural natural period for one degree of freedom

T = wave period

ξ = damping ratio

c = global damping including structural, hydrodynamic and soil damping

It has to mention that DAF cannot be applied directly to stress or displacements since non-linear effects are to be dominant on the structure response. For this, another methodology combined with the DAF should be applied which is explained below.

Necessarily, the DAF must consider several aspects of the body physics which are:

- Dynamic effects due to frequency encounter (w/w_n close to 1)

- **P-Δ** or **P-Delta effect,** which refers to the abrupt changes in ground shear, overturning moment, and/or the axial force distribution at the base of a sufficiently tall structure or structural component when it is subject to a critical lateral displacement.
- Surge and Sway drift due to deformation by environmental loads.
- Horizontal offset due to hull form fabrication and installation.

P-Δ and horizontal offset should be always quantified since they will affect significantly the structure response since self-elevated units are relative flexible structures subject to large hull surge and sway displacements generally caused by environmental loads. Tolerances during fabrication will also lead to a "hull sway" increasing the non-linear effects.

Due to hull sway, the vertical spudcan reaction will present an offset relative to the centroid of the leg at the level of the hull. Thus the legs moments at the hull level will be higher compared to those calculated by a linear quasi-static analysis.

Two calculations are proposed in the document DNV RP – C104 section 4.4.4. One offers a methodology to quantify the DAF for the total base Shear only, and the second considers the hull horizontal displacements, used to quantify dynamic effects, P-Delta effect, horizontal drift (considering wave direction) and offset of hull. The second method is the one considered for the calculations in this study.

Because the instantaneous wave/current force resultant for a jack-up platform is not at the effective center of mass, equivalent "inertial" forces are derived which are to be applied at the platform effective center of mass of the model in quasi-static global analysis. By superposing the effects of the linear wave loading with the structural response linked to an Inertial load (calculated separately which represent a correction of the static approach) one can calculate the influence of the dynamic response on the base reactions and motions. Once again, this approach represents a powerful method since it includes the effect of the miss-alignment of the structure during installation, hull environmental drift, and out of straightness during the construction to predict the dynamic effects. A procedure to determine the inertial force is now presented.

- A calculation of the hull displacements caused by the fabrication, wind, wave and current have to be done to establish the hull displacement amplitude (P-Δ effect). The hull displacement may typically be chosen in the hull center, and normally the displacements from the wave phase angles corresponding to maximum and minimum base shear can be used to determine the displacement amplitude. This is done through a static analysis.

- In a global analysis the above may be obtained by applying a unit horizontal load (inertial load) at the platform effective center of mass. The inertia load is obtained by scaling a unitary load called *"F_{Unit}"* with a scaling factor (SFAC).
- It is necessary to mention that when it is referred to an unitary horizontal load, it will represent the behave of the structure in the particular horizontal direction where the force is applied, so several simulations should be performed to be able to describe the whole dynamic and other effects on the analysis, which will give the hull displacement by a unit force in the direction evaluated.

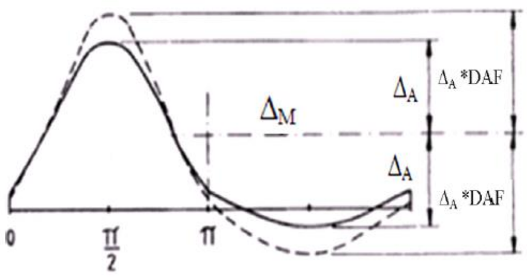


Figure 9. Dynamic effects corrected by hull displacements, Figure 4-7 taken from DNV GL RP C104-4.4

$$F_I = F_{unit} \text{ x} \frac{\Delta_A (DAF - 1)}{\Delta_{unit}} \quad \textbf{(10)}$$

Where,

Δ_A	= amplitude value of total hull displacement wave/current (quasi-static).
Δ_{unit}	= the hull displacement from the unit force applied at the platform effective center of mass
DAF	= Dynamic amplification factor
SFAC	= Δ_A (DAF - 1)/ΔUnit
Δ_A (DAF - 1)	= the hull displacement representing the dynamic amplification inertia force:

The P-Δ effect can be also represented as an inertial force. Thus adding to the ones determined to account the dynamic effects, one can *simulate* the non-linear dynamic response of the structure. The Inertial load linked to the P-Δ effect can be modeled as a horizontal load determined with the following procedure

$$H = W\Delta/\mathrm{l} \quad \textbf{(11)}$$

$$\Delta = \alpha(\gamma_{f,D} e_0 + \gamma_{f,E} e) \quad \textbf{(12)}$$

$$\alpha = \frac{1}{1 - \frac{P}{P_E}} \quad \textbf{(13)}$$

$$P_E = \pi^2 EI/(Kl)^2 \quad \textbf{(14)}$$

Where,

H	= Horizontal inertial load.
W	= nxP. Elevated hull weight (including payload)
n	= number of vessel legs
P	= Average load on legs at hull level [N]
P_E	= Euler load
Δ	= total hull sway in the considered wave direction
e_0	= e_1+e_2 e_3. Maximum horizontal offset of the platform, including initial out-of-straightness of legs [m]
e	= sideway 1st order deflection of barge due to wind, waves and current include dynamic effects.
$\gamma_{f,D}$	= load factor deformation loads [-] –
$\gamma_{f,E}$	= Load factor environmental loads [-]
e_1	= out-of-straightness [m]
e_2	= hull leg clearances [m]
e_3	= heel of platform [m]

Once the Inertial loads are determined, it is possible to obtain the standard structural response under a static load (non-variant in time or frequency). Reaction forces, stress distribution and motions can be calculated for every inertial load (linked to each wave heading) that is interested to evaluate then, by applying the superposition theory, we can combine such results after scaling the response for the inertial force, with the linear quasi-static wave loading and hydrostatic load case.

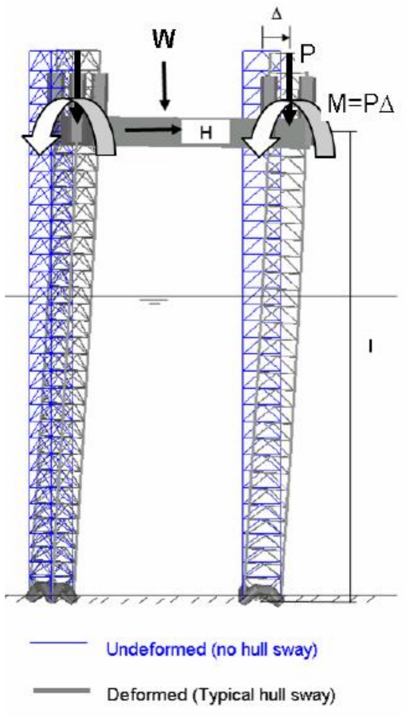


Figure 10. P-Δ effect by horizontal loads. Figure 4-9 of DNV RP-C104

To obtain the structural response at each wave heading, the procedure should be repeated applying the respective inertial loads in the wave direction and subsequently combined with the results obtained with the quasi-static analysis. Finally it is possible to observe the better consistency with the reality when referring to base shear forces, vertical forces, bending moment, stress distribution and displacements.

This procedure is valid only for a specific geometrical configuration, so it is understood that the methodology should be repeated for other geometrical configurations or operational conditions.

2.7.1 Some relevant notes

Depending on the structure, typical values for damping ratios may be found and used for a first estimation. According to the standard DNV RP-C104 4.4.5, *"typical values for jack-up vessels in survival condition are expected to be around 6 to 9% but it should not be taken higher than 7% without justification…The total damping coefficient, c, includes structural damping, hydrodynamic damping and soil damping. All of these contributions are difficult to determine,* *and none of them should be neglected".* Besides this dependency, it will be difficult to select a representative total damping ratio since it will be also dependent on the excitation frequency.

A clear difference between both operational conditions is identified at this point. The damping for the survival condition is expected to be lower in comparison with the damping of the semi-jacked condition due to the contribution of the hull hydrodynamic damping which will vary with the heading angle, and with the incoming wave period.

Is important to remark that this work is not intended to evaluate a specific rig design or either report the performance or load capability of any existing structure. The product obtained from this work will serve to understand the general behave of such structures and get an idea of the loads that WTIV may face on site, which is a valuable information for design stages.

2.8 Problem Physics Discussion

In this section are presented the points the author consider are important to perform the global response study of the WTIU according the information that has been presented in the section 2.3, 2.4 and 2.6 of this document.

It is notice that special attention should be given when performing a global response study of a WTIU. Additionally, some aspects are identified and marked as important to take care when performing the study, which presented and described as follows:

- Geometry of the structure: Hull form, legs and features of the possible jack up system should be known to define load limits, as well as drag coefficients to determine accurately loads acting either on the hull or the legs.
- Methodologies for wave induced loads as well as wind loads, inertial forces, earthquake, tidal effects, and others shall be correctly defined according to recognized references or previous studies.
- Modeling of the connection of legs with the sea bottom should be modeled properly for correct overturning moment estimation as well as structure response. Depth of the spud cans and interaction of them with the soil should be well known to guarantee the minimum requirements by the standards.

- When using Morison formulation for loads acting on structures, update of the form coefficient for the geometry of the column must be performed precisely to assure quality of results.
- Dynamic analysis of the structure should be performed to determine displacements and accelerations. It has to be guaranteed that structure response will not present resonance for the in-site conditions
- 3D modeling of the structure is required to be performed since CFD analysis is requested. Attention to flow modeling around structure must be considered.
- Stability study of the structure in the case of the study should be performed to guarantee safety during operations.
- Hull motions and accelerations (RAO) due to lateral oscillations, base shear force, base reaction moment and base reactions in each leg must be reported when finished the studied.
- It should be reported all the loads acting on specific points such as junctions or areas where may be required and structural analysis in the elastic, useful during the design stage.
- Methodologies for added mass estimation for multibody motion must be consider. Special attention should be given since operating condition to be analyzed is semi submerged jack-up condition.

2.8.1 Advantages and limitations of Deterministic Linear Quasi-Static Analysis.

The advantages, disadvantages and limitations to apply a deterministic linear quasi-static analysis are presented now.

Some advantages are:

- Suitable to determine Global Response of the vessel in Survival condition for large detailed models.
- Offers a first good approach of Base Shear and Bending Moment estimation
- Accounting of the multibody hydrodynamic, fluid structure interaction and ship motion.
- Added mass, Drift forces and Damping can be accounted as well as variable functional loads, permanent loads, environmental loads and deformation loads
- Possible to perform load transfer from global model for local strength assessment of legs, assessment of tubular joints, hull deck structure, spudcans and capacity of jacking systems.

- RAO'S can be determined for all operational conditions. Motion of the center of gravity and hull center is used to understand the ship motions under the loads mentioned.
- Counting of Structure-Soil interaction which guarantees a realistic modeling of the structure fixity and their effects on the structural response.
- Linear flow solvers are able to catch the majority of the wave loads effects on the structure for which is not usually required turbulent models since inertial loads are to be dominant rather than drag forces.
- Morison model offers good approximation for wave load estimation, differing in no more than 25% with RANS simulations. This demonstrate its usefulness to evaluate strength related safety aspects for high hull elevations. (From the work "Wave load and structural analysis for a jack-up platform in freak waves" discussed in the chapter 3 of this document).
- Possible to account second order bending and axial loading (which reduces lateral stiffness)
- Regular linear wave theory will be enough to characterize the global response of the structure.

Some dis-advantages and limitations are:

- To assess the global response of a specific location, non-linear wave theory may be used to account the effect of bound waves on the dynamic response.
- If linear theory is used, drag from Morison equation is linear since is based on linear wave kinematics. For a realistic approach, non-linear wave kinematics in combination with a determistic or stochastic approach should be considered.
- Time variant simulations may be needed to catch structural non-linearities of the response, solved with a dynamic analysis.
- If dynamic effects are to be significant, a Structural Dynamic response analysis will be mandatory to determine the response of the structure in specific locations under certain environmental condition. Nevertheless, the present modified quasi-static approach will be suitable to describe the majority of the dynamic effects in the global response of the structure even for detailed FE models. This will allows to identify a range where dynamic forced response will be needed decreasing global computational calculations. Local models cannot be assessed with this modeling technique (I.E moonpool effect on hull-leg connection).

-

3 STATE OF THE ART

This section presents a briefly description of the work from other authors related with the physical problem to be studied. Explanation of their work, special considerations and results are mentioned since their work is considered useful for the proposal of our study. A summary of each reference is presented as follows.

3.1 Reference review #1: A Parametric Study of the Non-Linear Dynamic Behavior of an Offshore Jack-Up Unit

Work presented by Martin S. Williams, Richard S.G. Thompson and Guy T. Houlsby, on 1997. The Abstract of this work is says as follows:

> *"The dynamic response of an offshore jack-up unit to environmental loads has been investigated using a two-dimensional, nonlinear finite element model. The model includes realistic representations of the wave loading, the geometric non-linearities of the rig legs and the complex non-linear effects of combined loads on the spudcan footings…. It is shown that the accurate non-linear modelling of both the legs and the spudcan footings has a significant effect on the rig dynamics. The widespread practice of modelling the footings as simple pinned supports may be non-conservative for some sea states".*

For the study of the structure response, a dedicated finite element software is used to characterize nonlinear effects on the structure, this means that a Dynamic Analysis is performed. Modeling is performed in 2D so wave forces are assumed to be aligned with the axes of symmetry of the rig.

Directional seas are not studied in this case and so torsional displacement modes of the rig cannot be modelled due to the 2D model (This is considered as one of the limitations of the authors work).

Morison equation is used to determine the loads on the legs (idealized as equivalent cylinders). Regarding to the wave kinematics and wave non linearity's, they are modeled using Stokes fifth order wave theory. No further loads besides incident wave load is considered. RAO of the structure as well as forces in the base are given considering 3 different junctions of the structure with the sea bottom.

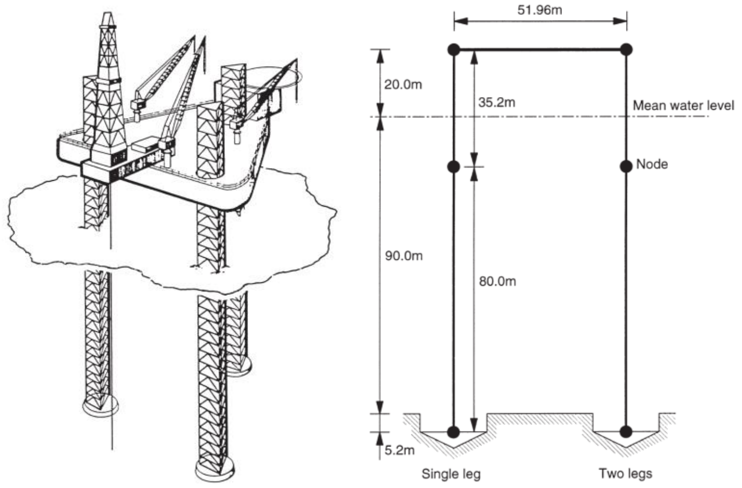


Fig. 1. A typical jack-up unit. Fig. 2. Plane finite element model of a representative jack-up.

Figure 11. Typical Jack-up Unit and Plane Finite element model of a representative jack-up. Fig 1 and 2 respectively. (M. Williams, 1999)

A comparative study between quasi-static analysis, and, Dynamic analysis is performed. The objective is compared how the loads are amplified considering different models of the soil-leg fixation to demonstrate that the widespread pined condition not often offers the most conservative approach. For this study is used Pined fixation type, Fix (clamp) condition, and an additional mathematical model which represents accurately the spudcan interaction in contact with clay, called Model B (from the author Martin CM. "*Physical and numerical modelling of offshore foundations under combined loads".* D.Phil. thesis, University of Oxford, 1994).

The author found that for the different fixation conditions, the natural frequency of the structure varies significantly which conditions the dynamic response of the structure.

Table 1. Main particulars of WTIV.

Fixation Type	Structure N.P
	[s]
Pined	8.3 (0.12 Hz)
Model B	6.6 (0.15 (Hz)
Fixed (Clamp)	4.6 (0.22 Hz)

For the Quasi-Static Analysis, the maximum loads and hull displacements are registered for the pinned condition, followed by the Model B and Fixed condition. This might make us infer that pinned condition will be always more conservative than other types of fixation models.
Later, the author performs a dynamic analysis and compares the Hull displacements with the wave frequency. Peak values are identified in the respective natural periods and in the second harmonics since significant energy is linked to it. This behave is expected due to the wave non-linearity's.

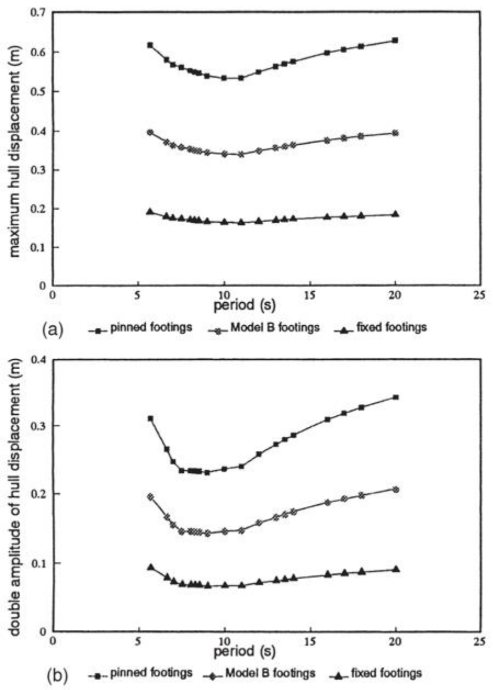


Figure 12. Quasi-static displacements for a Wave Height of 13m. Fig 5 from (M. Williams, 1999)

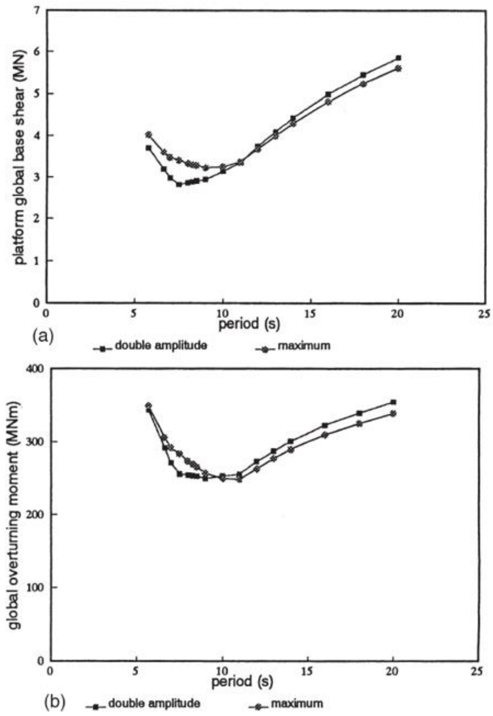


Figure 13. Variation of total rig loads for a wave height of 13m. Fig 6 from (M. Williams, 1999)

Here is observed that for a limited range of frequency, Model B presents larger displacements in comparison with the other cases. This means that pinned conditions not often will be the most conservative approach, so attention should be given when setting this parameter.

Consequently, comparing the Dynamic Amplification factors against the frequency ratio "w/wn" interesting findings are shown where maximum values are registered for the Model B besides the loads registered in this case with the quasi-static analysis were lower for this model comparing with the pinned condition.

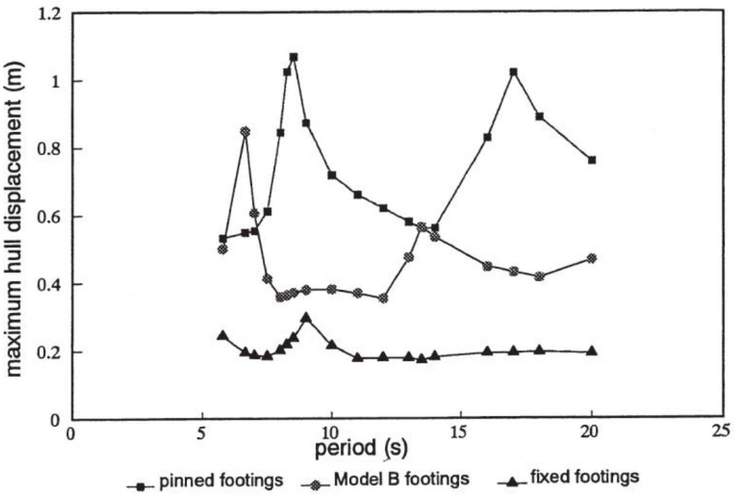


Figure 14. Dynamic Maximum hull displacement for 13 m waves. Fig 8 (M. Williams, 1999)

The points plotted represents the DAF for each type of fixation, determined with the formulation of DAF given in the section 2.7 of this document. Solid lines represent cases where Model B and Pined condition are used with 0.05 and 0.06 of damping respectively. Points do not match exactly numerically but they offer a good approximation for the model B and Pinned condition, with more discrepancies with the fixed condition.

This results represent an interesting finding that must be considered for all types of analysis when designing or verifying load limits on Jack-up Units. DAF determined with the formulation in section 2.7 will offer a good approximation for the load increments besides a quasi-static analysis is used. Nonetheless, attention should be given when modeling the soil-leg link.

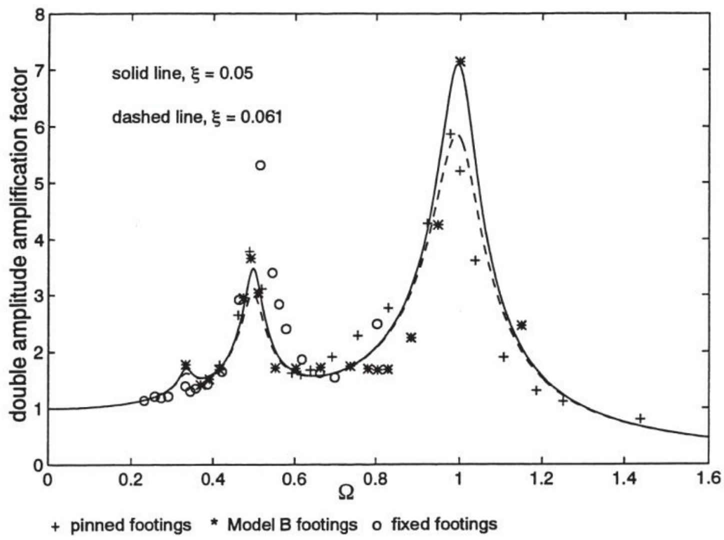


Figure 15. Linear approximations to double DAF curves. Fig 12 (M. Williams, 1999)

Other studies such as the listed below describe different models to represent the Soil-leg interaction. Models such as elastic-plastic, linear springs, fix joints, pin joints, clay and silica models are some of the models that are mentioned. This demonstrates the importance of selecting to right model for the specific site conditions since the response of the structure may not match with the reality. Meanwhile the dynamic response of the structure is an issue of special concern, it will be also the type of model selected to stablish the fixation of the structure.

- *"Effects of Foundation Models on Jack-up Site Assessment"* from ZHANG Jian, TANG Wenxian, SU Shijie, GAO Chao, and
- *"Impact loads on a self-elevating unit during jacking operation. A methodology incorporating site-specific parameters for weather window assessment"* from Viktor D. And Fredrik O.
- *"Numerical modelling of the dynamic interaction between jack-up vessel legs and the seabed",* from Jorrit-Jan Serraris, Mike Woning.
- *"A FE procedure for calculation of fixity of jack-up foundations with skirts using cyclic strain contour diagrams"* from H.P. Jostad, Ø. Torgersrud and H.K. Engin, H. Hofstede.
- *"JACK-UP LEG AND JACKCING SYSTEM DESIGN LOADS IN TRASIENT PHASES"* from Jenny Yan Lu, Grezegorz Malinowski, Robin Weizheng Xiang, Colin Nelson and Rick Rogers.

3.2 Reference review #2: Wave Load and Structural Analysis for a Jack-Up Platform in Freak Waves

Work presented by Ould el Moctar, Thomas E. Schellin, Thomas Jahnke, Milovan Peric in the Journal of Offshore mechanics and Antarctic engineering (2009)

The Abstract of this work is the following:

> *"It was analyzed the effects of freak waves on a mobile jack-up drilling platform stationed in exposed waters of the North Sea. Under freak wave conditions, highly nonlinear effects, such as wave run-up on platform legs and impact-related wave loads on the hull, had to be considered. Traditional methods based on the Morison formula needed to be critically examined to accurately predict these loads. Our analysis was based on the use of advanced computational fluid dynamics techniques. The code used here solves the Reynolds-averaged Navier–Stokes equations and relies on the interface-capturing technique of the volume-of-fluid type. It computed the two-phase flow of water*

and air to describe the physics associated with complex free-surface shapes with breaking waves and air trapping, hydrodynamic phenomena that had to be considered to yield reliable predictions. Lastly, the finite element method was used to apply the wave-induced loads onto a comprehensive finite element structural model of the platform, yielding deformations and stresses."

This work results from the necessity of determine with accuracy the load limits of jack-up units after the oil spill happened in the Gulf of Mexico due to hurricane Katrina. This work differs from previous one presented since is introduced the usage of CFD coupled with FE solvers to determine loading on a jack-up platform. The objective is determine the discrepancies and the feasibility of using Morison Formulation for Leg loadings instead of CFD with direct numerical integration.

The author uses a CFD solver which is able to solve the Fluid kinematics by the Reynold Average Navier-Stokes (RANS) method considering the interface-capturing method of VOF (volume of fluid) to account compressibility effects. Subsequently, CFD calculations are coupled with a FE solver able to resolve the dynamic motion equations in time domain. Time domain simulations are justified due to highly non-linear wave effects, non-linear behave of foundation and dynamic effects.

The second analysis covers the same aim with the difference that the hydrodynamic loads are determined with the Morison formulation, later transmitted to the FE model and solved to determine the structure response.

A comparison is done using the base shear force and overturning moment registered on the platform when exposed to freak waves (storm waves) 11.6 m and 23.7 m. Simulations are run considering both CFD and Morison Formulation and finally compared. The study revealed that predictions based on the use of the Morison formula differed by not more than 25% in the worst cases from predictions in obtained with CFD techniques.

It is observed in the next graphs that results obtained from Morison Formulation follow with a good approximation the approach obtained by RANS for waves of 11.6 m. In the case of a 23.7 m wave height, a big concordance on the base reactions is found with both approaches but peak values differs in the worst cases around 25% which can be justified by the wave non-linearities that Morison Formulation can't catch. These comparative results demonstrated the general usefulness of the Morison formula to assess strength related safety aspects although only for cases of high hull elevation.

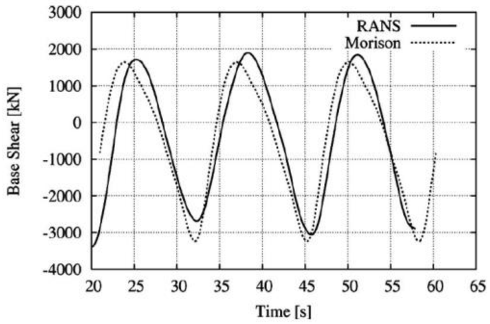


Figure 16. Comparative results of base shear for the 11.6m wave. Fig 13 (O. Moctar, 2009)

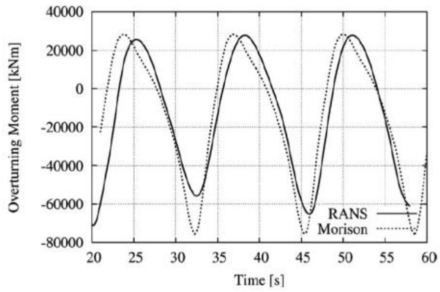


Figure 17. Comparative results of overturning moment for the 11.6m wave. Fig 17 (O. Moctar, 2009)

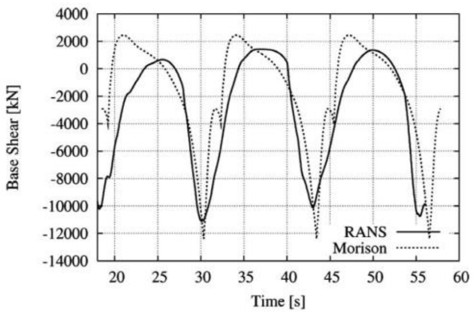


Figure 18. Comparative results of base shear for the 23.7m wave. Fig 16 (O. Moctar, 2009)

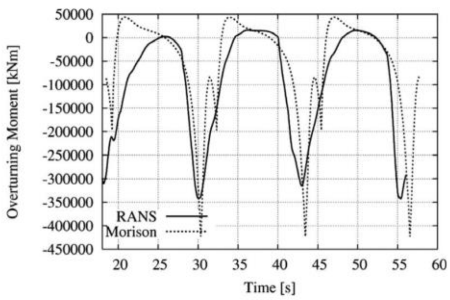


Figure 19. Comparative results of overturning moment for the 23.7m wave. Fig 20 (O. Moctar, 2009)

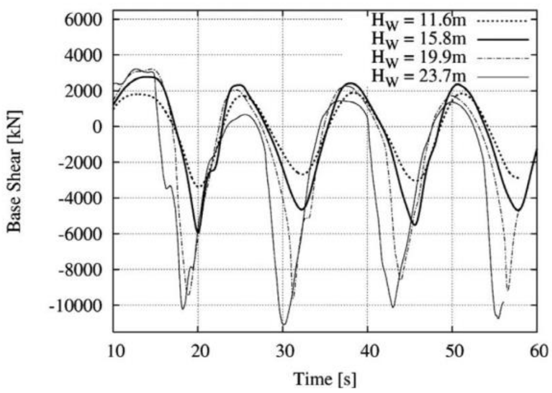


Figure 20. Time histories of base shear. Fig 9 (O. Moctar, 2009)

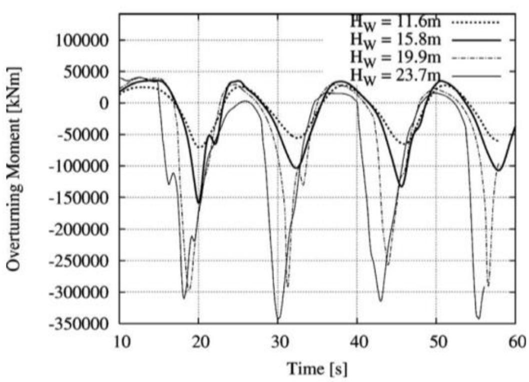


Figure 21. Time histories of overturning moment. Fig 10 (O. Moctar, 2009)

Besides the important findings of the author, it will be necessary to evaluate cases of lower hull elevations with waves attacking the hull directly. Since pressure distribution will depends on the incident angle and hull shape, it would be necessary to rely on methods such as CFD techniques to predict wave loads on irregular surfaces.

3.3 Reference review #3: Sea Loads on Ships and Offshore Structures

Work presented by O.M. Fatilsen, Professor at the Department of Maritime Technology Norwegian Institute of Technology. (1993).

The author presents his book as a material focused on calculations and considerations for wave-induced motions and loads for Ships and Offshore Structures. Some of the considerations for the analysis explained in the book are taken as references for the modeling of the physical problem in this document. Some of them are mentioned now.

- Depending on Reynolds, Flow separation may occur generating transition areas for drag coefficient. When located in transitional condition of Reynolds, drag coefficients may increase due to flow separation. One source could be given due to small bilge keel radios which leads also to an increment of the drift forces.
- When considering slender elements where flow detachment is presented, vortex induced vibration should be an issue of concern and must be accounted when evaluating current loads and dynamic structural response. The evaluation of the stroudal number can offer the vortex period for which structure might me excited, depending on Reynolds Number and the geometry of ship (flow separation) and due to the presence of Von Karman vortexes'. This phenomena may be found in the legs of a Wind Turbine Installation Vessel, or other structures with slender elements like Tension Leg Platforms or Semisubmersibles. Vortex excitation period must be considered during the dynamic response analysis of the structure.
- Offshore structures present a high amount of nonlinear effects that can't be notice by analytical formulations. Numerical simulations are capable to account the nonlinearities of the structure, environmental loading and soil-structure interactions. It also offers an enormous advantage against model tests, since scale effect may affect the results affecting the predictions for the real dynamics of the system.

3.4 Notes and Comments Concerning WTIU Design

With the information presented before, a variety of points had been discussed for other authors in the past, serving as a reference and guidelines for the study presented in this document. Considering this references and others indicated in section 7, it is listed a number of points the author considers important to perform the global response study of WTIU.

Some aspects identified and marked as facts of special worry are the following:

- Geometry features of the structure: Hull form, legs and the jack up system should be modeled with sufficient detail to catch major effects on such elements. It is of special worry to determine with accuracy the load limits of the structure especially during extreme response.
- Methodologies to determine wave induced loads as well as wind loads; inertial forces, earthquake, tidal effects, foundation fixation, and others shall be correctly defined according to recognized references or previous studies to account major non-linear effects. The dynamic response will be conditioned by all this parameters.
- Modeling of the connection of legs with the sea bottom should be modeled properly to guarantee that numerical simulations represent the real structure dynamics. Depth of the spudcans and interaction of them with the soil should be well known and modeled according to site specific parameters. Pin conditions for leg fixation can be used for early design stages but it won't be recommended for detailed designs.
- Dynamic analysis of the structure will be the best option to determine displacements and accelerations considering structural non-linearity's and dynamic effects due to frequency encounter. Special care should be given when verifying loads in the range of resonance.
- Usage of Dynamic Amplification Factors represents an alternative and reliable option to characterize dynamic responses but special attention should be given when selecting the foundation models to represent the soil-leg interaction if needed to perform a specific site assessment.
- 3D modeling of the structure is required since CFD analysis must be used to determine hydrodynamic loads on the hull. Flow characterization is an issue of special concern to model accurately inertial and drag forces on submerged bodies.

- Hull motions and accelerations (RAO) due to lateral oscillations, base shear force, base reaction moment and base reactions in each leg must be reported for risk reduction during operations. Exposer to different headings and critical geometrical configurations should be evaluated and reported to prepare the operation manuals of the structure.
- Methodologies for added mass estimation for multibody motion must be considered. Special attention should be given since operating condition to be analyzed is semi submerged jack-up condition.
- Load Cases and Load combination should be defined to proceed with the respective calculation with every case of evaluation. The conditions to be evaluated are the Semi-submerged condition and the elevated condition. Each of this case is previously analyzed to determine the operational load combination. The loads acting on the structure for each configuration are presented in table 2.

Table 2. Loads considered for the load combination assessment.

Condition / LC	Wave Loads	Current Loads	Wind Loads	Buoyancy	Weight
Semi-Submerged	x	x	-	x	x
Survival	x	x	-	-	x

- Wind loads are not considered in this study meanwhile the main aim is characterize the structure global behave since wave loads are to be dominant. Self-weight of the structure as well as Buoyancy, are accounted when valid. For the semi-submerged condition, the buoyancy will take part since the Hull is partially submerged. Later, when for the elevated condition the hull is no longer in contact with the water so no buoyancy will be perceived. The buoyancy of the leg is neglected since cylindrical legs are assumed to have openings which means that no dry compartments exists in them.

4 METHODOLOGY

In this chapter it is explained the methodology used to perform the Global Response Analysis of WTIV in semi-submerged condition. A flow diagram is provided for the general understanding and global appreciation required for the study. Further information is given regarding the software employed for the Hydrodynamic modelling and Structural Modeling. Limitations of the software as well as relevant assumptions and considerations for the study performed are also given.

4.1 Global Response Analysis

If a Global Response Analysis is required to be performed, the procedures indicated in the flow charts of this section should be the minimum required for a proper analysis. The study requires a wide multidisciplinary knowledge in hydrodynamics, structural mechanics and soil-structure interaction.

A global response analysis implies built a simulation where the vessel geometry, site specific parameters and environmental data are the input data for the simulation model. The simulation model is the result of the interaction of 2 coupled or un-couple sub models called, structural model and hydrodynamic model.

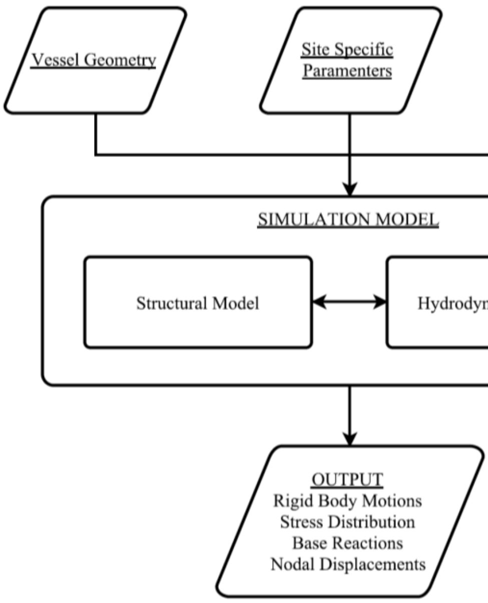


Figure 22. Flowchart displaying input data, simulation model, sub-models an output interaction. .

The hydrodynamic model is used to represent the environmental loading on the structure according to the information known for the site, which are later transmitted to the structural model where motion equations are solved considering the external forces on the body. The output of the analysis will cover mainly the response amplitude operators of the system, a global nominal stress distribution in the model, base reactions and nodal displacements.

A step by step description is now presented. The first stage of the analysis involves the organization of environmental and site data available for which the structure should be assessed. With this, all the external loads can be defined and set in the FE model when prepared.

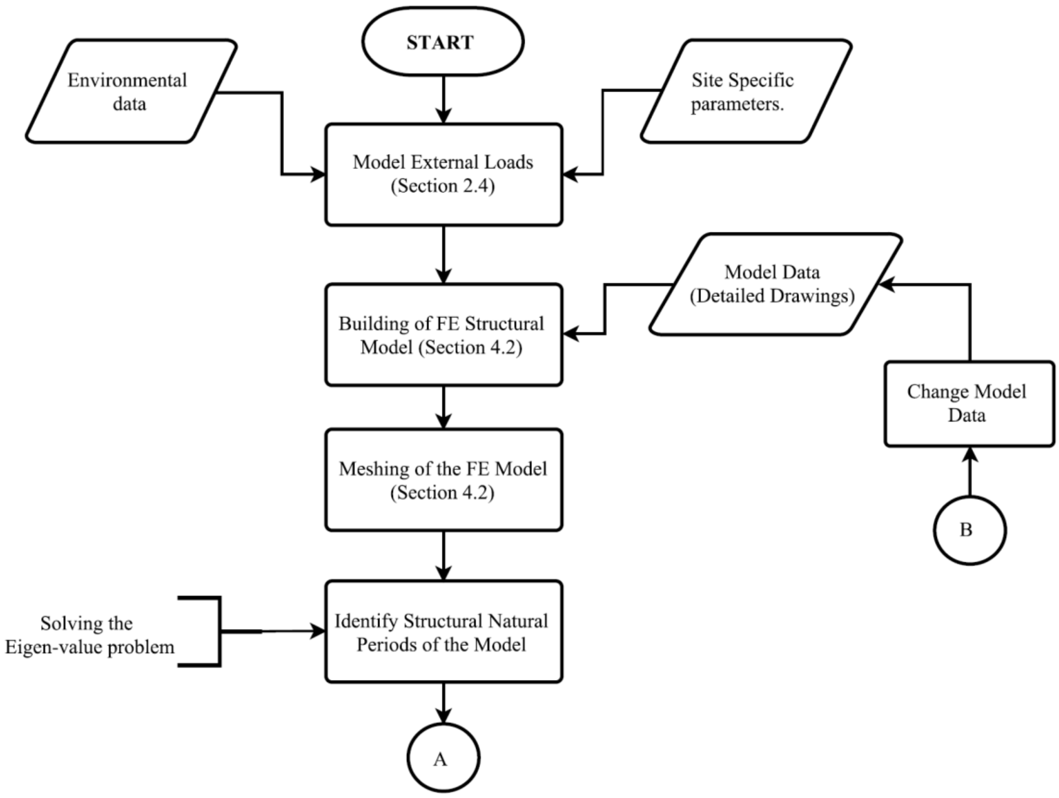


Figure 23. Flow-chart Global Response Analysis.

The second step consists in the preparation of the FE structural model considering the detailed data given by the designer. If necessary, simplifications of the model can be done according recommended practices for FE calculations. It is important to select the right type of elements when building the model so balance between accuracy and computational time consuming is reached.

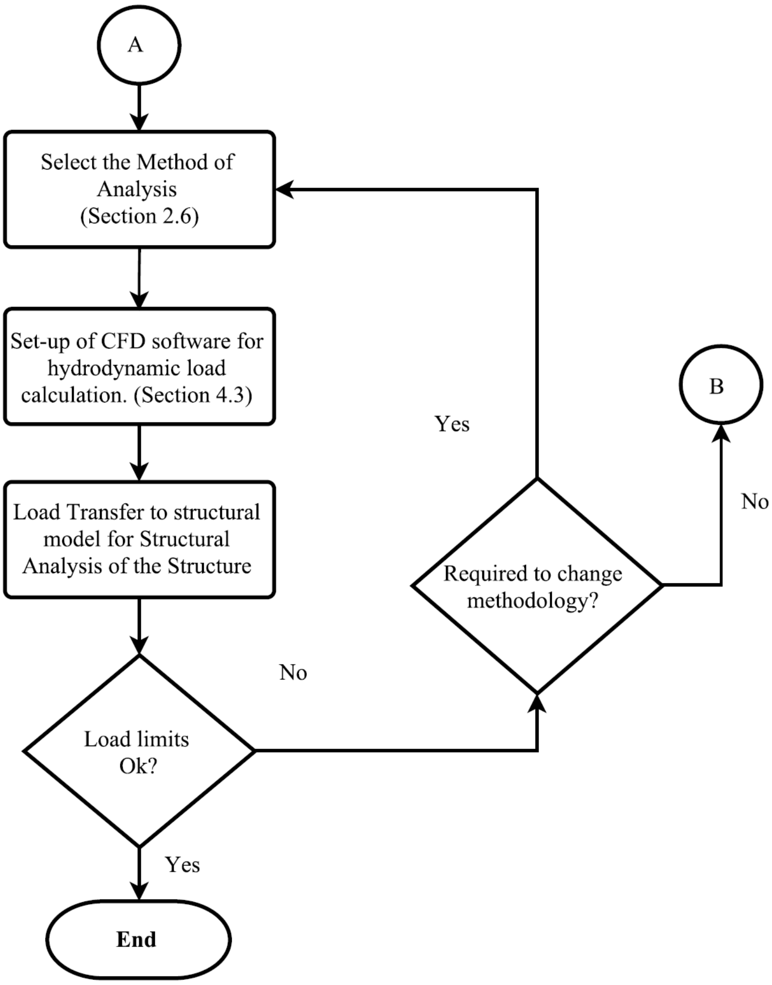


Figure 24. Continuation. Flow-chart Global Response Analysis

Once the FE model is build, meshing of the model is the next stage. Special attention should be given when preparing the mesh mainly with the element shape and element size since the accuracy of the approach depends on it. With the mesh prepared an Eigen-value analysis would be performed to identify the structural natural periods of the model. Such values serve to verify if significant dynamic effects are expected for in the structure response. This information in combination with the site parameters and environmental data is used to select the type of analysis to be performed for the global response analysis.

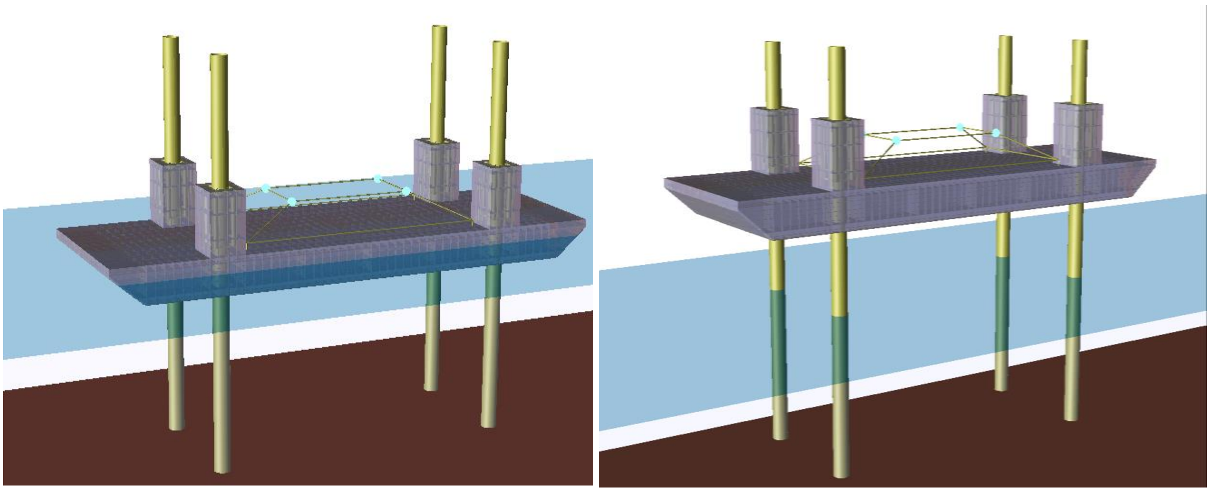
Now selection of the method of analysis is done where deterministic or stochastic, linear or non-linear, and static, quasi-static or dynamic analysis should be defined. The section 2.6 of this document describes the possible analysis to be performed.

Subsequently, a CFD software is employed to determine the hydrodynamic forces acting on the model. The modeling of the environmental forces should be carried using recognized numerical methods, validated with experimental data. When external loads are determined, a load transfer from to the FE model should be performed to compute the structural analysis (static, quasi-static or dynamic). Finally, hull displacements, reaction forces and stress distribution can be analyzed to verify the load limits of our model.

4.2 Model Data

The case being analyzed is a Wind Turbine installation Vessel (WTIV) with the main particulars reported below. Dimensions for the modelling are supplied by DNV GL, Gdynia office in Poland to evaluate a realistic design. Further information than the indicated below cannot be given due to confidential agreement with the company.

It is requested to evaluate the WTIV at two different operational conditions at 3 specific locations defined by the water depth. The operational conditions are the semi-jacked (semi-submerged) and the survival condition. The aim of such considerations is to understand the global behave of the structure under wave loading for different geometrical configurations and so, to perform a comparative analysis to identify the maximum risk-operation between the two conditions. It is not the intention of this study to evaluate a structural design at an specific site. Main particulars considered for the vessel modeling are presented in table 3.



a) Semi-submerged condition b) Elevated/Survival condition

Figure 25. Modeling of operational conditions in FE software.

Table 3. Main particulars of WTIV.

PARAMETER	Value	Unit
Length	120	[m]
Beam	42	[m]
Depth	9,5	[m]
Tonnage (non -loaded)	9797	[tons]
Gross Tonnage (Loaded)	14797	[tons]
Drat Semi-Submerged (Equilibrium)	2,52	[m]
Air gap (Static Clearance-Survival)	10	[m]
Soil Penetration	5,5	[m]
Max Wave Height (Hs)		
-Semi-Submerged	2	[m]
-Survival	10	[m]
Wave Period Range	0-13	[s]
Current Velocity (*)	5	[m/s]
Wind Speed	0	[m/s]
Hull Inclination	0	[°]
Water Depth (WD)	30-40-50	[m]
Number of legs	4	[unit]
Leg Length	100	[m]
Leg Diameter	4	[m]

(*) Current Velocity is assumed to be constant along the vertical

For the 2 operational conditions shown above, the structure is analyzed at 3 different water depths 30 m, 40 m and 50 m. This will lead to different geometrical configurations which will modify the natural frequencies for the single degree of freedom problem (SDOF)

4.2.1 Geometrical Features

It is needed to discern how the geometrical configurations affect the Global Response of the structure. The main worries are the amplification of the structure response due to dynamic effects due to the geometrical configurations.

It is known that with a change of the geometry, the mass is redistributed affecting the inertial properties of the structure and natural frequencies. This will be the starting point of the analysis and the main fact that will uncover the behavior of the structure.

The geometrical configurations analyzed were selected according to the following criteria's. Each configuration defines a set of loads acting on the structure.

- For the Semi-submerged condition the draft considered for the vessel is the one for the still-water condition (hydrostatic equilibrium) with the gross tonnage weight. This emulates de equilibrium condition just before the hull starts to upraise above the free surface, thus legs are not submitted to axial loads rather than the one linked the extra-buoyancy due to change of the free-surface. This condition defines a loading condition as:
  - Horizontal forces produced by the waves, acting on the hull and legs of the vessel
  - Vertical forces produced by the excess of buoyancy coming from the wave.
  - Overturning Bending moment due to horizontal forces.
  - Load amplification of Base Shear and Overturning Bending moment due to P-Delta effect.
  - Load amplification of Base Shear and Overturning Bending moment due to resonance effect in the surge and sway motion.
- For the Elevated condition, an air gap of 10 m is considered as design criteria. Therefore for any water depth, the hull will be located at the specified distance measured from the still water level to the vessel keel. This condition defines a loading condition as:
  - Horizontal forces produced by the waves, acting only on the legs of the vessel.
  - Vertical forces produced by the weight of the structure.
  - Overturning Bending moment due to horizontal forces.
  - Overturning Bending moment due to resultant vertical forces (P-Delta Effect).
  - P-Delta Effect.
  - Load amplification of Base Shear and Overturning Bending moment due to resonance effect in the surge and sway motion.

With an overview of the loading panorama and with the operational conditions defined, it is presented a table indicating the main geometrical features of the structure for cases being evaluated.

4.2.2 Center of Gravity

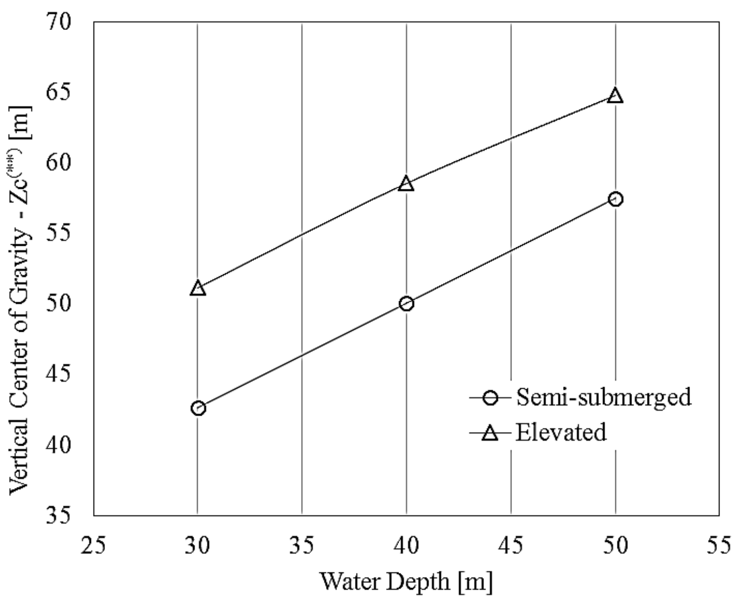
The location of center of gravity is tracked and presented in table 4. It is seen that when increasing the water depth, the center of gravity of the structure will raise. From this point 2 verifications can be made: the theoretical Euler load limit and the change of the inertia.

Table 4. Location of center of gravity.

Operational Condition	Water Depth (WD)	X_c	Y_c	$Z_c^{(*)}$	$Z_c^{(**)}$
	[m]	[m]	[m]	[m]	[m]
Semi-submerged Loaded	50	56.26	0.00	10.00	57.48
	40	56.26	0.00	12.57	50.05
	30	56.26	0.00	15.17	42.65
Elevated - Loaded	50	56.26	0.00	4.77	64.77
	40	56.26	0.00	8.54	58.54
	30	56.26	0.00	11.14	51.14

(*) Vertical center of gravity Zc measured from the vessel keel

(**) Vertical center of gravity Zc measured from the Seabed



(**): Z_c is measured from the seabed.

Figure 26. Variation of Vertical center of gravity for different for different WD.

When considering the Euler load to identify the theoretical buckling limit, it is expected that with the hull upraise the leg strength against buckling will be reduced inversely proportional to the square of increment of the vertical hull displacement.

$$P_E = \frac{\pi^2 EI}{kL^2} \qquad \textbf{(15)}$$

$$k = \frac{3EI}{cL^3} \qquad \textbf{(16)}$$

Where,

- P_E = Euler Load for vertical columns
- E = Module of elasticity of steel
- I = Moment of Inertia of the cross section
- K = Column effective length factor. $K = 2\sqrt{c}$
- c = Stiffness coefficient. Calculated with the bending flexibility and shear flexibility of the column. Further detailed calculation procedure is given in Appendix A-A.1 of DNV RP-C104

The column effective length factor plays a crucial role for the length strength since it depends on the type of fixation connection (defined by the leg penetration and soil properties). As more rigid the soil-leg connection, the buckling limit is expected to be reduced. In the same way, as more slender the column, buckling limit will be reduced.

Certainly the lateral stability of the column will depend on the ratio between the axial load being applied and the column geometry. Shorter Columns will be more stable and as lower the axial load, lower the lateral deformation. Semi-submerged operational condition will be less sensible to lateral displacements since no preloading on legs is given, contrary to the elevated condition where legs are submitted to axial loads so P-Delta effect will be significant.

4.2.3 Model Inertial properties

When verifying the effect geometry changes on the structure inertia, interesting results are founded (valid for the model and water depth range considered).

Since the structure is attached to the seabed, the structure will be likely to rotate from a point in the bottom, contrary to the case when the vessel is floating where the rotation is made from the longitudinal center of flotation. In consequence, we must focus on the inertial properties measured from the center of rotation.

Figures 27 and 29 shows the variation of the main moments of inertia I_{xx} and I_{yy} with the water depth. Each of them define the resistance capacity of the structure to be moved for the sway and surge motion respectively.

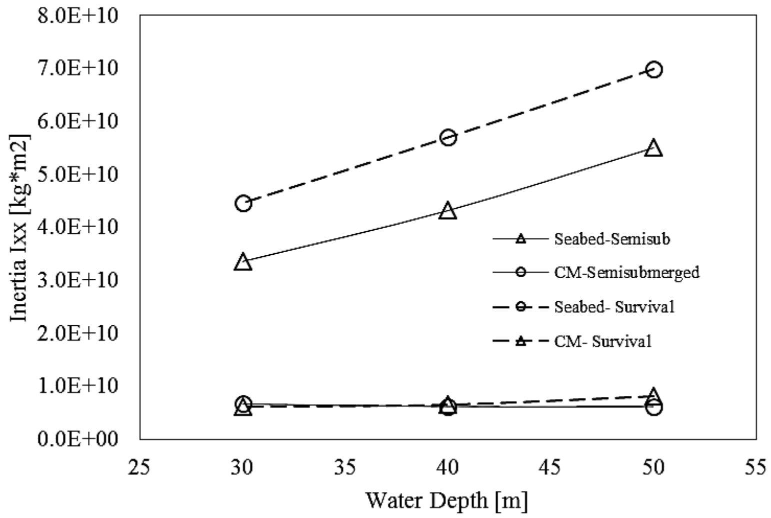


Figure 27. Variation of I_{xx} for different for different WD.

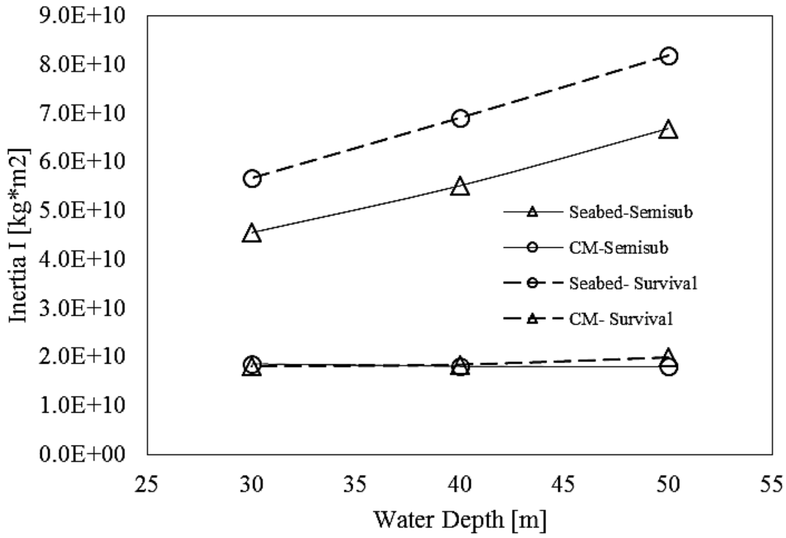


Figure 28. Variation of I_{yy} for different for different WD.

Here is notice that semi submerged condition will be likely to rotate easier than the elevated (survival) condition since the inertia in the main directions is smaller when compared. This reveals that under the same loading, by means of a static load supposal, the semi-submerged condition will present larger displacements.

In particular to the semi-submerged condition, I_{xx} is around 35% smaller than I_{yy} for the range of water depth considered. This founding reveals that it will be expected to have larger displacements and so load increments for beam sea headings than for head or following seas. Values of inertias can be observed in table 5 and 6.

Table 5. Inertial Properties for different geometrical configurations at CM.

Operational Condition	WD	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{xz}
	[m]	[kg*m^2]	[kg*m^2]	[kg*m^2]	[kg*m^2]	[kg*m^2]	[kg*m^2]
Semi-submerged Loaded	50	1.82E+10	6.24E+09	1.67E+10	-2.66E+09	-6.56E+05	-5.17E+07
	40	1.81E+10	6.18E+09	1.66E+10	-2.66E+06	-8.88E+05	-7.75E+07
	30	1.86E+10	6.69E+09	1.66E+10	-2.66E+06	-1.12E+06	-1.03E+08
Elevated - Loaded	50	1.94E+10	7.46E+09	1.67E+10	-2.66E+06	-2.97E+05	-1.16E+07
	40	1.84E+10	6.51E+09	1.67E+10	-2.66E+06	-5.29E+05	-3.74E+07
	30	1.87E+10	6.14E+09	1.66E+10	-2.66E+06	-7.61E+05	-6.33E+07

Table 6. Main moments of inertia measured at the sea bottom level.

WATER DEPTH	Measured from the seabed				Measured from the CM			
	Ixx		Iyy		Ixx		Iyy	
	kg*m^2		kg*m^2		kg*m^2		kg*m^2	
[m]	SEMISUB	SURVIVAL	SEMISUB	SURVIVAL	SEMISUB	SURVIVAL	SEMISUB	SURVIVAL
50	5.50E+10	7.00E+10	6.69E+10	8.18E+10	6.21E+09	8.04E+09	1.80E+10	1.99E+10
40	4.32E+10	5.71E+10	5.51E+10	6.90E+10	6.18E+09	6.51E+09	1.81E+10	1.84E+10
30	3.36E+10	4.47E+10	4.55E+10	5.67E+10	6.69E+09	6.14E+09	1.86E+10	1.81E+10

The ups and down of the I_{xx} and I_{yy} is justified due to the inertial contribution of the legs when combined with the hull.

The previous description will be valid just for this particular case and it cannot be generalized as a global tendency for all WTIU. A particular study should be carried covering this aspect to understand how the structure rigidity is affected.

It is expected for the cases when the inertia increase under the same environmental exposure, hull sway and dynamic effects will reduce and so they will increase when decreasing the inertia in the directions considered. Thus, it is suppose that beam seas will present higher loading conditions in the support points.

4.3 Simulation Model

The simulation consists in the preparation of 2 sub-models that are:

- A hydrodynamic model for numerical simulation of vessel rigid body motion in waves and calculation of the hydrodynamic loads in terms of pressure fields acting on the structure surface. Simulations in this study are performed in frequency domain.
- A structural model where static or dynamic equations of motion are solved. The finite element model is used to solve the equations where a failure criteria may be stablished and for the structural assessment of the vessel design.

Sections 4.4 and 4.5 will present the general considerations for the preparation of the sub-models.

4.4 Structural Model

The geometrical FE structural model was prepared with Sesam GeniE, a software tool developed by DNV GL aimed for the design and analysis of fixed and floating offshore. The FE model consists of four legs, jack houses and hull. The spudcans were not modeled since no specific design is intended to be evaluated so they were modeled as pined boundary conditions located in the point where soil-leg connection is given. For the modeling of the structure, principal and secondary structural members are represented. Details of the structural arrangement are provided by DNV GL Gdynia office to perform realistic calculations however, they are subject to confidentiality and will not be presented in this document. The modelling is performed in accordance with the Class Guidelines of DNV GL – CG – 0127 (2015) briefly commented below.

The global model is prepared to represent accurately the global stiffness with respect to the objective for the analysis. The model is used to calculate nominal global stresses in primary members away from areas with stress concentrations. Such areas where local stresses are to be assessed are out of the scope of the global analysis and local models should be used to study the hotspot areas. The global finite element model developed is shown in figure 29.

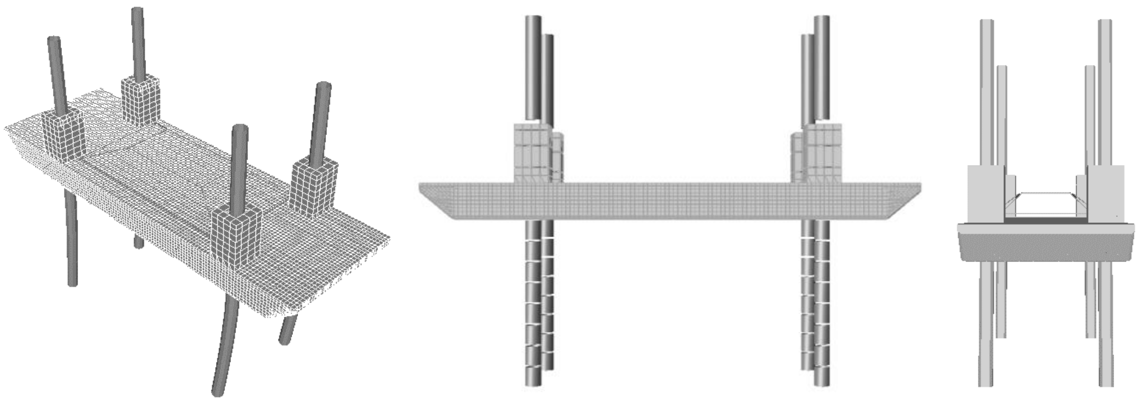


Figure 29. Global FE model build. Loading planes for incoming wave headings. 90 degrees (middle figure) and 180 degrees (rightmost figure).

4.4.1 Principal Structural Elements

The principal structural elements as the hull shell, longitudinal and transversal bulkheads, frames, double bottom, upper deck, jack-house and girders are modeled with 4-node shell elements. Figures 30, 31 and 32 present a 3D view of how the elements where modeled in the software *Sesam GeniE.*

The hull model is composed by shell and beam finite elements. The sectional properties of the particular beams have been set to give the resultant hull section characteristics equal to those obtained in the hull structural design information supplied. Thus the model represents the global hull bending stiffness in the vertical and horizontal direction. The procedure used was the lumping technique which is described later on.

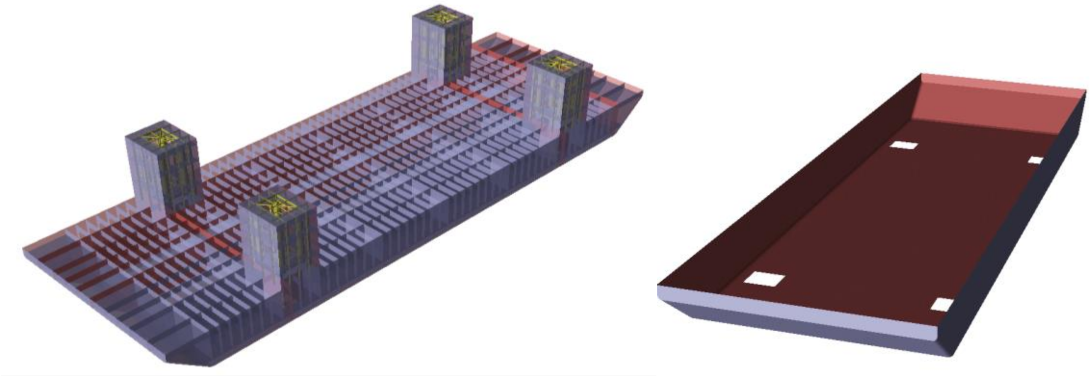


Figure 30. Hull shell and hull structure built.

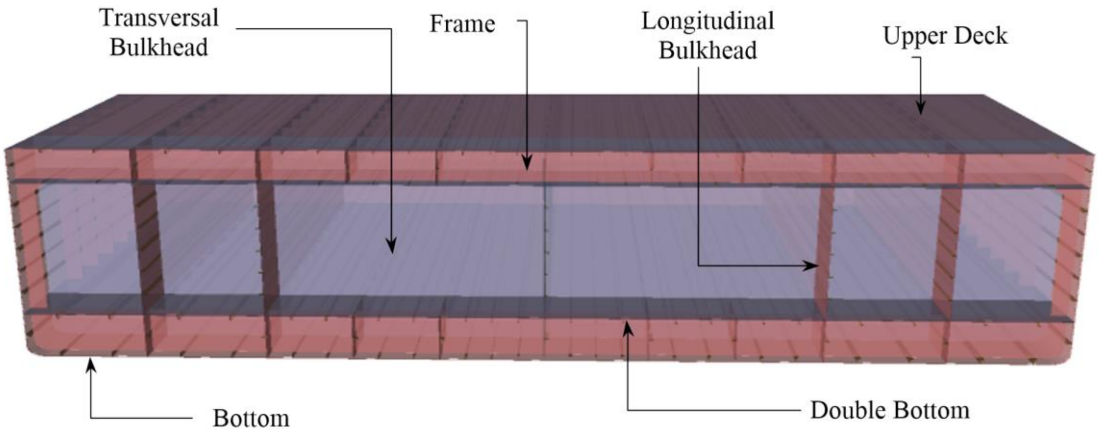


Figure 31. Modeled amidships section description.

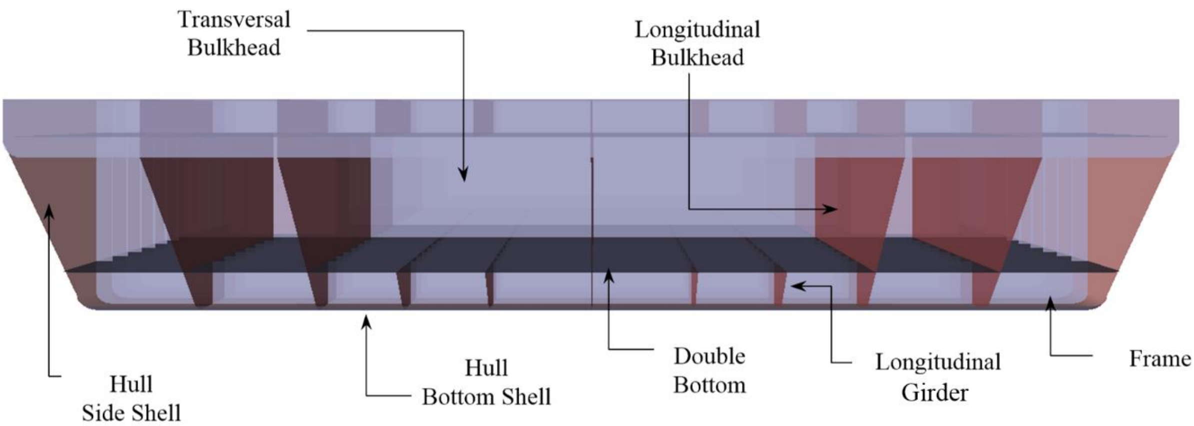


Figure 32. Fore section.

4.4.2 Secondary Structural Elements.

Secondary structural elements as bars, and stiffeners form the hull and jack house structure are modeled with 2-node beam elements. No solid elements where used.
In this thesis, the legs are modelled as 2-node beam elements with specific stiffness. A partition of the hull leg is made in several segments to determine forces in specific points. The beam sectional properties and their longitudinal distribution have been set to represent actual bending and tension/compression stiffness. Since no shell or higher order finite elements are used, the modeling won't allow the verification of high stress concentration points.

Due to the number of stiffeners, a big number of nodes and elements are created when generating the mesh of the model which increases considerably the computational time required to solve the structural problem for 1 set of loads. To avoid such situation the lumping technique is applied with the recommendations of DNV GL Class Guidelines for FE analysis. (DNV GL – CG – 0127, 2015).

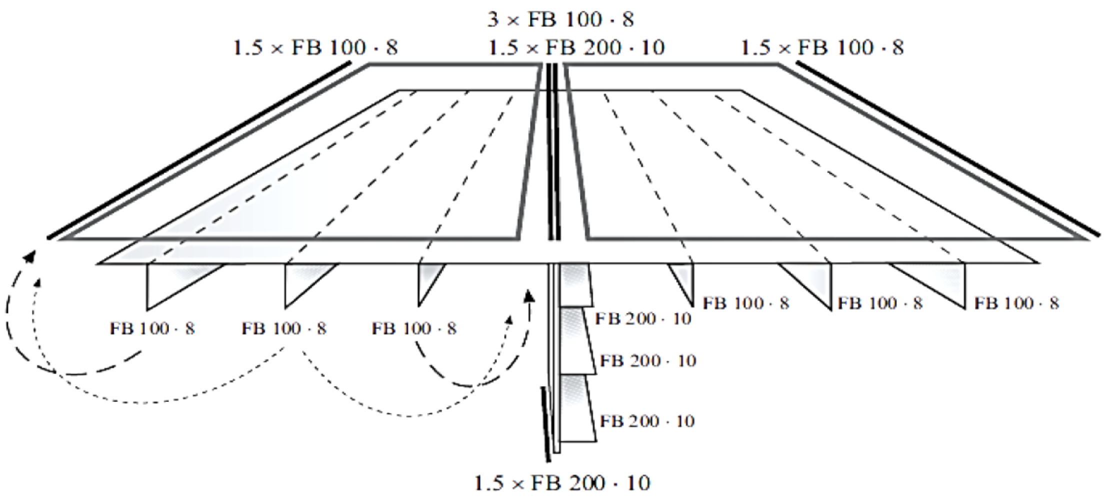


Figure 33. Example of plate and stiffener assemblies. Fig 2-5 DNV GL – CG – 0127

Stiffeners are lumped to the nearest mesh-line and it will remain as beam elements with the only condition that with the merging, the cross-section area of the elements merged is to be the same as the sum of the areas of the lumped stiffeners; bending properties are irrelevant since the objective is to keep constant the ship cross-sectional area. As a criteria, no more than 3 stiffeners are merged in an equivalent element to assure that the stiffness of the panel is not affected due to the geometrical changes. Final FE model is represented with figures 34, 35 and 36.

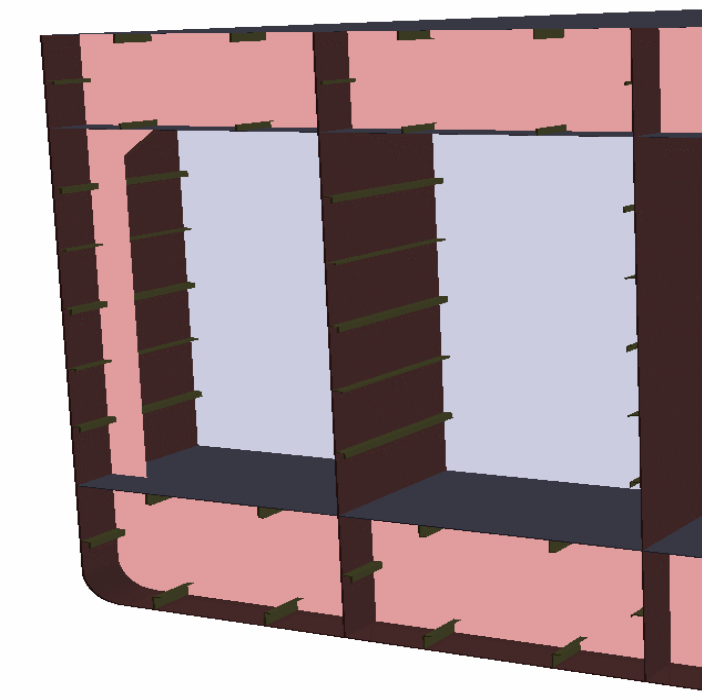


Figure 34. Equivalent stiffener modeling in transversal cross section view.

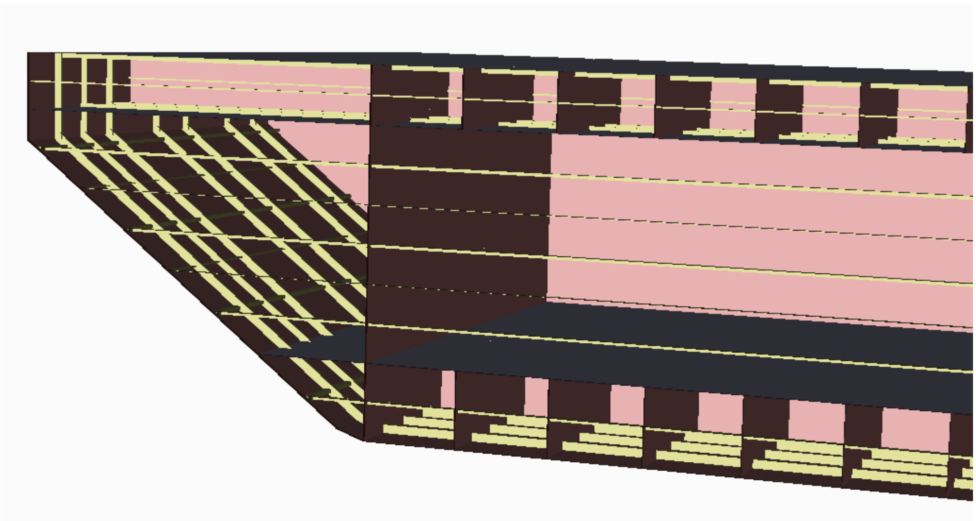


Figure 35. Stiffener modeling in longitudinal section view

One important issue during the structural modeling of WTIV is how is modeled the hull-leg connection since it is commonly the most highly loaded part of a jack-up leg for the elevated condition, just below the lower guide. The leg/hull interaction will mainly depend on the design concept. Three important elements can be identified: the fixation system, the jacking system and the upper & lower guides.

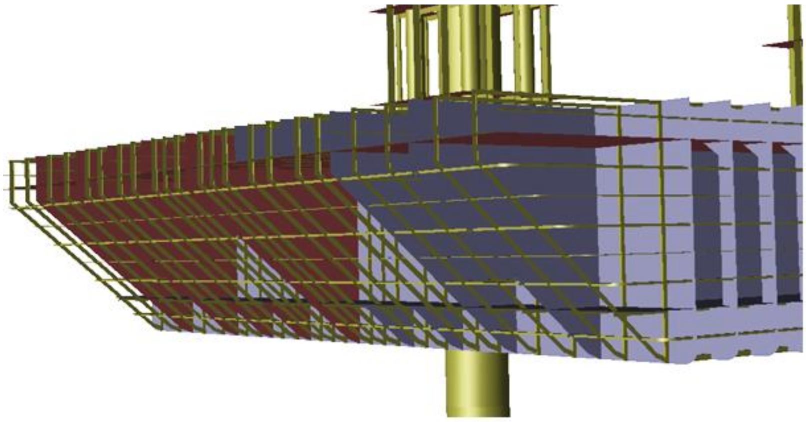


Figure 36. Stiffener modeling in the fore part of the vessel.

The fixation system is a piece of equipment located between the leg and the hull to avoid relative movement of the leg and maintain the desired hull elevation. The fixation system can be racks, pinions or rigid bars which secure the leg, transmitting bending moment between leg and hull by vertical tension and compression. In this condition the legs are not in touch with the guides so no additional forces are transmitted from the legs to the jack-house and hull. A representation of the elements described is presented in figure 37.

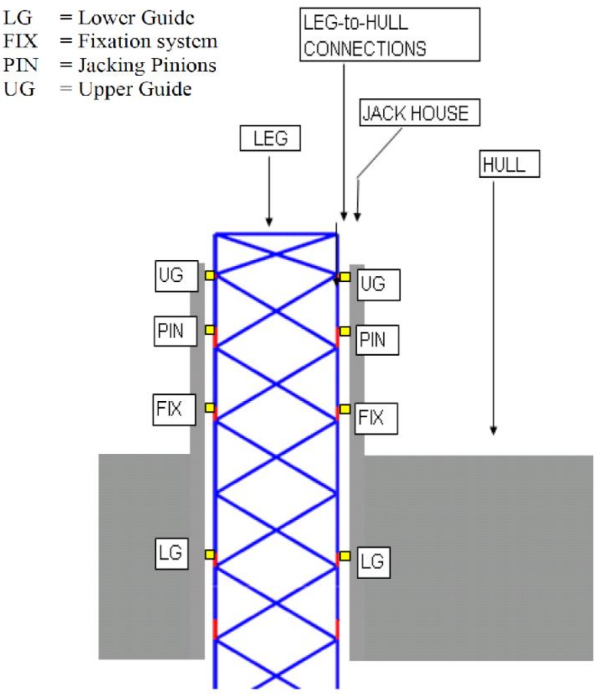


Figure 37. Typical leg-to-hull connection detailed leg model. Hull and jack house simplified with beams. Fig 4-3 DNV GL – RP – C104.

The jacking system is a set of components rigidly attached to the jack-house and so to the hull. This system is the one that makes possible the raising of the vessel. Gears with pinions, pin and hole hydraulic systems, etc. Under environmental loading such system lightly rotates and the guides come into contact with legs distributing considerable a portion of the leg bending moment.

The upper and lower guides are part of the jack-house structure which will mainly support the leg when given a rotation due to environmental loading, misalignment or other. The guides will mainly transfer horizontal forces between the legs and hull structure. The figure shows how the low transfer is given.

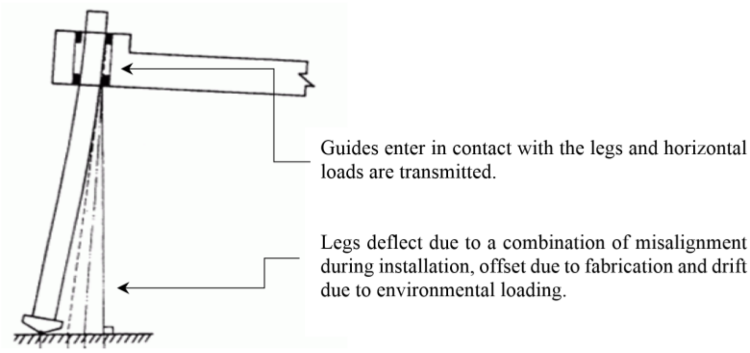


Figure 38. Contact between legs and guides. Fig 4-8 DNV GL RP – C104

DNV GL Gdynia office provided a simplified jack house model performed in previous research studies. Legs are built up by a steel tube with a diameter of 4 meters with holes for the jacking pins driven with a hydraulic system. Holes are not modeled in this case. Figures are now presented where it is shown how the jack-house and the elements of the jacking system where modeled. Figure 39 represents the jack-hose FE model.

With the application of beam elements for the leg modelling, it is considered for the analysis the usage of rigid bars to model the leg hull interaction. The bars acts as a representation of the fixation system during the elevated condition connected to the hull and jack-house in 8 nodes per plane (one plane at the hull bottom and another in the top of the jack-house). The objective is somehow emulate a rigid connection representing the fact that the the leg cross section remain constant. Better modeling methodologies will be available in other references as well it is known that the usage of shell elements will offer a much better solution however, this technique was selected since from previous studies performed by DNV GL Gdynia, the approach is suitable for the global understanding of the structural interaction. Figures 40 represent the dianl representation of the leg-hull connection.

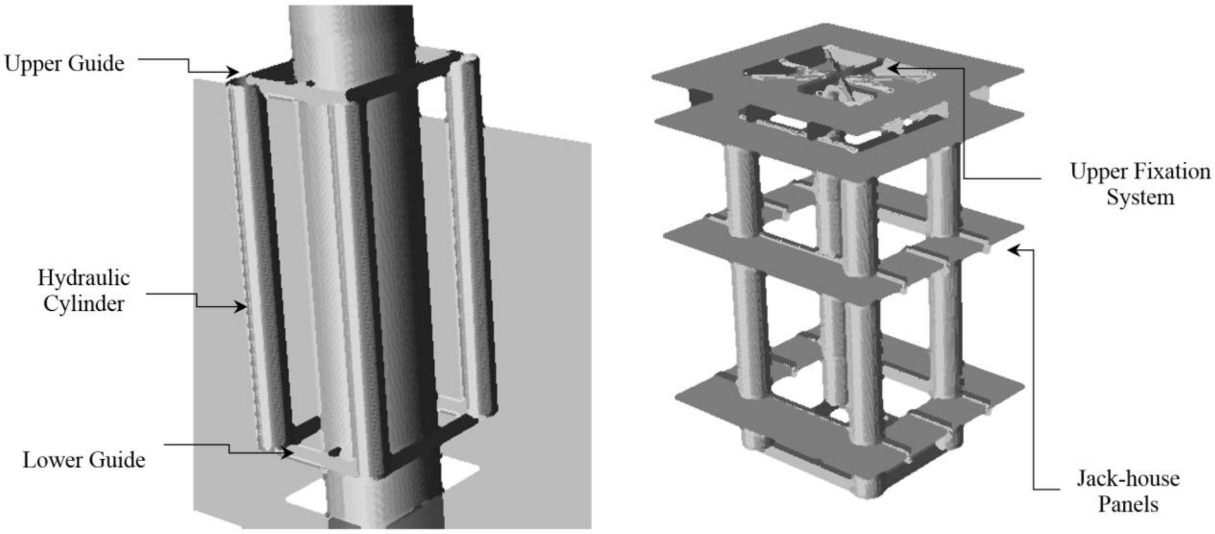
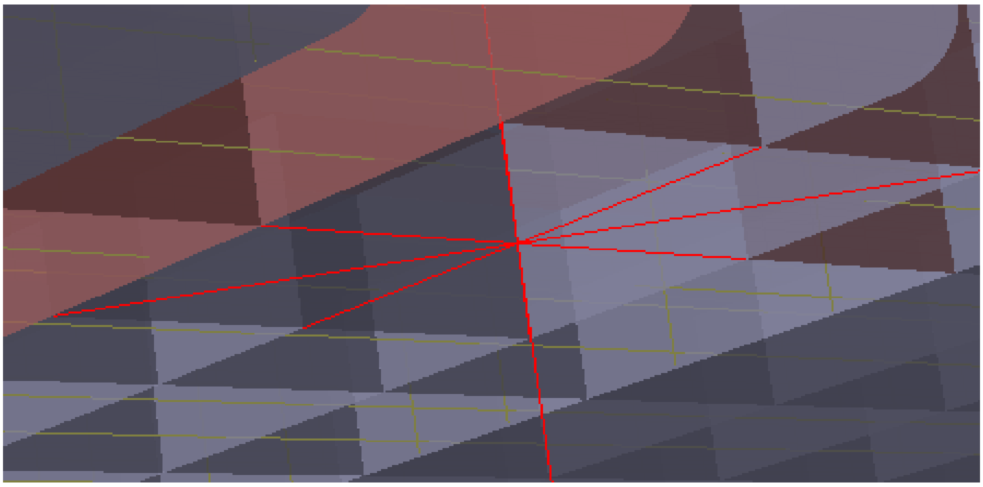
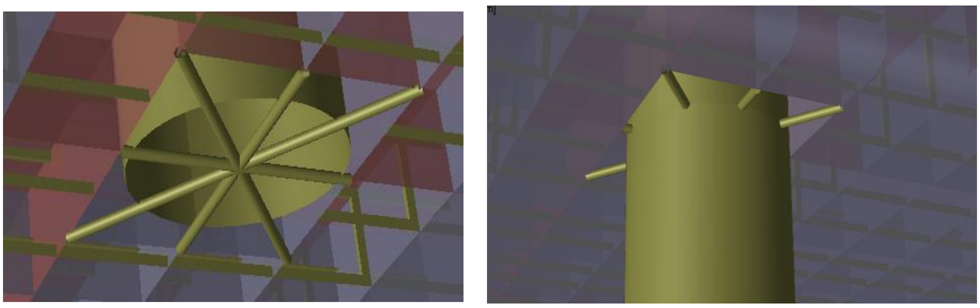


Figure 39. Contact between legs and guides.



(a)



(b) (c)

Figure 40. (a) Construction of the Leg-Hull connection with beam elements.
(b) Leg guides modeled as rigid bars and the interception serves as connection.
(c) Lower part of the leg joined at the bars interception.

4.4.3 Deck loads and Boundary Conditions

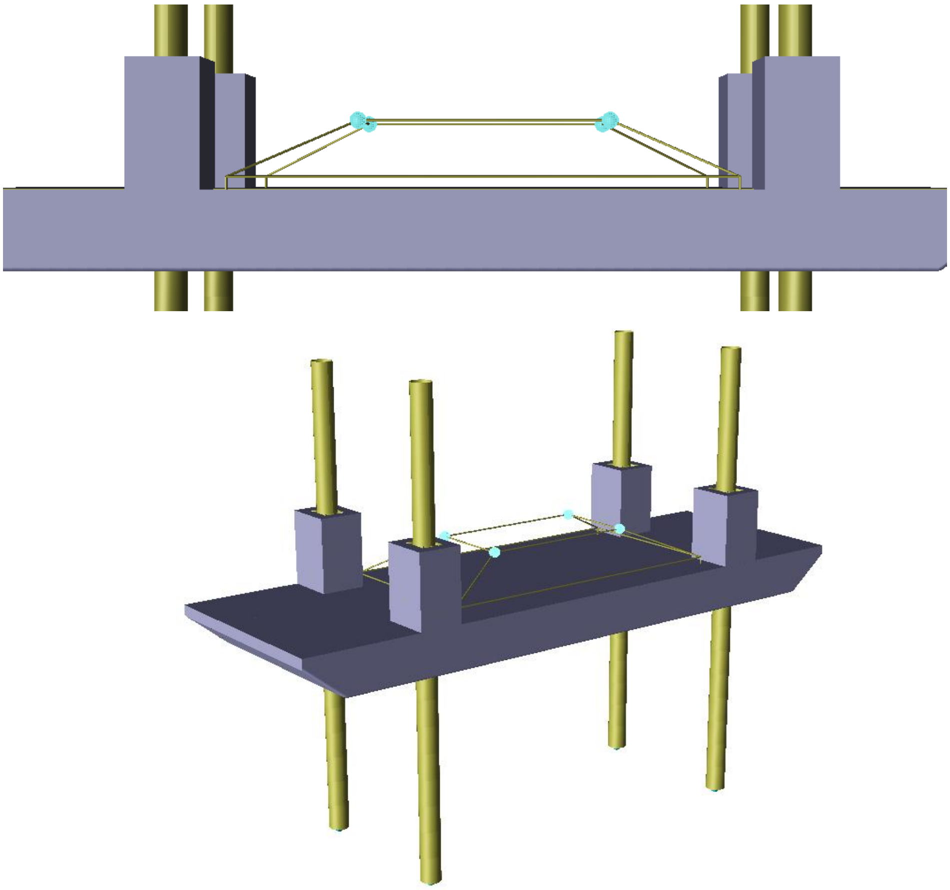
When the structure is modeled, loading conditions and boundary conditions are the next stages for the global model. A deck load of 5000 tones is considered to be distributed in the middle deck area to represent the components of the wind turbines to be installed. To model such loads, mass points are used and they are located in a weightless rigid structure. This is done to consider such mass (total of 15000 Tones) for the modal and dynamic analysis. Bars are modelled rigidly, with really small cross section and massless, so these parameters won't affect the main structural frequencies. Figure 41 exemplify a WTIV in transient phases and figure 42 shows the final representation of FE model developed for our studies.

Figure 41. Example of WTIV during transient phase and cargo on deck. http://www.siemens.com/press/pool/de/pressebilder/2011/industry_solutions/300dpi/IIS201104935-01_300dpi.jpg

A key step for the FE model is define the boundary conditions. As it was commented in previous sections, this represents an issue of special worry for WTIV modeling since the dynamic response of the structure can be conditioned for such restrictions. According to DNV standards and other references discussed in other sections, the possible boundary conditions for the elevated condition are:

- Fix Boundary conditions
- Pinned Boundary condition
- Spring Boundary conditions
- Linear and non-linear foundation models

- Solid linear and non-linear FE model of the foundation.



(a)

(b)

Figure 42. (a) Model of deck load in FE model; (b) Isometric view of model arrangement.

The type of restriction at the leg-soil connection will produce loads on the lower parts of the legs in lesser or major proportion since this also defines the rigidity of the structure. At the end it will be a matter of the combination of soil stiffness, hydrodynamic damping, soil damping, and total mass with the structural stiffness and structural damping (which are constant in time). Additionally, each of this parameters will vary depending of the input frequency (contrary to the structural stiffness and damping) which complicates the calculation process due to the non-linear interactions. Finally, for the purposes of the investigation carried, pinned condition at the bottom leg connection is assumed since many years from now, modeling of jack-up structures had been carried with such assumptions as conservative way to examine the order of magnitude of the loads and the structure response. If needed a site specific response, modeling non-linear foundation models should be considered for the most suitable and less conservative solution. Figure 43 shows the equivalent representation of the fixation type used for the study.

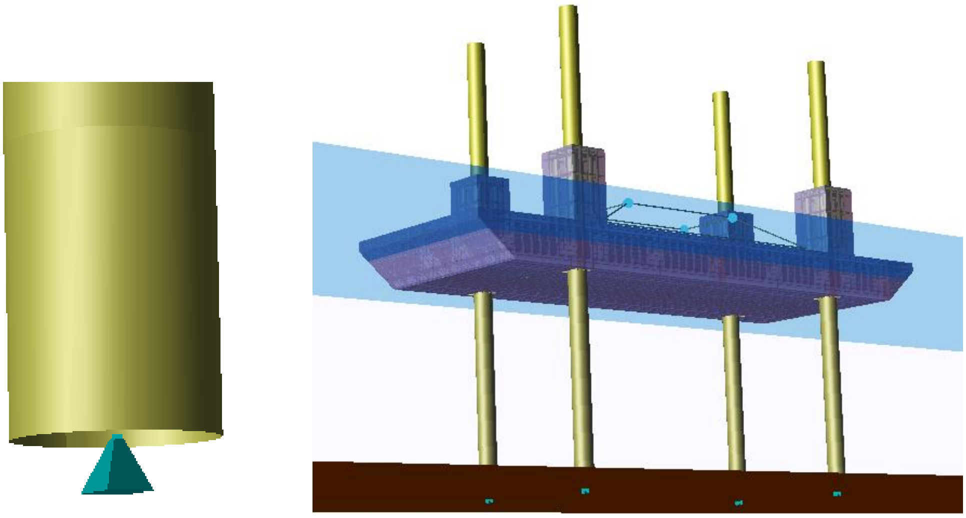


Figure 43. Leg boundary condition in beam element (at node) and final structural model of WTIU

4.4.4 Meshing

The meshing of the structural model is the last but not less important parameter for the FE modeling. Structural response results depend in high proportion on the mesh density. The criteria's stablished in DNV GL- CG- 0127 and DNV GL –RP – C104 are considered and maximum mesh size should be decided considering a proper stiffness representation and load distribution as commented in previous sections of this document.

The standard mesh arrangement is modeled in a way that the grid points are located at the intersection of primary members. In general, the maximum element size taken was in a way to have at least one element between each longitudinal girder, stiffener, and transverse webs. I.e the minimum value between this 3 spacing's is considered as the *nxn* size for the meshing.

The aspect ratio of the elements was considered not be bigger than 4 and lower than 2. If the elements does not meet the criteria, these were divided in 2 defining triangular elements until a proper element shape was found. The stiffener spacing before applying the lumping technique was 25 cm but after apply it, and depending of the number of elements merged, the stiffener spacing changed in the side shell, bottom shell and deck. The values used for the element size were 50x50 cm and 75x75 cm.

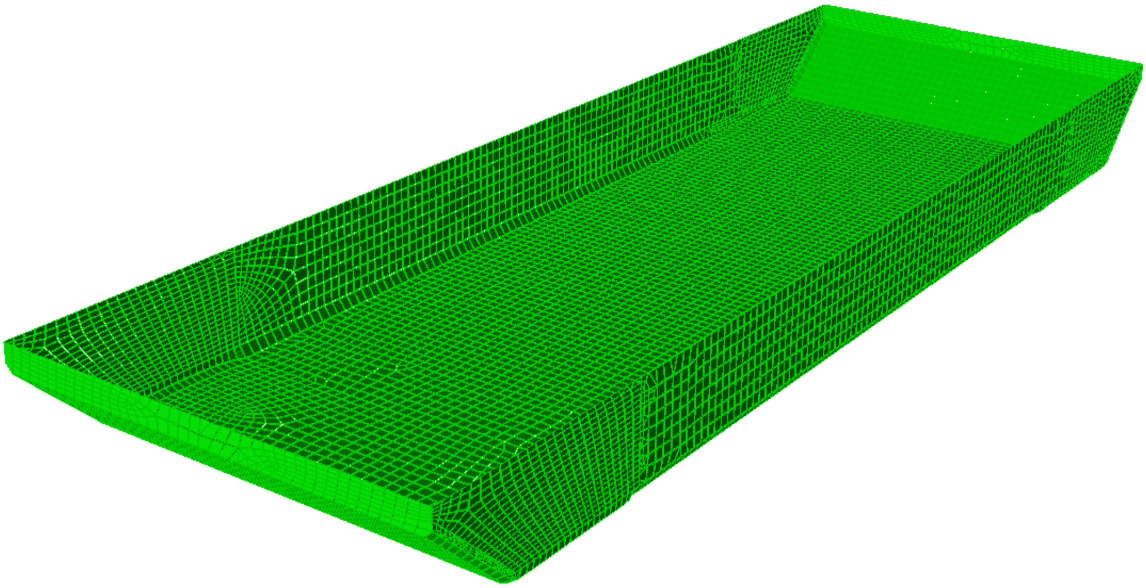


Figure 44. FE Hull mesh build with 4-node shell elements.

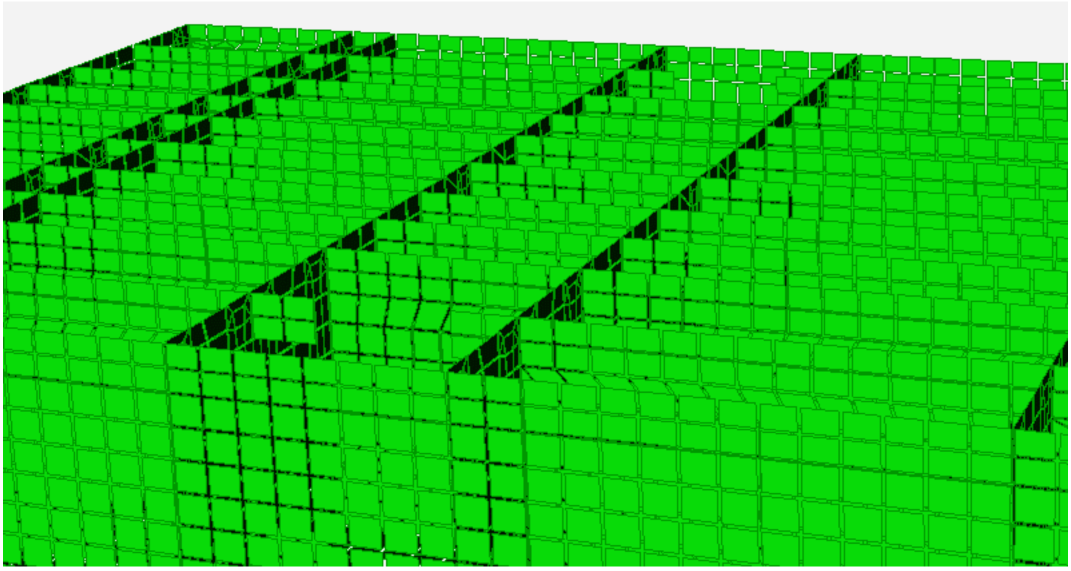


Figure 45. Principal structural element mesh build with 4-node shell elements.

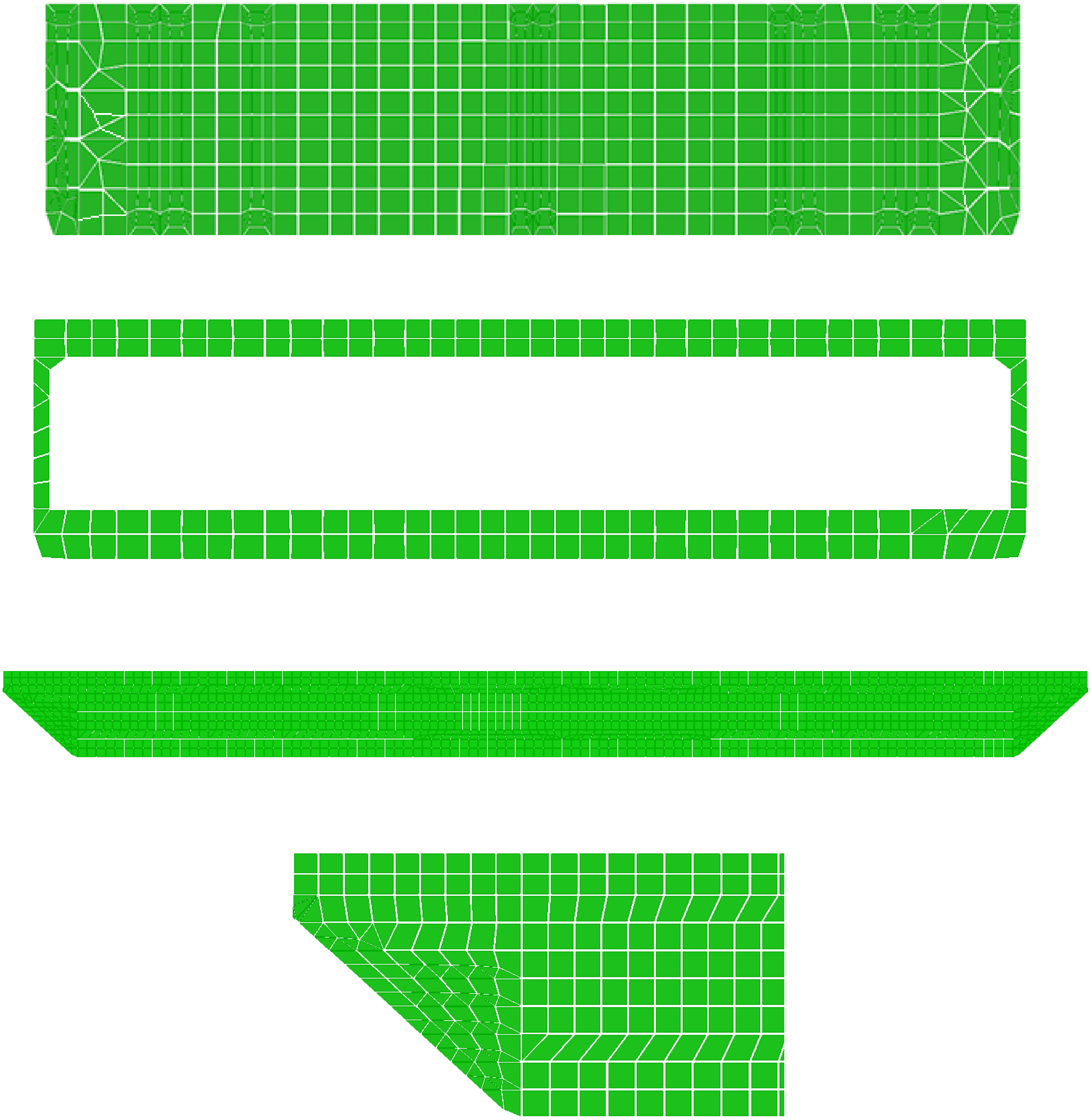


Figure 46. From top to bottom of figure, transversal bulkhead, frame and longitudinal bulkhead mesh.

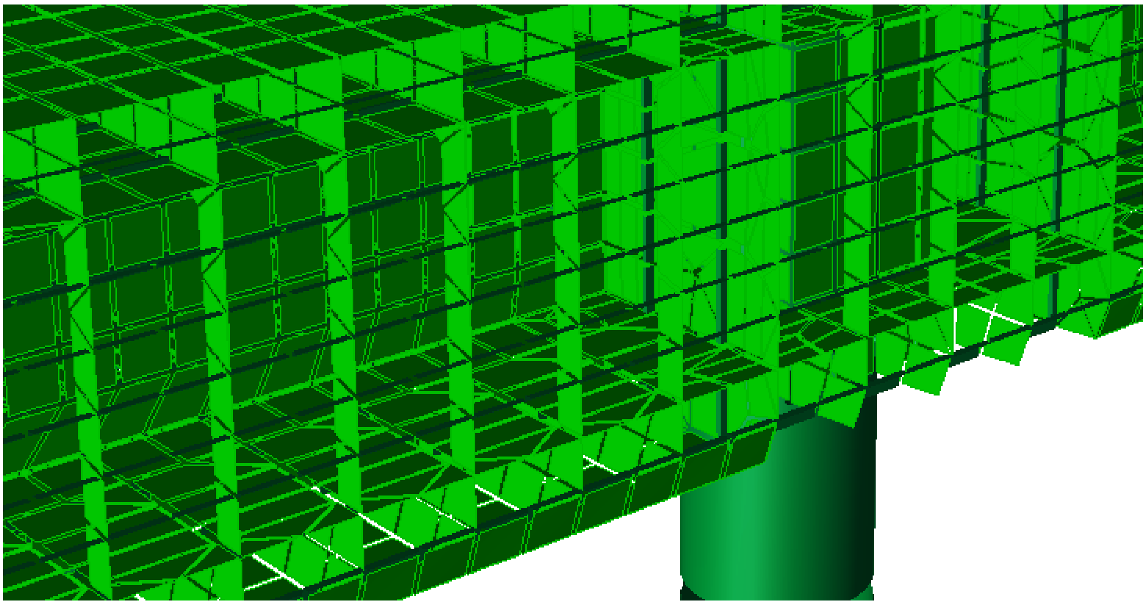


Figure 47. Mesh arrangement. Primary and Secondary structural elements.

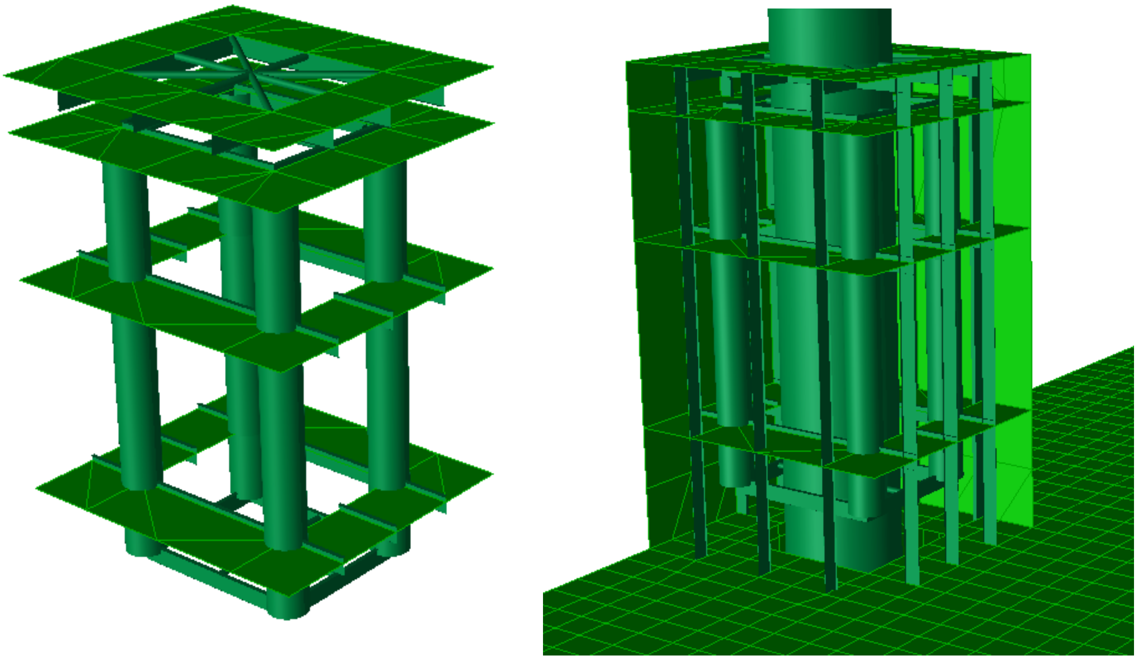


Figure 48. Jack House model mesh.

4.4.5 Modal Analysis

A modal analysis is necessary to identify the structural natural periods for which a verification of the stiffness should be performed. On behalf of this situation, a fully detailed FE model is developed without the application of the lumping technique and main geometrical properties and Eigen values are identified. The method used for the modal analysis is the Lanczos eigenvalue method available in the *Sesam GeniE* software. Since the number of elements and nodes generated for this model implies long computational time (up to 24 hours for the modal analysis and around 3 hours for a static solution with a two 2.2 Hz processor, 8 core each and 128 Gb of Ram), a simplification of the model is performed applying the lumping technique where stiffeners are merged to reduce the amount of elements and nodes.

The lumping procedure is verified using as a comparison criteria the difference between both models regarding the main geometrical parameters and differences between natural periods. The aim of this is mainly to decrease the computational time without scarifying the representation of the global stiffness of the structure. Once the both models are build and the properties are reported, the following features are identified and compared in tables 7 and 8.

Table 7. Detailed and simplified model features comparison.

Model	Mass	X_c	Y_c	Z_c	I_{xx}	I_{yy}	I_{zz}
	[Kg]	[m]	[m]	[m]	[kg*m^2]	[kg*m^2]	[kg*m^2]
Detailed	9693027.67	55.8844	0	7.396	1.69E+10	6.00E+09	1.49E+10
Simplified	9704930	55.9158	0	7.432	1.69E+10	6.00E+09	1.49E+10
Difference	-0.12%	-0.06%	0.00%	-0.49%	-0.15%	-0.05%	-0.25%

Table 8. Structural natural periods for detailed and simplified model

Detailed Model				Simplified Model			
Number of elements		130221		Number of elements		33530	
Number of Nodes		69551		Number of Nodes		15315	
CPU time (hr) - LANCZOS		26.08		CPU time (hr) - LANCZOS		1.08	
No	Eigen Value	Frequency	Period	No	Eigen Value	Frequency	Period
	[1/s^2]	[Hz]	[s]		[1/s^2]	[Hz]	[s]
1	2.37	0.245	4.08	1	2.23	0.24	4.20
2	2.55	0.254	3.94	2	2.30	0.24	4.14
3	2.81	0.267	3.75	3	2.56	0.26	3.92

Small differences are found regarding to the location of the center of mass and moments of inertia in the main directions. Additionally, a significant reduction of the computational time for the modal analysis is reached, with differences up to 5% between the surge, sway and yaw natural periods. Heave, pitch and roll motions are not in the same range of natural frequencies as it’s commented in the previous sections and in DNV GL- RP – C104. In table 9 you can find the values to which it’s making reference.

Table 9. Modal comparison between detailed and simplified models.

Difference # of elements		Reduction 74.3%
Difference # of Nodes		Reduction 78.0%
Difference CPU time (hr) - LANCZOS		Reduction 95.9%
Eigen Value	Frequency	Period
%	%	%
-5.98	-2.94	2.86
-10.71	-5.39	4.96
-9.81	-4.71	4.57

Finally, structural natural response is characterized for every geometrical configuration. Wave induced loads are excluded but stationary and gravity loads as well as legs and hull hydrodynamic added mass are accounted for the calculation of the natural periods for each degree of freedom (DOF). It is known that natural periods will vary depending on the wave incoming frequency since the added mass will change nonetheless, to account such variations the added mass computed by 3D potential flow theory is represented as concentrated masses distributed in the respective nodes, in the areas where the structure is in contact with the fluid. This procedure is automatically performed by the software *HydroD* - *Wadam* (explained in section 4.5) and transmitted to *Sesam GeniE* for the Eigen value calculation of every DOF at each incident wave frequency. These values are used for the dynamic response characterization.

Finally, the structural natural oscillations periods are determined and since no significant variation is found between frequencies, a representative value is given for each NP linked to a DOF and reported in the table 10. This parameter is determined with the representative damping of the structure. Some special comments regarding this aspect are now given:

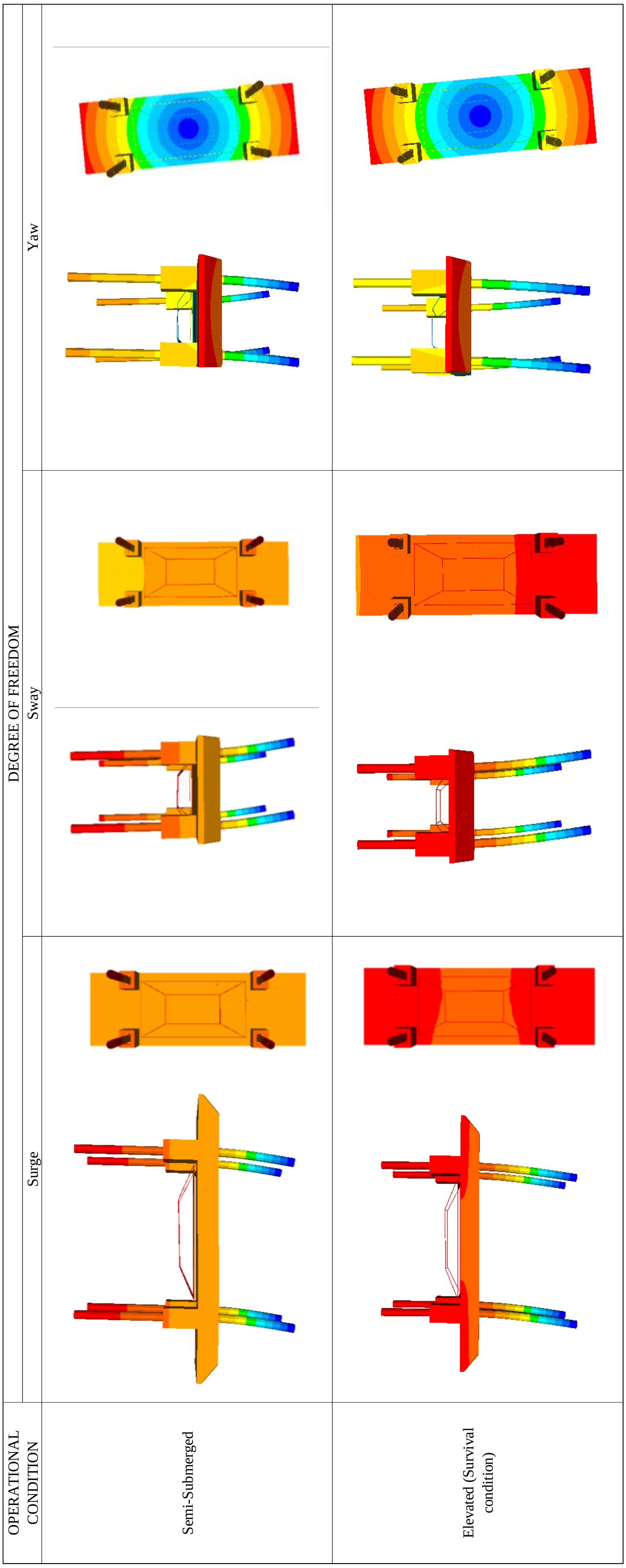
- Cross section of legs generates coefficients of added mass between 1.08 and 0.86 according to Morison formulation, valid for the range of incoming wave periods considered. For the elevated and semi submerged condition, the added mass linked to the legs of the vessel won't affect significantly the total mass matrix since the major contribution is coming from the vessel weight. Thus the added mass of the legs can be neglected as a conservative assumption, and resonance range can be define with an error bar of +/- 10% of the mean value.

Table 10. Structure natural periods for different geometrical configurations.

Operational Condition	WD	Surge NP	Sway NP	NF Heave NP
	[m]	[s]	[s]	[s]
Semi-submerged Loaded	50	4.20	4.14	3.92
	40	2.74	2.70	2.12
	30	1.98	1.94	1.52
Elevated - Loaded	50	5.28	5.24	4.16
	40	4.21	4.16	3.30
	30	3.23	3.18	2.52

A representation is now given with figure 49 to show the body displacements for every DOF through a color code comparison. The red color characterize higher displacements, while blue represents nodes with zero displacement.

Figure 49. Graphical comparison of modal response for Semi-submerged and Elevated condition



4.5 Hydrodynamic Model

A hydrodynamic model must be developed to represent the wave and current environmental loads. Considering the operational conditions to be studied, environmental exposure limitations have to be defined for every condition, which essentially are the significant wave height, wave peak period, current velocity and maximum water depth. This has to be done since for every operational condition safety must be guarantee and the merely method to do it is establishing operational limits. Some guidelines to define the operational environmental limitations can be consulted in DNVGL standards and recommended practices (DNV-OS-J301).

4.5.1 Environmental Parameters

For the semi-submerged and the elevated (survival) condition, the parameters considered for the environmental load modelling are presented in table 11.

Table 11. Environmental exposure limitations

PARAMETER	UNITS	SEMI-SUBMERGED	ELEVATED
Significant Wave Height, H_s	[m]	2	10
Peak Period, T_p	[s]	2.5 – 5.5	2.5 – 5.5
Incoming wave frequency range$^{(*)}$	[s]	1 – 13	1 – 13
Current Velocity, U_0	[m/s]	5	5
Max Water Depth, WD_{max}	[m]	50	50

$^{(*)}$The wave height for incident waves is defined by the wave breaking limit at the specific water depth.

The wave periods mentioned are considered to verify the influence of the dynamic effects on the structure response for both operational conditions. The significant wave height represents the maximum wave that the vessel can see for the specific operational condition, i.e. if the Hs is exceeded by the wave breaking limit, Hs will be considered as the maximum wave the vessel will stand meanwhile it is the limit operational condition stablished.

4.5.2 Hydrodynamic Software and Wave Theory.

The software used for the hydrodynamic calculations was a DNV GL software tool called *HydroD WADAM*. It is an interactive tool developed for computation of hydrostatics and stability, as well as wave loads and motion response for ships and offshore structures.

The software is a 3D potential flow solver able to determine the wave kinematics with either incident or diffractive wave, for hydrodynamic load calculations on irregular bodies. This software is capable to embrace the following parameters:

- Hydrostatic data and inertial properties
- Response amplitude operator calculation comprising:
    - First and second order wave exciting forces and moments (incident and diffractive wave)
    - Hydrodynamic added mass and damping
    - First and second order rigid body motions
    - Sectional forces and moments
    - Steady drift forces and moments
    - Wave drift damping coefficients
    - Internal tank pressures

- Calculation of selected global responses of a multi-body system
- Automatic load transfer to a finite element model for subsequent structural analysis including:
    - Inertia loads
    - Line loads for structural beam element analysis
    - Pressure loads for structural shell/solid element analysis
    - Pressure loads up to the free surface

Since our interest is characterize the global structure response and not a site specific assessment, regular waves are considered for the modeling, wave non-linearity's are neglected since output of the analysis will be just the structure RAO's, and a constant current profile is considered with a velocity of 5 [m/s] for drag linearization of Morison equation. The following assumptions are considered for wave and current loads on the legs and hull of the case of study.

Regarding to the regular wave theory applied the following aspects are considered

- 3D potential flow theory in combination with diffractive wave is used to solve the wave kinematics and pressure field on the hull. Direct numerical integration in frequency domain is performed to determine the pressure distribution on the hull surface considering the hydrostatic condition and linear wave loading. This procedure is valid just for large bodies since Potential flow theory is not considering the flow detachment thus it neglect the drag forces
- First order velocity potential is used to determine the wave kinematics and no further orders are considered in this study, thus wave harmonics are not accounted in the structure response.

4.5.3 Wave Propagation and Wave Breaking Limit

- The wave propagation and current directions are collinear. Wave headings considered for the study are head sea (180 degrees) and beam sea (90 degrees). The objective is to identify separately the surge and the sway motion of the structure. Besides no further headings are investigated, it is assumed and expected that beam sea heading will be the critical heading since a more hull area is exposed to hydrodynamic wave loading.
- The design wave height considered for a given wave period (wave length) satisfies the largest wave steepness condition determined with the procedure stablish in the point 3.4.6.1 form the standard DNV – RP – C205 (Maximum wave height and breaking waves in shallow water).

$$\frac{H_b}{\lambda} = 0.142 \tanh \frac{2\pi d}{\lambda} \tag{15}$$

Where,

H_b: Wave breaking limit

λ: Wave length

d: Water depth

Figure 50 represents the wave breaking limit for different water depths as well as the maximum wave height exposure for each operational condition.

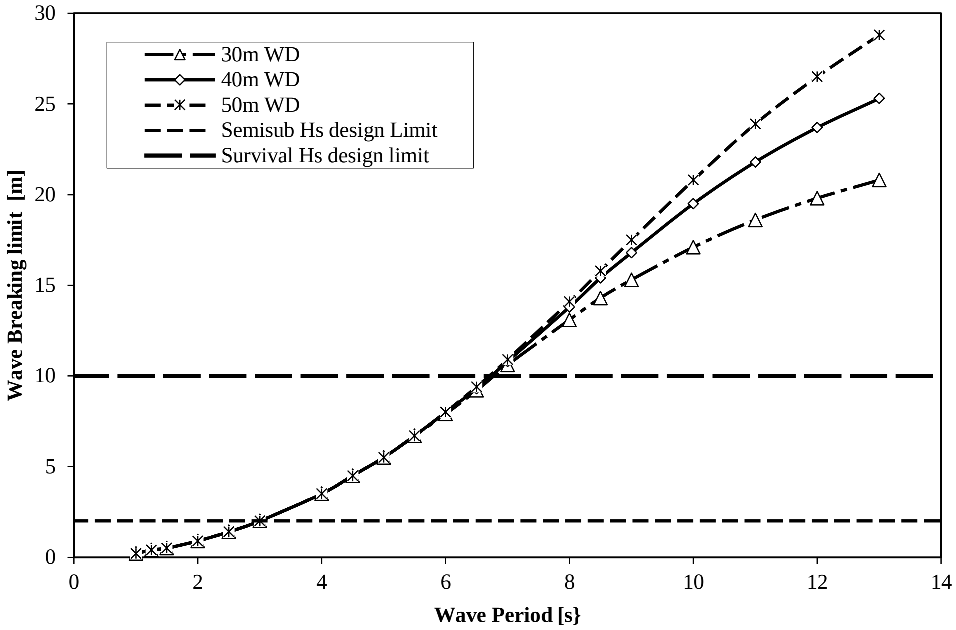


Figure 50. Wave Breaking Limit at Specific Water Depth

4.5.4 Morison Equation

- For the modelling of the drag forces for small body components the Morison equation is used to solve the wave kinematics determined with the diffractive potential (this since structure is fixed). Drag and added mass coefficients are assumed depending on the leg cross section to determine the slender bodies contribution. The parameters assumed for the 4[m] leg diameter were: Morison properties considered are presented in table 12.

Table 12. Morison properties for Vessel Leg. Added mass and drag coefficients for hydrodynamic calculations.

PARAMETER	VALUE	UNIT
Diameter	4	[m]
Thickness	0.1	[m]
Cd	0.7	[-]
Ca	1	[1]

In the case of bodies presenting non-negligible drag and inertial effect (i.e. a non-negligible combination of inertial and drag loads), the following procedure is applied:

- For large bodies where drag forces cannot be neglected, inertial loads may not be sufficient to describe the loads acting on the body and either the added mass and damping. For such cases a better approach for such parameters can be obtained correcting the added mass and potential damping with the contribution of mass and damping due to viscous drag. This can be determined applying the Morison formulation.
- Morison formulation will consider the characteristic length of the geometry (Leg diameter) and wave kinematics obtained from recognized numerical methods that don't consider viscous effects (In first instance Potential Flow Theory). Drag coefficients used are taken from tables reporting such parameters, or eventually from similar or equivalent cross sections. Later, superposition of both effects (Inertial + Viscous loads) is performed to correct the loads acting on the bodies, and to correct the total added mass and hydrodynamic damping.

The WTIV is analyzed in *HydroD Wadam* defining a "Panel" model, considering the mesh generated for Hull FE model. The pressure distribution around the hull is determined with the diffractive potential and applying direct numerical integration. Since the panel match with the hull mesh of the FE model, hydrodynamic pressure can be transmitted directly to the FE model and equations of motions can be solved under the dynamic wave loading.

Afterwards, a "Morison" model is defined now which comprise the elements where hydrodynamic loads will be determined with the application of the Morison Equation. This applies to the vessel legs since these are consider slender bodies thus the procedure can be applied… Using the properties defined earlier for the legs (added mass and drag force coefficients) and in combination with the wave kinematics, forces are determined and transmitted to the FE model in the same wave is performed with the "Panel" model.

Figure 51 and 52 represents the components of the hydrodynamic model developed in HydroD Wadam.

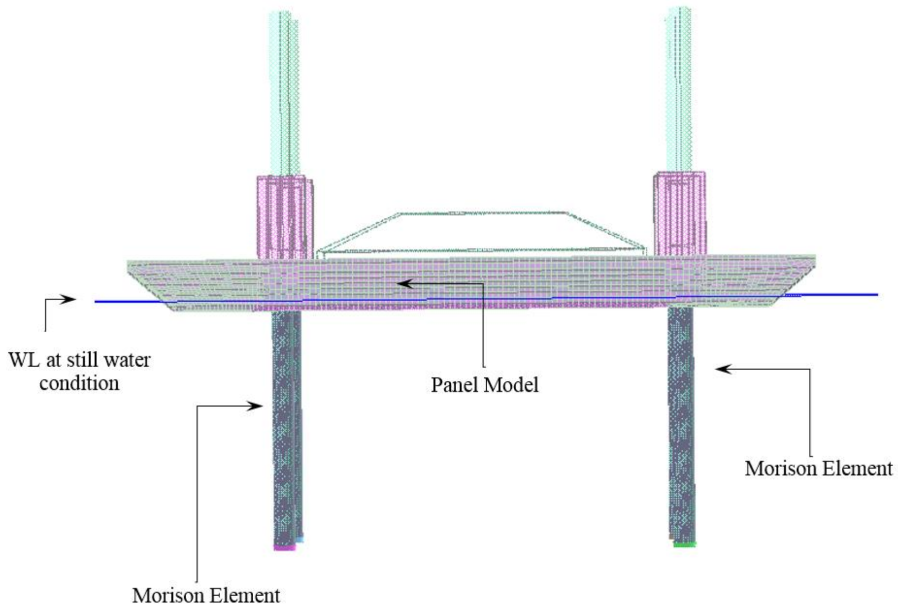


Figure 51. Hydrodynamic model components.

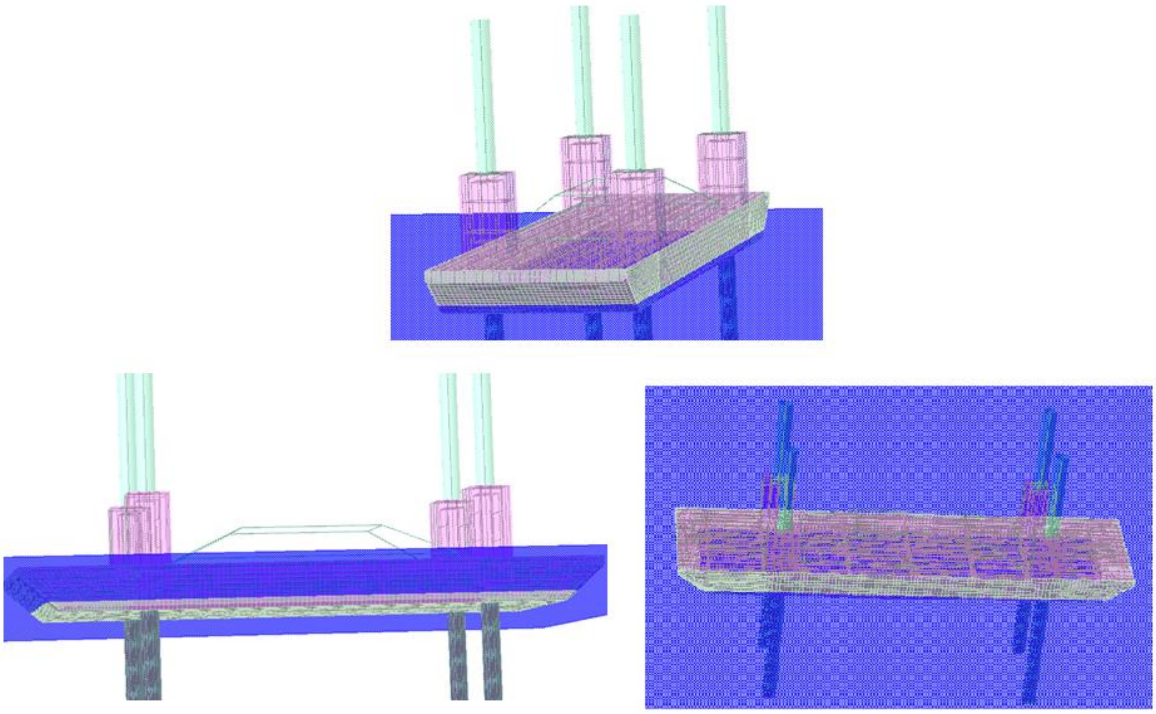


Figure 52. Hydrodynamic model representation in HydroD Wadam.

4.6 Determining Dynamic Response. Data Post Processing

The characterization of the global response analysis implies the handling of a significant amount of data. Thus a data post processing should be performed for which a custom script is built in *Visual Basic (VB) for Applications* from Microsoft Excel for the handling and analysis of the results obtained with the simulation model.

As commented in other sections, model the dynamic response of the structure requires the study of the FE model under dynamic load, here solved with a quasi-static approach to determine the stress distribution of the condition considered. Later, a dynamic amplification factor is used to account the dynamic effects due to the coincidence of wave frequencies and structural natural frequencies (DAF's are modeled as equivalent inertial forces acting on the body). Is a fact that this statement comprise a single case of the entire analysis still, several cases must be analyzed and the process carried for it, is presented below.

- For one specific water depth, hydrodynamic simulations are performed for the range of wave periods defined. A total of 20 periods are considered for every heading. (20 hydrodynamic simulations).
- Headings considered for the analysis were 90 and 180 degrees. This gives a total of 20x2=40 simulations linked to one specific water depth and one operational condition.
- Previous procedures should be performed considering 3 different water depths to verify structure response at different depths. 30, 40 and 50 m depths were considered given a total of 120 simulations at this point.
- Two operational conditions should be analyzed. This document is limited to the study of the semi-submerged and the elevated condition which defines a total of 120x2=240 hydrodynamic analysis.
- Each of this hydrodynamic analysis gives 1 set of external loads acting on the vessel. The structure is solved for every set of loads applying a quasi-static structural analysis therefore a total of 240 structural analysis are executed.
- To consider the dynamic effects, DAF's are determined for every wave period and heading to estimate the equivalent inertial force to be applied on the structure to include the response amplification. This means that 240 inertial loads are determined (one for every simulation) and the structure is solved for each load with a static analysis.
- The data generated from both structural analysis (external loads and inertial loads) is used to build a data base in VB, used to perform the load case combination since such procedure have to be performed manually in the software *Sesam GeniE*. The data base is built considering the base shear on the vessel legs, bending moments and hull displacements in the range considered.
- With the data base, one can emulate different load combinations to generate the dynamic response of the structure for different geometrical configurations without performing additional simulations. Since the analysis considered is a deterministic linear analysis

under linear wave loading, the theorem of superposition is applied for the load combination.

- Once the procedure is established and automatized, just rest to generate a set of load combinations to investigate the influence of certain parameters in the structure dynamic response for both operational conditions.

5 CASES OF STUDY. GLOBAL RESPONSE OF WTIV IN FINITE WATER DEPTHS DURING TRANSIENT PHASES.

In this chapter is presented a detailed explanation of the cases studied to characterize the global response of a WTIV during semi-submerged and elevated condition. The objective is summarize the risk exposure of the vessel when operating in semi-submerged condition compared with the elevated condition. Dynamics had been quantified as well as the effect of the of the water depth in the structure response. Results are presented in terms of reaction forces as base shear and vertical forces, global overturning moment and hull displacements. With the comparative analysis, a risk table is built showing the governing operational condition.

5.1 Case 1. Quasi-Static vs Dynamic Response

To uncover the influence of the dynamic effects on the structure response, a comparison is done between a pure quasi-static analysis vs the dynamic response analysis method proposed in this document. Since *Martin S. and Richard S.G* demonstrate the importance of dynamic effects in an elevated platform (section 3.1), our task is summarized to demonstrate the importance of dynamic effects in the semi-submerged operational condition. For this, information in table 13 and 14 is considered as input for the analysis.

Considering the given input, quasi-static and dynamic analysis are applied and the RAO's of the structure are determined for a 1 [m] wave. The response is described in terms of total base shear, total vertical force, global overturning moment, hull surge and sway drift. Results are now presented and commented.

In the figures 53 and 54 it is presented the DAF of the structure response for incident waves of 90° and 180° (DAF is calculated with equation 8, section 2.7), exciting the sway and surge motion respectively. It's observed that larger amplification is found for the surge motion since its representative damping is lower than the one for the sway motion. This can be justified since when the hull moves, major amount of water is displaced by the hull with the sway motion than for the surge due to additional hull area contribution.

Table 13. Input conditions. Design Parameters Case 1.

Water Depth	50	[m]
Range of wave period	1-13	[s]
Wave Height	1	[m]
Elevated Hull Weight	14.8	[Ton]
Leg Effective Length Factor	2	-
Number of legs	4	-
Leg OD	4	[m]
Leg Thickness	0.1	[m]
Leg ID	3.97	[m]
$\Upsilon_{f,D}$ Load factor for deformation loads	1	-
$\Upsilon_{f,E}$ Load factor for environmental loads	1.3	-
Representative Damping. Semi-submerged		
-Sway	25	[%]
-Surge	15	[%]
Surge NP (T0) Semi-submerged	4.20	[s]
Sway NP (T1) Semi-submerged	4.14	[s]
Yaw NP (T2) Semi-submerged	3.92	[s]

Table 14. Jack-up system geometrical features. Case 1.

Distance between upper to lower guide	24000	[mm]
L.G to base line	2250	[mm]
Air Gap	0	[mm]
Sea bed penetration	5000	[mm]
Clearance of guides	20	[mm]
Fabrication Tolerances (e1)	10.00	[mm]
Hull Leg Clearances (e2)	41.46	[mm]
Heel of Platform (e3)	0.00	[mm]
Total Horizontal Offset (e0)	51	[mm]

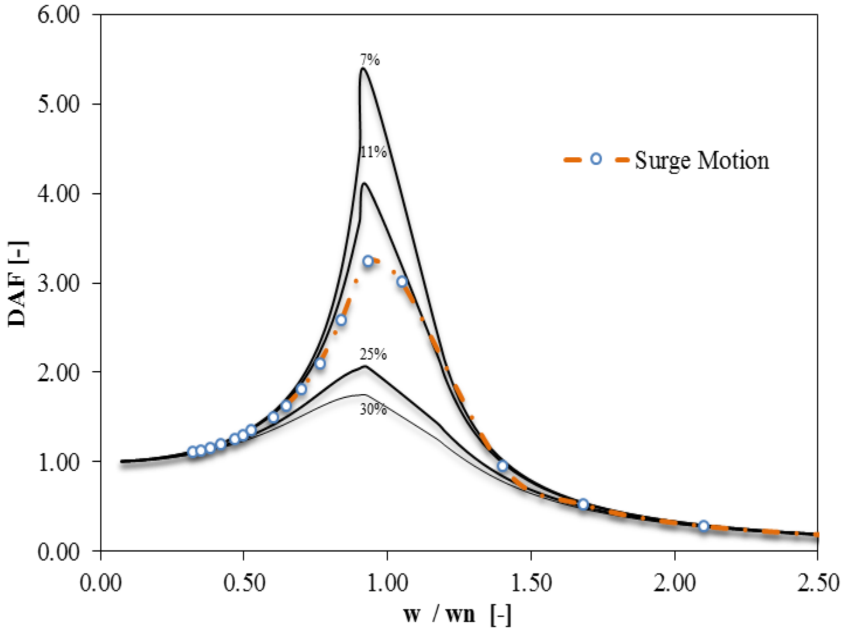


Figure 53. DAF for 180° incident waves. Semisubmerged. Case 1

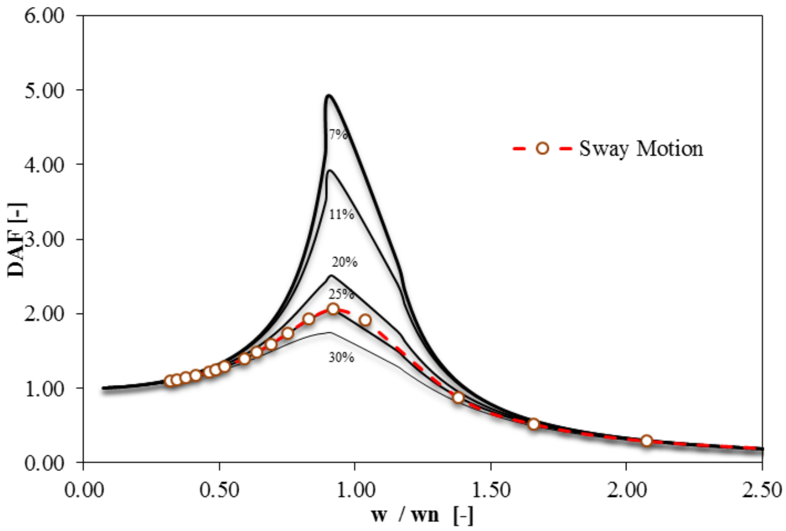


Figure 54. DAF for 90° incident waves. Semisubmerged. Case 1

This higher damping for the 90° incident waves is traduced in lower load increments in the resonance range for the dynamic response. At resonance, it is distinguished that surge motion can be amplified up 3 ½ times regarding to the static response, and 2 times for the sway motion.

When verifying the shear response in figure 55-a, a curve with peaks and troughs on the frequency domain is found. The presence of troughs along the frequency domain is justified by the wave cancelling effect, reliant on the relation between the wave length and leg spacing, and so the relation between the length and breadth of the ship with the wave length. Figure 56 shows how the wave forces act in in opposite way on each pair of legs which reduce the resultant wave load. It is seen that such effect have significant consequences on the structure response. Similar features are found for the vertical force and global overturning moment in the frequency domain.

As regards to the base shear, among all the peaks the maximum values reported are about 10 and 3.7 [MN] for 90° and 180° incident waves respectively. As expected, the 90° heading was the one to present larger base shear.

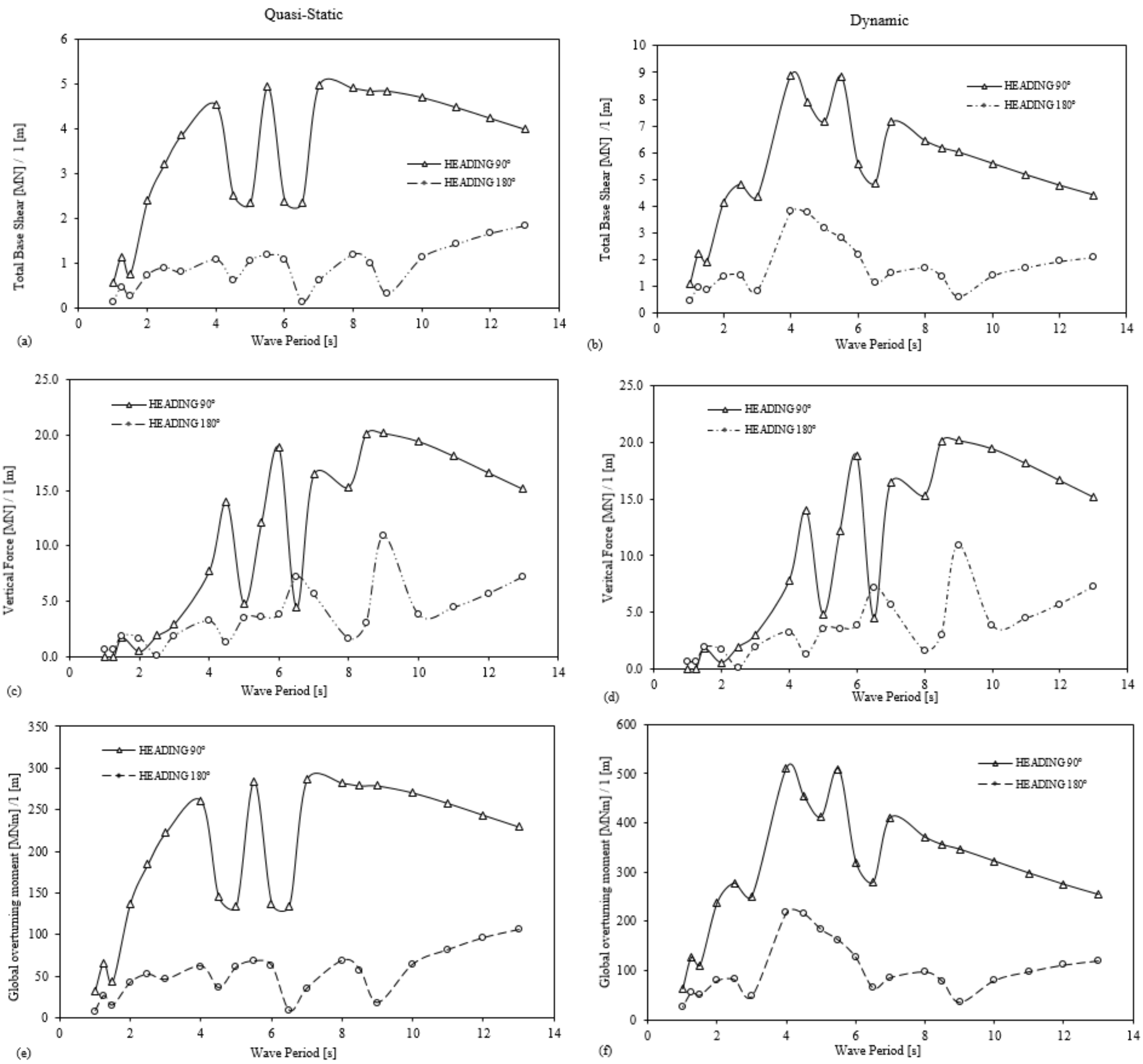


Figure 55. Quasi-static and Dynamic Respoonse for design waves -Case 1. (a) Quasi-static Base Shear; (b) Dynamic Base Shear; (c) Quasi-static Vertical Force; (d) Dynamic Vertical Force; (e)Quasi-static Global Overturning Moment; (f) Dynamic Global Overturning Moment.

The figure 55-b shows the dynamic base shear response of the structure in which load increments are perceived. Maximum values are now registered close to the natural frequencies attributable to resonance effect. Peak values registered are 8.9 and 3.8 [MN] for beam and head seas respectively, revealing load increments of 79% and 107%. Such increments are produced due to dynamic effects as well as P-Delta effect. This values correspond to a 1 m wave and are presented in table 15.

Table 15. Max Base Shear Comparison. Case 1, Quasi-static vs dynamic.

Sea Heading	Base Shear Static	Base Shear Dynamic	Dynamic / Static (DAF B.S)
	[MN]	[MN]	[-]
90°	4.98	8.90	1.79
180°	1.84	3.80	2.07

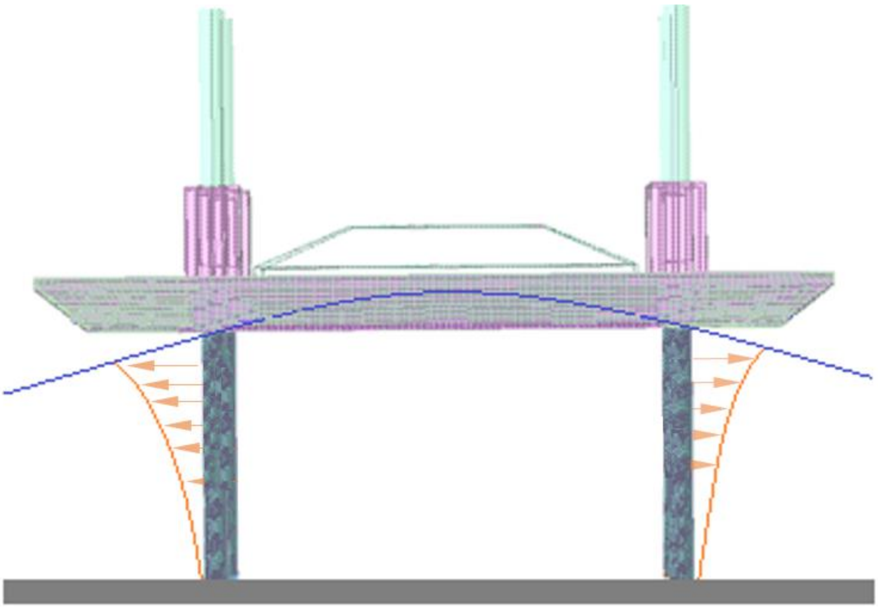


Figure 56. Wave force cancelling representation.

For 180° heading, the total base shear load will increase proportional to the wave period after waves of 9 seconds, taking place due to hull drift. Similar behave can be presented for the 90°, both justified since for long periods the structure will try to follow the wave trajectory which is traduced in Wave length/ Ship length (WL/SL) or Wave length/ Ship Beam (WL/SB) >1.

Vertical reaction forces are generated as a response to the excess of buoyancy caused by the change of the free surface. These are uplift forces that should be considered for any type of analysis since some leg structural elements like spudcans, will be sensible to such forces. For this reason total vertical reaction forces are measured and reported for both analysis.
Heave natural period is larger than the surge and sway natural periods so it won't be excited by the wave frequencies. Hence no significant amplifications are perceived for the vertical forces. Maximum uplift forces are around 22 and 11 [MN] for beam and head seas, this will be an equivalent of 5.5 and 2.75 [MN] of uplift force on each spudcan for a 1 m wave.

Peaks of vertical forces can be located where at the periods where maximum sagging or hogging bending moment are expected. Is in this condition when maximum shear vertical forces can be registered. To observe at which wave periods such effect can occur, table 16 shows a ratio between the wave length with the ship length and beam. Where ratios equal to 1 is traduced to maximum bending moments and vertical forces will be expected.

Figures 55e and 55-f represent the overturning moments for the range of periods considered. Maximum values are found close to the natural periods (4.2 seconds for this case) and they are presented in table 16 and 17.

Table 16. Wave length ratio with ship main geometric parameters.

Wave number	Wave Period	Wave length in [m]			WL/SL			WL/SB		
	[s]	Wd 30m	Wd 40m	Wd 50m	Wd 30m	Wd 40m	Wd 50m	Wd 30m	Wd 40m	Wd 50m
1	13.0	196.4	216.6	231.2	1.64	1.81	1.93	4.68	5.16	5.50
2	12.0	177.0	193.6	204.8	1.48	1.61	1.71	4.22	4.61	4.88
3	11.0	157.4	170.2	178.1	1.31	1.42	1.48	3.75	4.05	4.24
4	10.0	137.3	146.4	151.3	1.14	1.22	1.26	3.27	3.49	3.60
5	9.0	116.8	122.4	124.8	**0.97**	**1.02**	**1.04**	2.78	2.91	2.97
6	8.5	106.5	110.4	112.0	**0.89**	**0.92**	**0.93**	2.53	2.63	2.67
7	8.0	96.1	98.7	99.6	0.80	0.82	0.83	2.29	2.35	2.37
8	7.0	75.5	76.3	76.5	0.63	0.64	0.64	1.80	1.82	1.82
9	6.5	65.5	65.9	66.0	0.55	0.55	0.55	1.56	1.57	1.57
10	6.0	56.1	56.2	56.2	0.47	0.47	0.47	1.34	1.34	1.34
11	5.5	47.2	47.2	47.2	0.39	0.39	0.39	**1.12**	**1.12**	**1.12**
12	5.0	39.0	39.0	39.0	0.33	0.33	0.33	**0.93**	**0.93**	**0.93**
13	4.5	31.6	31.6	31.6	0.26	0.26	0.26	0.75	0.75	0.75
14	4.0	25.0	25.0	25.0	0.21	0.21	0.21	0.59	0.59	0.59

Wave number	Wave Period	Wave length in [m]			WL/SL			WL/SB		
	[s]	Wd 30m	Wd 40m	Wd 50m	Wd 30m	Wd 40m	Wd 50m	Wd 30m	Wd 40m	Wd 50m
15	3.0	14.1	14.1	14.1	0.12	0.12	0.12	0.33	0.33	0.33
16	2.5	9.8	9.8	9.8	0.08	0.08	0.08	0.23	0.23	0.23
17	2.0	6.2	6.2	6.2	0.05	0.05	0.05	0.15	0.15	0.15
18	1.5	3.5	3.5	3.5	0.03	0.03	0.03	0.08	0.08	0.08
19	1.3	2.6	2.6	2.6	0.02	0.02	0.02	0.06	0.06	0.06
20	1.0	1.6	1.6	1.6	0.01	0.01	0.01	0.04	0.04	0.04

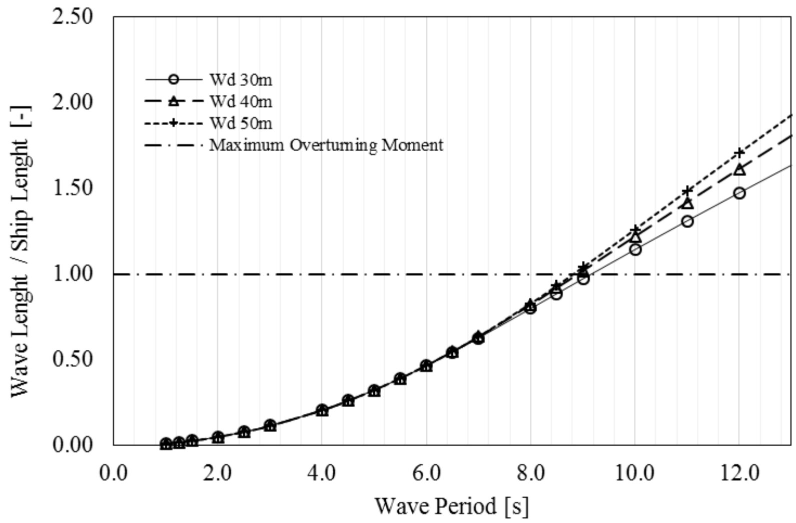


Figure 57. Wave length – Ship length ratio for different Water depths. Head Seas

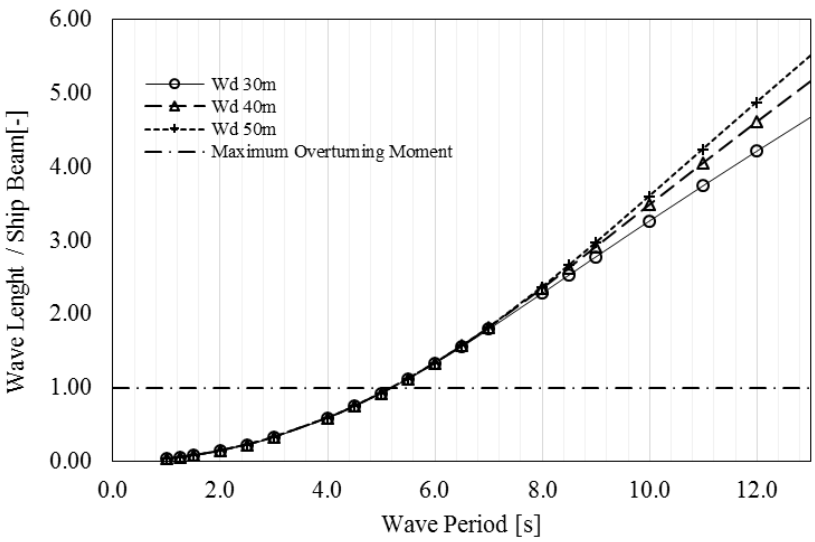


Figure 58. Wave length – Ship Besm ratio for different Water depths. Beam Seas

Table 17. Max Global Overturning Moment Comparison. Case 1, Quasi-static vs dynamic.

Sea Heading	Max GOM-Static	Max GOM-Dynamic	Dynamic / Static (DAF GOM)
	[MNm]	[MNm]	[-]
90°	286.34	511.78	1.79
180°	105.64	218.31	2.07

Significant magnitudes are also found close to the 9[s] and 5 [s] for Head and Beam sea respectively, due to sagging or hogging effect. This reveals that it will be important to verify the periods where dynamic effects will be significant and so the periods where maximum sagging and hogging condition will be expected.

To conclude the Case 1, hull drift and heave motion are compared for both headings applying quasi-static and dynamic analysis. Figure 59-a and 59-b shows the hull motions for 180° incident waves. Sway amplitudes are negligible since there is no source of excitation for this heading. Regarding to the structure response under 90° incident waves, figures 59-c and 59-d presents the hull motions for both quasi-static and dynamic analysis. Large amplification of the hull motions are found. Amplification for the surge and sway motion is notice in table 18.

Table 18. Max Hull motions for 180° incident waves. Case 1, Quasi-static vs dynamic.

Sea Heading	DOF	Static	Dynamic	Dynamic / Static (DAF)
		[m]	[m]	[-]
180°	Surge	0.085	0.179	2.11
90°	Sway	0.225	0.447	1.99

It ca be mentioned that when using quasi-static approach either surge or sway motion are described as proportional to the wave period since structure will tend to follow the wave pattern.

When considering the dynamic analysis, surge and sway motion for head and beam seas respectively, achieve their maximum close to the natural frequency because of resonance and P-delta effects.

Finally, maximum hull surge and sway drift registered for head and beam seas were 0.23 m and 0.5 m. This is valid for the input waves mentioned, without any contribution of other source of external loading as it can be the wind and other relevant sources.

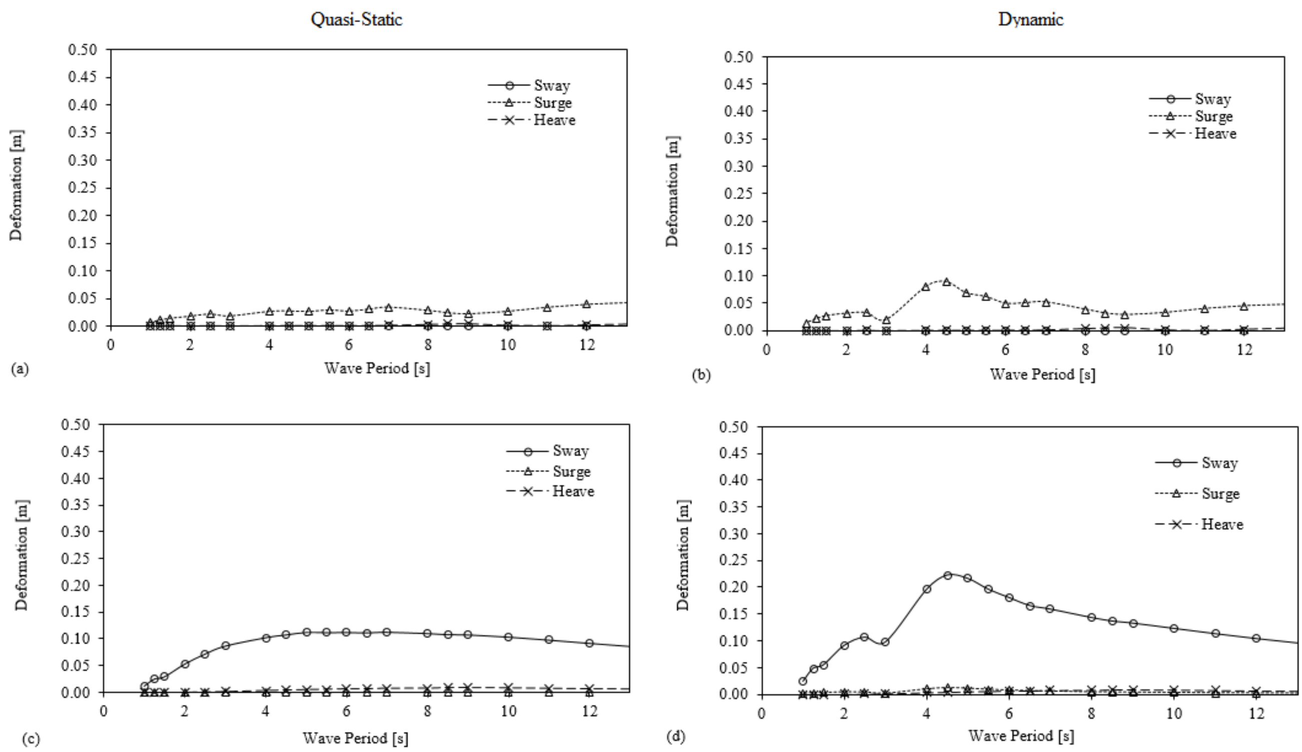


Figure 59. Hull motions by Quasi-static and Dynamic Response Case 1. (a) Quasi-static 180° heading; (b) Dynamic 180° heading; (c) Quasi-static 90° heading; (d) Dynamic 90° heading.

5.2 Case 2. Semi-Submerged vs Elevated Condition

With the results of the case 1, it is understood that dynamic effects must be considered when evaluating the structure response of a WTIV in semi-submerged and elevated operational condition. Furthermore the elevated condition commonly serves as design load case for the major leg and jack-up structural element design however, industry had seen many structural failures during transient phases. Thus is proposed to quantify and compare the loads perceived by the structure in both operational conditions and verify the risk of operating in transient phases.

Different inputs are defined according to each operational condition and further analysis is performed varying the water depth in which the vessel is operating. The objective is to verify how the structure response varies with the water depth since every change of geometry will modify the structural dynamic response for both operational conditions. It is believe that for a certain set of input parameters, the semi-submerged condition will represent a more critical case than the elevated condition. Under this hypothesis, analysis are performed and results are given in terms of total base shear, global overturning moment and hull displacements. Natural periods of the structure are presented in the table 19 and 20, section 4.4.5.

Table 19. Input conditions. Design Parameters Case 2.

Water Depth	50	[m]
Max Hs Semi-submerged	2	[m]
Max Hs Survival	10	[m]
Elevated Hull Weight	14796600	[kg]
Leg Effective Length Factor	2.0	-
Number of legs	4.0	
Leg OD	4.0	[m]
Leg Thickness	0.1	[m]
Leg ID	3.97	[m]
$\Upsilon_{f,D}$ Load factor for deformation loads	1	-
$\Upsilon_{f,E}$ Load factor for environmental loads	1.3	-
Representative Damping. Semi-submerged		
-Sway	25	[%]
-Surge	15	[%]
Representative Damping. Survival		
-Surge	7	[%]
-Sway	7	[%]

Table 20. Jack-up system geometrical features. Case 1.

PARAMETERS	SEMI-SUBMERGED	ELEVATED	UNIT
Distance between upper to lower guide	24000	24000	[mm]
L.G to base line	2250	2250	[mm]
Air Gap	0	10000	[mm]
Sea bed penetration	5000	5000	[mm]
Clearance of guides	20	20	[mm]
Fabrication Tolerances (e1)	10.00	10.00	[mm]
Hull Leg Clearances (e2)	41.46	41.46	[mm]
Heel of Platform (e3)	0.00	0.00	[mm]
Total Horizontal Offset (e0)	51	51	[mm]

To simulate a realistic case, the response of the structure is built considering the wave breaking limit and the environmental wave limit exposure (Hs). In this way, structure response is obtained for the maximum wave amplitudes and wave lengths that the vessel can face for each operational condition and at a specific water depth. Table 21 list all the waves considered the range of periods considered

Table 21. Waves considered for Simulation Model.

Wave Period	SEMI-SUBMERGED CONDITION			SURVIVAL CONDITION		
	Wave Heights			Wave Heights		
	30m WD	40m WD	50m WD	30m WD	40m WD	50m WD
[s]	[m]	[m]	[m]	[m]	[m]	[m]
1.0	0.20	0.20	0.20	0.20	0.20	0.20
1.3	0.40	0.40	0.40	0.40	0.40	0.40
1.5	0.50	0.50	0.50	0.50	0.50	0.50
2.0	0.90	0.90	0.90	0.90	0.90	0.90
2.5	1.40	1.40	1.40	1.40	1.40	1.40
3.0	2.00	2.00	2.00	2.00	2.00	2.00
4.0	2.00	2.00	2.00	3.50	3.50	3.50
4.5	2.00	2.00	2.00	4.50	4.50	4.50
5.0	2.00	2.00	2.00	5.50	5.50	5.50
5.5	2.00	2.00	2.00	6.70	6.70	6.70
6.0	2.00	2.00	2.00	7.90	8.00	8.00
6.5	2.00	2.00	2.00	9.20	9.30	9.40
7.0	2.00	2.00	2.00	10.00	10.00	10.00
8.0	2.00	2.00	2.00	10.00	10.00	10.00
8.5	2.00	2.00	2.00	10.00	10.00	10.00
9.0	2.00	2.00	2.00	10.00	10.00	10.00

Wave Period	SEMI-SUBMERGED CONDITION			SURVIVAL CONDITION		
	Wave Heights			Wave Heights		
	30m WD	40m WD	50m WD	30m WD	40m WD	50m WD
10.0	2.00	2.00	2.00	10.00	10.00	10.00
11.0	2.00	2.00	2.00	10.00	10.00	10.00
12.0	2.00	2.00	2.00	10.00	10.00	10.00
13.0	2.00	2.00	2.00	10.00	10.00	10.00

Calculations are performed and response of the structure is determined for both conditions. Since the elevated condition is usually the design load case, our analysis will be focus to compare the structure response in semi-submerged condition against the maximum values reported for the base shear, vertical reaction forces, overturning moment and hull displacements for the elevated condition. In this way if the response of the structure during the semi-submerged condition results in larger loads and displacements, it will uncovered the importance to study this condition since loads are expected to be bigger than the common design operational condition. Input waves are the ones defined with the information given in table 10, section 4.5.1 and 4.5.3. Now, Results are now presented and discussed.

Figure 60 shows the structure base shear response for the waves considered for the 180° and 90° degrees heading of the semi-submerged condition. Additionally the structure is evaluated at 30 m, 40 m and 50 m of water depth due to the significant differences of inertia. The dynamic response of the elevated condition is evaluated and the maximum values for the base shear for both headings are plotted as horizontal asymptotes to verify if the semi-submerged conditions exceeds this load limits. A color code is used to identify easily the respective curves.

The figure 60-a corresponds to the total base shear response for 180° headings. In this case the elevated condition governs in all the range of water depth considered. On the other hand, figure 62-b represents the response at 90° heading. It is observed that at 30m of water depth the semi-submerged condition will prenset siginificant larger base shear than the elevated condition since lowest inertias are reported at 30 m.

Waves for the semi-submerged condition are lower in amplitude due the design limit exposure defined for each operational condition, but the effective force applied on the structure is larger due to the hull area exposed to hydrodynamic loads.

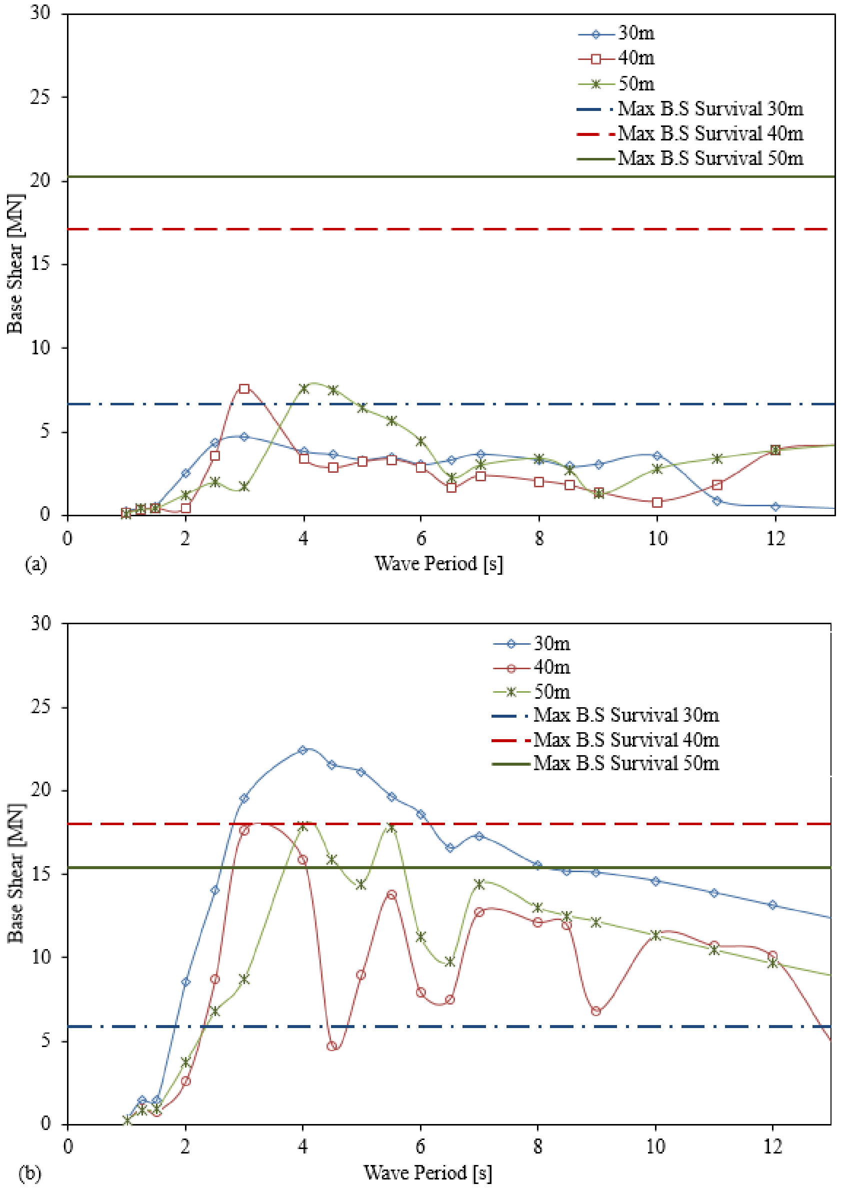


Figure 60. Total Base Shear – Case 2. (a) 180° heading; (b) 90° heading.

In both cases, loads on the cylindrical legs will tend to be the same in magnitude as long as the wave amplitude is identical for both cases nonetheless, if the hull is exposed to hydrodynamic pressures caused by wave loads, structure will percieve a substantial increment of the horizontal load proportional to the projection of the hull wet area perpendicular to the wave heading. To this will be added a uplift force coming from the wave buoyance.

As general comment, it is observed that with the increment of the water depth, either for head or beam seas, the base shear will tends to increase which is expected due to the contirbution of the P-Δ effect. This is attributable since leg deflections appear as a consequence of axial compressive loads affecting the leg stability causing higher hull drift and so shear increments.

For 40m and 50m water, large base shear are also reported but the gap with the elevated condition is reduced. However it is shown that besides the semi-submerged condition is submitted to lower wave amplitudes than the elevated condition (wave heights of 10 m) shear forces exceed the typical governing case.

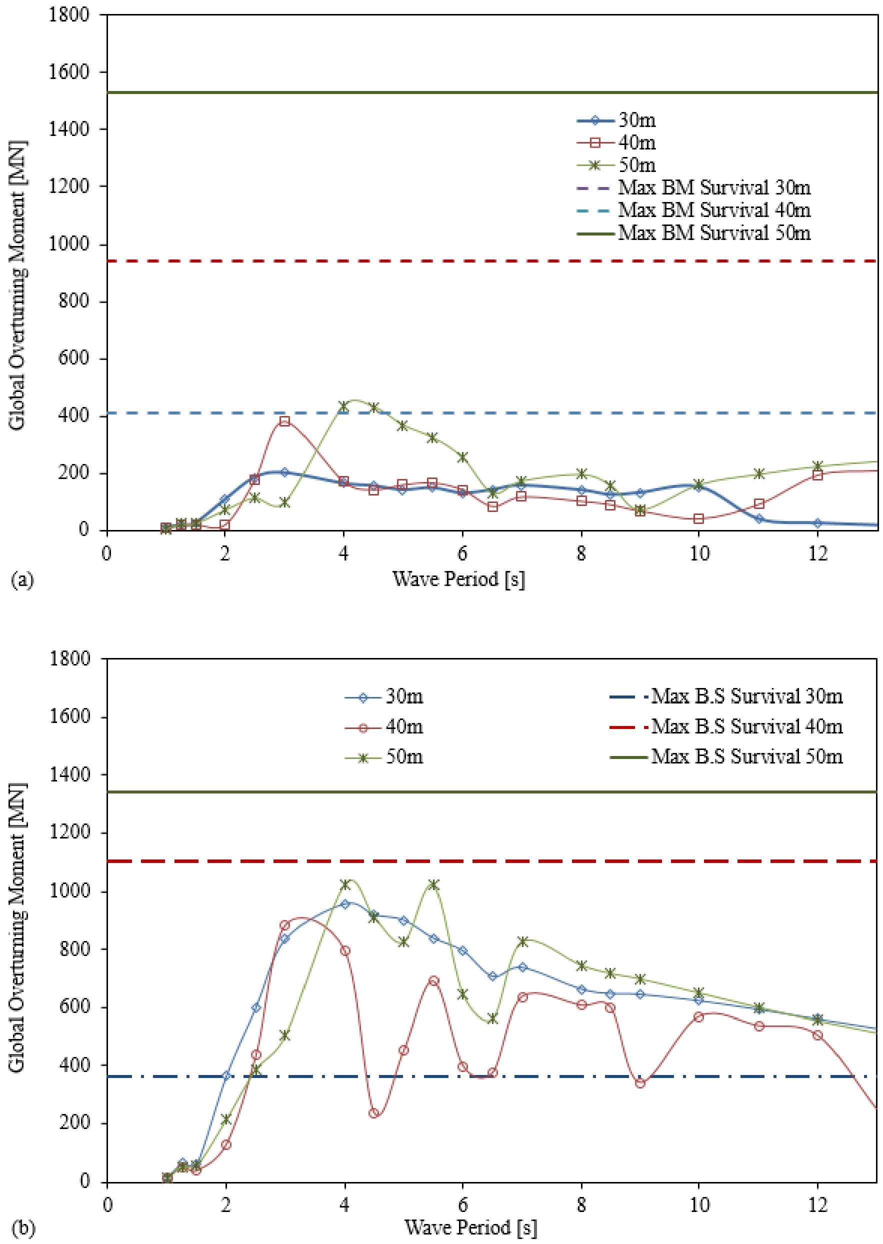
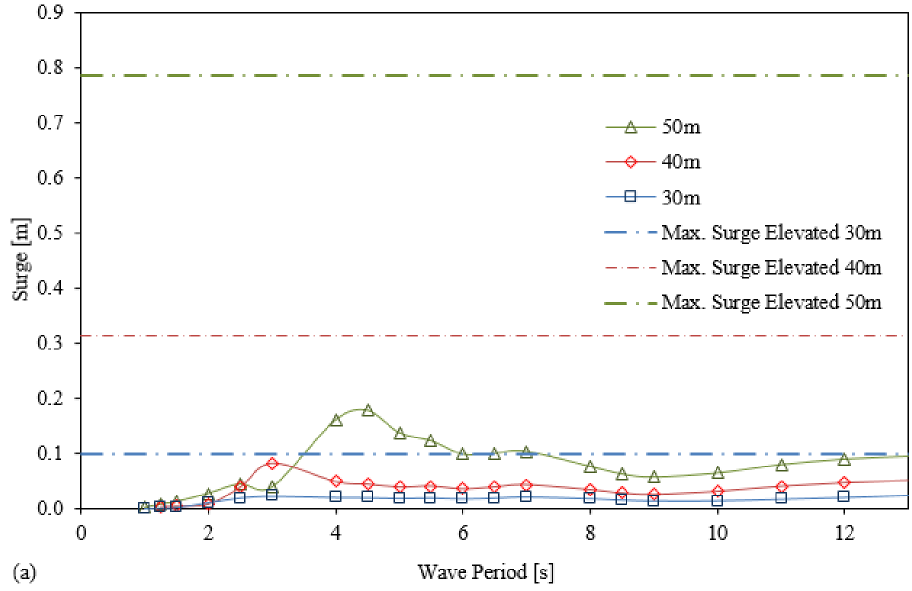


Figure 61. Global Overturning Moment – Case 2. (a) 180° heading; (b) 90° heading.

Corning to the global overturning moment figure 61-a and 61-b display the response the semi-submerged condition for head and beam seas respectively. Maximum moments registered for the elevated condition are determined and represented as well as horizontal asymptotes. For 180° headings, the overturning stability limit is never ixceded the water dpeths considered.

Contrary for 90° headings the overturning limit is exceded at 30 m water depth while for 40 m and 50 m a safer gap is reported so elevated condition governs in terms of overturning moment.



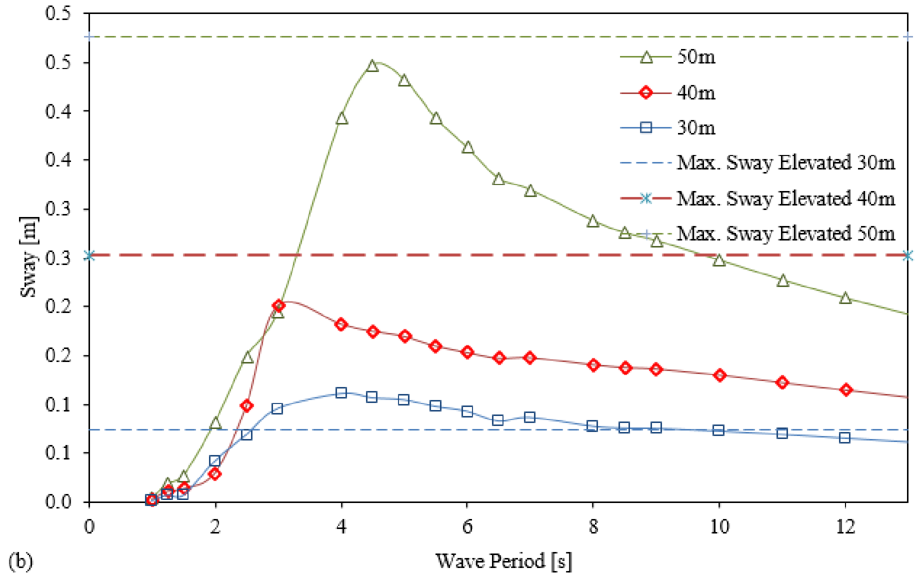


Figure 62. Hull Surge and Sway motion – Case 2. (a) 180° heading; (b) 90° heading.

The influence of the water depth in the hull motions for the semi-submerged condition is now studied. Figure 62-a and 62-b presents how the surge and sway motion varies with the excitation of head and beam seas. It is observed that for both degrees of freedom, hull drift displacements willl increase with larger water depths.

The maximum displacements are reported close to the respecive sructural natural periods of each geometrical configuration. Furthermore the maximum values will be registered at large wave incident periods, acreditable to the decrease of the structure stiffness when increasing the water depth. Finally sway motion is always larger than the surge displacements where maximum values where about 0.5 m, and for the surge motion around 0.2 m. When comparing the hull displacements with the elevated condition, hull amplitudes are never exceeded.

Particularly for the Semi-submerged condition, eventought the inertia of the structure increases with the water depth, this behave can be explained due to load in the legs simply since more area is exposed to current loads and dynamic pressure.

To close this case of analysis, the table 22 summarize the findings of this study.

Table 22. Summary of limits exceeded. Semi-sub. Vs Elevated. Case 2.

PARAMETER	HEADING	30m WD		40m WD		50m WD	
		Semi-Sub.	Elevated	Semi-Sub.	Elevated	Semi-Sub.	Elevated
Base Shear	180°	-	x	-	x	-	x
	90°	x	-	x	-	x	-
Overturning Moment	180°	-	X	-	x	-	x
	90°	x	-	-	x	-	x
Surge Drift	180°	-	x	-	x	-	x
	90°	NA	NA	NA	NA	NA	NA
Sway Drift	180°	NA	NA	NA	NA	NA	NA
	90°	x	-	-	x	-	x

5.3 Case 3. Effect of Wet Hull Area on Lateral and Vertical Loading.

When the hydrostatic equilibrium is lost due to the jacking-up of the hull, the loading condition of the vessel will change significantly. This study will verify the loading of a WTIV in transient condition before the desired elevation for installation is achieved. This condition stills involve the hull partly subgmerged.

During this transient condition, the wet hull area will decrease reducing the net wave loading from the specific wave heading however, vertial compressive loads will increase significantly since hydrostaic equilibrium is lost, and the weight of the structure will be dominant against the buoyancy given by the displaced volume. Compresive loads legs are a source of lateral isntability and they may increase base shear and overtutning moment if horizontal forces are important.

It is proposed to verify how the net horizontal loads and the vertical loads change when varying the hull wet area. For this four water lines are considered including the hydrostatic equilibrium condition. These are 2.52 [m], 2[m], 1,5 [m] and 1[m] and just 1 water depth is analized. Simulations are prepared applying waves of 1 [m] waves under and the site conditions stablished in the table 13 for the Case 1. All simulations are run at 50 m water depth.

The table 23 shows how the changes of draft modifies the leg preloading based on the hull elevated weight. Variations up to 50% are reached with the draft lines evaluated.

Table 23. Leg Preloading. Case 3.

Draft	Immersed Volume	Hull Elevated Weight	Leg Pre-loading
[m]	[m^3]	[MN]	
2.52	13044	0.0	0.00%
2	9430	50.0	34.52%
1.5	9256	51.7	35.72%
1	6869	75.7	52.30%

The different drafts considered will modify the effective hull wet area exposed to hydrodynamic loads produced by the incoming waves. In the table 24 and 25 its exposed the changes of hull exposed area and maximum net drift forces acting on the vessel.

Its observed that a change of 1 [m] would mean a reduction between 30% and 40% of the area which also means a reduction around 50% of the horizontal loading. This results will depend on the hull shape though, since most of the WTIV have a barge-type hull significant reductions as the ones found would be expected. Major reduction on the effective hull area is expected for headings of 90°. Table 24 and 25 shows the changes of the hull projected wet area and the changes of net pressure and net drift force.

Table 24. Changes of hull projected wet area. Case 3.

Draft	Hull Projected Area		Hull Area Reduction	
	90°	180°	90°	180°
[m]	[m2]	[m2]	[%]	[%]
2.52	311	106	0.0%	0.0%
2	225	84	27.7%	20.6%
1.5	220	63	29.0%	40.5%
1	164	42	47.3%	60.3%

Table 25. Changes of Net Pressure and Net drift force. Case 3.

Draft	Maximum Net Drift Force		Drift Force Reduction		Net Hydrodynamic Horizontal Pressure	
	90°	180°	90°	180°	90°	180°
[m]	[kN]	[kN]	[%]	[%]	[kPa]	[kPa]
2.52	4982	1838	0.0%	0.0%	16.0	17.4
2	3616	1570	27.4%	14.6%	16.1	18.7
1.5	2713	1018	45.5%	44.6%	12.3	16.2
1	1936	938	61.1%	48.9%	11.8	22.3

The table 26 shows how the vertical forces will change for every loading condition, passing from a harmonic load with a magnitude not higher than 20 [MN] in total, to 85 [MN] compressive loads for the preloading considering. This compressive loads reported are the ones causing the lateral instability and so the base shear and global overturning moment increments.

Table 26. Changes of Net Vertical forces. Case 3.

Draft	Maximum Net Vertical Force		Change of Vertical Force	
	90°	180°	90°	180°
[m]	[MN]	[MN]	[%]	[%]
2.52	20	11	0%	0%
2	-61	-64	401%	682%
1.5	-63	-81	414%	843%
1	-85	-85	523%	874%

The draft changes will modify the structure dynamic response since hydrodynamic damping and the added mass will change. Both parameters will tend to decrease when decreasing the draft line for which will be expected to increase the dynamic effects and increments on the structure natural frequencies. The following figures present an estimation of the DAF for the new structural damping of the structure at the given drafts. These figures reveals that the response will be amplified as expected due to hydrodynamic damping reduction.

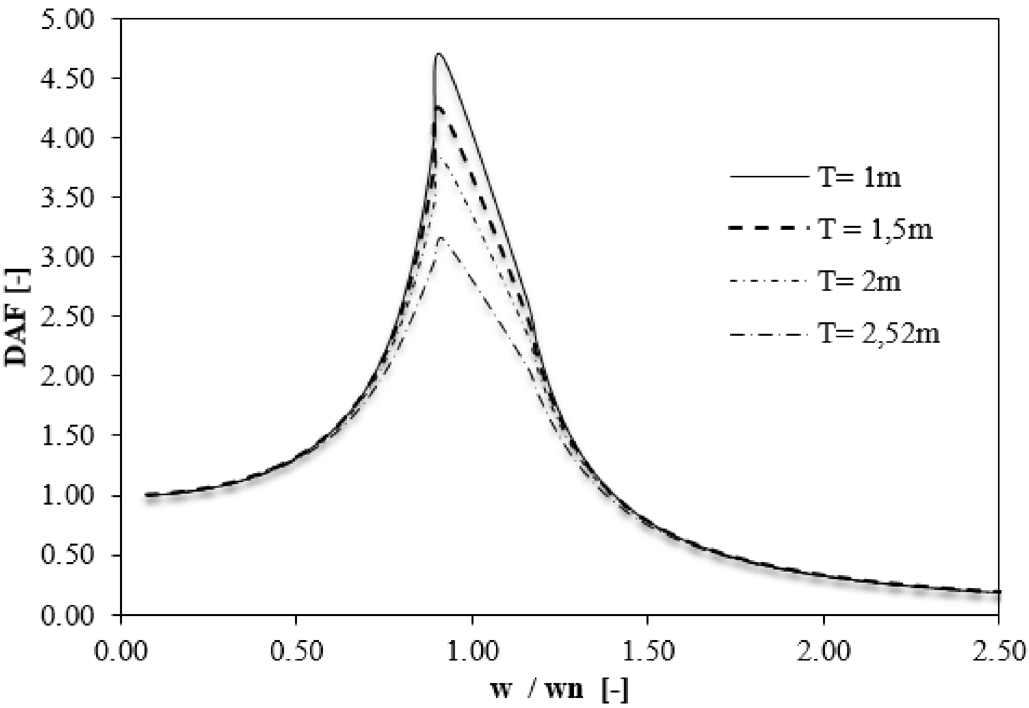


Figure 63. DAF for 180° incident waves. Semisubmerged with different drafts. Case 3

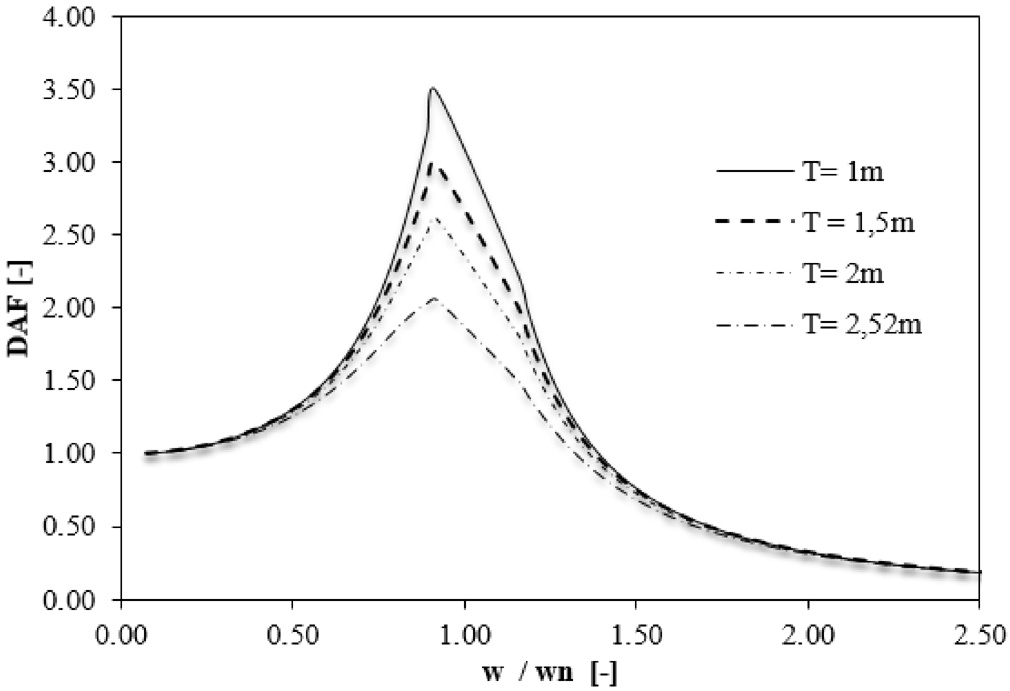


Figure 64. DAF for 90° incident waves. Semisubmerged with different drafts. Case 3

Figure 65 shows the RAO for the base shear, global overturning moment and surge and sway displacements for every condition evaluated. This calculations are made with the representative damping of the structure for the conditions evaluated.

Here is observed that maximum values will slightly move to large periods. Far from resonance, loads will decrease with decreaments of draft. However, amplifications are registered close to the resonance generating hiegher amplitudes than for the hydrostatic equilibrium condition.

The findings of this analysis bring to the light the importance of accounting dynamic effects in the semi-submerged condition since they can change drastically the structure response.

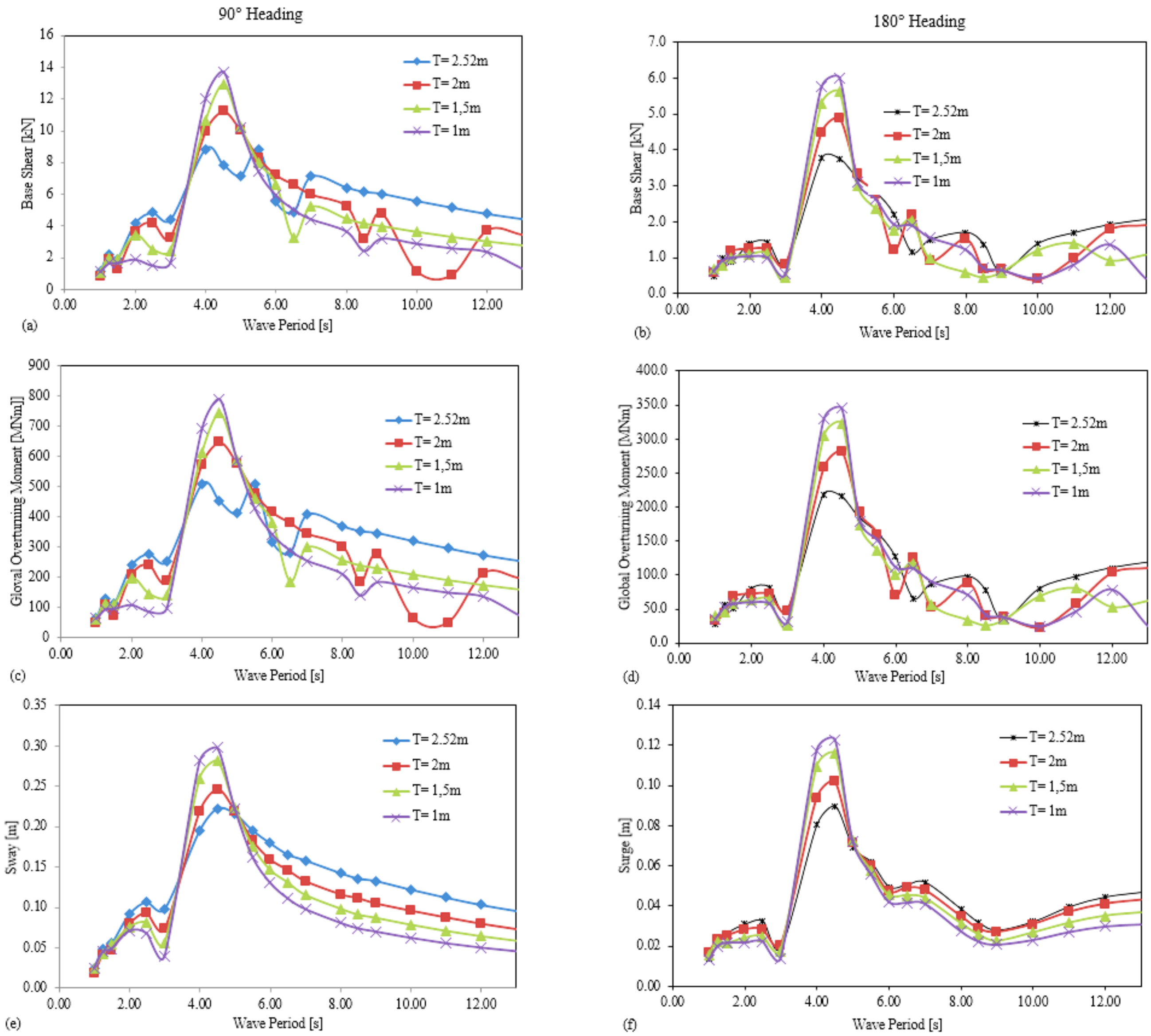


Figure 65. DAF for 90° incident waves. Semisubmerged with different drafts. Case 3

6 CONCLUSIONS

6.1 SUMMARY

A summary and relevant information is given product of the previous analysis, where are discussed some considerations of the process for the global response analysis of Wind Turbine Installation Vessels during semi-submerged and survival operational condition. Additional comments regarding to the structural response of the structure in the semi-submerged condition are also provided to describe the operational risk and safety related to it.

The analysis of the global response of a Wind Turbine Installation Vessel is a multi-physics problem where high structural non-linearity's and non-linearity's of the external loading take part at the same time. For this, big emphasis in the modelling techniques and considerations should carefully and delicately prepared when performing such analysis. This since validation of the simulations become a difficult task in the reality.

The information given in this document is considered to be very valuable since it has been determined that operating in semi-submerged condition can compromise the vessel integrity and safety during operation. The evidence of this work can be useful for design stages since its compulsory the global understanding of the vessel operation and the physics behind it.

Thought it is not intended to evaluate a specific design, the author considers as significant contribution to the field the following set of comments as result of the studies mentioned in this document.

For the Hydrodynamic Modelling:

- Methodologies for wave induced loads should be correctly defined to generate a good representation of the loading acting on the structure studied. Linear Potential flow solvers are well known in the industry for hydrodynamic load calculation when no significant flow velocities or flow separation are expected. However, due to the presence of high non-linear structural effects, non-linear wave loading should be considered when evaluating the response of the structure in specific site conditions. I.e. second or third order approximation should be used to determine the wave kinematics since dynamic effects are expected.

- Fifth order Stokes theory can be used for wave load calculation to account the wave non linearity's. However if irregular surfaces are to be considered, it is preferred to consider CFD solvers to accurate describe the wave kinematics around the structure solid boundaries.

- For elements where the Morison Formulation is applicable, approximation will be accurate enough when considering the wave kinematics determined from potential flow theory. Previous studies had demonstrated that usage of RANS simulation with direct numerical integration of the pressure around the surface won't present meaningful differences for this type of elements. Morison formulation will be enough to catch the majority of effects without being conservative. (O. Moctar, 2009)
- Methodologies for added mass estimation for multibody motion must be consider and special attention should be given if the operating condition to be analyzed is semi submerged jack-up condition.

For the Structural Modelling.

- Geometry modelling will be an issue of special concern since the correct representation of the structure stiffness, mass distribution and inertial properties will contribute on the definition of the dynamic response of the structure. This will allow a realistic representation of the non-uniform stress distribution and the global understanding of the vessel respond to the considered loading.
- Soil-Leg connection modeling will be an important aspect for the dynamic response analysis of the structure. As commented by (M. Williams, 1999) it had been proved applying non-linear modelling to the legs and spudcan footings that significant effect on the rig dynamics are found when applying different leg-soil connections. The author concludes affirming that the widespread practice of modelling the footings as simple pinned supports may be non-conservative for some sea states.
- Had been proved according to DNV OS C-104 that with the application of a deterministic linear quasi-static approach the accuracy of the results won't be significantly reduced in comparison a deterministic non-linear dynamic analysis. This information is valid even for large detailed models however, if specific site assessment is requested it will be recommended to perform a deterministic non-linear dynamic analysis in time domain due to the large non-linear effects of the problem.

Regarding to the semi-submerged condition.

- Changes in the geometrical configuration produced operating in lower or larger water depths will significantly change the main inertial properties of the structure when considering the seabed as point of rotation. It is found that at lower water depths and when legs are attached to the seabed, the structure will be more susceptible to suffer large surge or sway deformations under the same loading when comparing to larger water depths.
- Relevant differences are found for the structure response when using quasi-static and dynamic analysis. It is known that for the elevated condition, dynamic effects are to be significant if resonance effect is expected. Calculations demonstrate that dynamic effects cannot be neglected when analyzing the semi-submerged condition since the total base shear, global overturning bending moment, vertical reaction forces and hull motions can present substantial increments.
- Base shear can be also amplified by P-delta effects caused by large hull drift, Fabrication tolerances as out-of-straightness, hull leg clearances and heel of platform. This deformations combined with vertical load on each leg (hull elevated weight) will generate additional overturning moments that increase the base reactions in the plane. The amplification will depend on the ratio between the vertical axial load and the Euler limit which define the leg lateral stability under axial loads.
- When hydrostatic equilibrium is lost and hull continues partly submerged, structure response will continue being critical since besides wave loading presents a decrease of 30% or 40% of horizontal loading, global damping of the structure will reduce causing larger amplifications due to resonance effect.
- Depending on the location where the vessel will operate, the structure response under dynamic loading can vary meaningfully. It has been registered for a set of water depths that the elevated condition will mostly govern in terms of base shear, global overturning moment and hull drift. However, for a given water depth it is found that the semi-submerged condition exceed the limits registered during the elevated condition. This reveals a high risk condition that many vessels can be exposed since for smaller deformations of the structure, the response can be dramatically affected compromising the structural integrity. I.e. operation in lower water depths can compromise the vessel integrity and safety of his operators.

6.2 Recommendations for Further Work

The investigation performed resulted in a comprehensive analysis on the dynamic response of WTIV under the conditions established. Additionally it is crucial to remark that simulations performed were not focus for the evaluation of a specific rig design and since simplifications where considered for the simulation model, still remain activities that must be performed for the validation the results found.

For Hydrodynamic simulations, it is known that usage of CFD techniques by potential flow solvers will offer reliable results however, due to the presence of non-linear effects and for the better representation of the hydrodynamic effects, more detailed analysis should be done:

- Potential flow theory should consider higher orders when determining the velocity potential to account the influence of frequency harmonics in the structure response.
- Constant current velocity profile is considered for drag linearization purposes however, this might be a conservative assumption, useful for early design stages. If detailed site assessment is requested, drag forces should not be linearized and irregular velocity profiles should be considered with information provided from a professional study of the site where the platform will operate.
- Vortex induced vibrations will be a phenomena that might affect the structure response. Dynamic response of the structure in semi-submerged condition should be evaluated under this condition meanwhile besides low wave heights will be expected, load amplification can appear due to resonance effect.

For the structural analysis, a detailed structural model will always offer a better representation of the vessel stiffness, mass, and inertial properties. Nonetheless solving the structural model with a quasi-static approach will neglect the majority of the effects on the structure offering non-realistic results. Usage of DAF will be a feasible solution in terms time consuming without compromising significantly the accuracy of the results. It is proposed that DAF methods for dynamic response analysis should be used just for early design stages since many non-linear effects take part at the same time. Thus non-linear dynamic forced response analysis should be considered.

Boundary conditions defined at the soil leg connection are commonly modelled as pinned boundary conditions. However this will modify the dynamic response of the structure resulting in non-conservative results for some sea states (M. Williams, 1999). Thus recognized modelling techniques for soil-structure interaction should considered for the correct representation of the structure capacity. This will lead to a correct representation the leg fixation and realistic representation of the stress distribution on the legs and its components (V. Daun, 2014).

Regarding to the type of simulation, deterministic approach can be used if interested in the non-uniform stress distribution on the structure under the specified loading. Frequency domain analysis will be useful to represent the structure response under linear regular waves at specific headings. Nonetheless vessel will face in the reality the exposure to non-linear waves and irregular sea states so it will be recommended to perform a time domain analysis and study

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