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Writer: Aron Amundsen	………………………………………… (Writer’s signature)
Faculty supervisor: Professor II, Jan Inge Dalane	
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Abstract

One of the processes early in the development of offshore oil and gas fields is the concept selection. Because semi-submersible and other alternative designs is very complex, a simplification in the early design phase could lead to time and cost savings. The objective of this thesis is to develop a simple spreadsheet, which estimates the hull dimensions and cost based on a few input parameters. The estimated hull must have sufficient stability, heave motions and air gap.

All the important hull parameters have been evaluated and data from relevant semis have been gathered. Based on these evaluations and data, the input parameters are selected and estimation equations for the parameters are developed. The input parameters for the spreadsheet are topside weight, weather condition and air gap margin. The estimations are mainly based on linear relationships and are shown to give reasonable values when compared to existing semi-submersibles. Especially the normal draft semis give very good estimations.

A parametric sensitivity study was conducted to look on the possibility to reduce heave motions. The analysis of different hull configurations showed that draft is the only parameter giving a noteworthy reduction. The necessity of reduced heave motions is the possibility to use steel catenary risers. The necessary reduction was chosen to be roughly 50 %. The study showed that a draft of 44 meters was necessary for this reduction, independent on semi weight. This deep draft alternative is included in the estimation spreadsheet.

To secure sufficient air gap, an air gap analysis was conducted for five semis generated with the estimation spreadsheet. The semis was analyzed for four different weather situations, which represent the most common locations for offshore oil and gas production. One of the locations is also analyzed in more detail. This detailed analysis show that the most critical weather situations are for periods below T_P and the additional response can result in an insufficient air gap. In addition to estimate the required air gap, the spreadsheet accommodates the possibility to define the wanted air gap margin. The analysis also show that the estimated semis have good stability and motions.

With only three simple input parameters, the estimation spreadsheet combines the presentation of hull dimensions, weight, stability and cost in a good and user-friendly way.

Acknowledgments

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I would also like to thank my faculty supervisor Jan Inge Dalane for the guidance and support during the work on this thesis. The thesis objective developed by him, has been very interesting.

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Abbreviations

BM	Vertical distance between center of buoyancy and metacenter
CB	Center of buoyancy
CG	Center of gravity
DP	Dynamic positioning
FPS	Floating production system
FPU	Floating production unit
GM	Vertical distance between center of gravity and metacenter
HCV	Horizontal center of gravity
H_S	Significant wave height
H_{100}	100-year maximum wave height
KB	Vertical distance between keel and center of buoyancy
KG	Vertical distance between keel and center of gravity
MC	Metacenter
RAO	Response amplitude operator
SCR	Steel catenary riser
T_P	Peak period
T_Z	Mean zero up-crossing period
ULS	Ultimate limit state
VCG	Vertical center of gravity

1. Introduction

One of the processes early in the development of offshore oil and gas fields, are the concept selection. The concept alternatives must be detailed enough to estimate functionality and cost. Because the semi-submersible and other alternatives are very complex designs, a simplification in the early phase is necessary to avoid unwanted planning time and costs. The objective of this thesis is to simplify the process of hull dimensioning for semi-submersibles in the early phase of a project by developing a simplified excel spreadsheet. This spreadsheet will give an estimate of hull design and cost based on a few simple parameters. The estimated semi-submersible should have good stability and motion characteristics. This will reduce engineering hours in the early phase of a project and will make experimenting with different semi-submersible designs easier.

The development of the spreadsheet consists of the following stages: evaluation of the relevant parameters and their influence on the model, document relevant theory for the design and analysis, design relevant semi-submersible hull configurations and perform hydrodynamic analysis on them, use the collected analysis data and theory to develop the spreadsheet.

2. The semi-submersible

The first semi-submersible platform in the oil and gas industry arrived in 1961 and used for drilling. After recognizing the good motion and stability characteristics of the semi-submersibles, it has since become one of the standard vessels for drilling, intervention and production offshore. Some of the advantages of semi-submersibles are large deck area, large topside load capacity, possible re-use of rig, less capex than fixed/spar, good motion and stability characteristics. The semi-submersible rigs are used for operations in intermediate (300 m) to ultra-deep water (4000 m).

The hull of a semi-submersible mainly consists of a pontoon and columns, shown in figure 1. The pontoon is the main contributor to the buoyancy and can be either a ring pontoon or two elongated pontoons. As a larger body, the ring pontoon gives more buoyancy and therefore can support larger topside loads. It also gives a symmetrical hull shape and therefore gives better motions for a fixed vessel. This is favourable for production semis, which holds large and heavy topside processing equipment and will stay at one location. The two elongated pontoons give a more streamlined shape, which give better speed and stability during transit between locations. This is favourable for drilling/intervention semis that will relocate to new areas regularly.

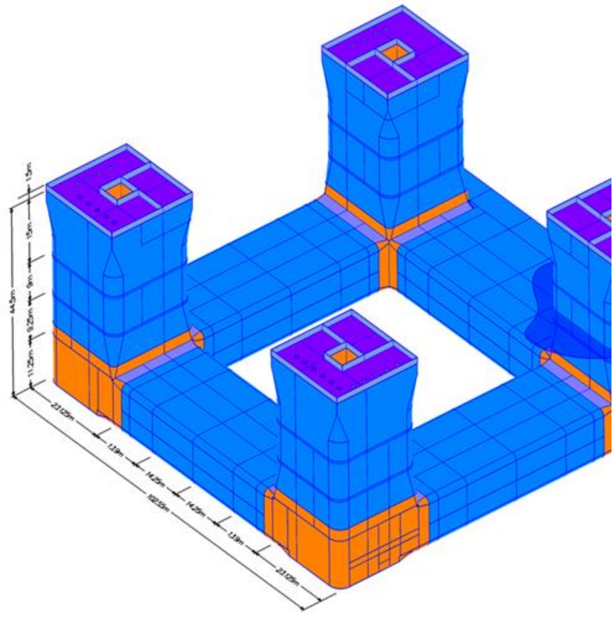


Figure 1 - Hull structure. Four-column design with ring pontoon.

As a semi-submersible floats freely in the sea, it needs station-keeping arrangements during operation on a location. Fixing the semi-submersible on the location is achieved either by a dynamic positions system (DP) or by mooring with anchors. DP uses propulsion to fix the position based on signals from satellites, seabed beacons and angular movements of risers to counter the movements from wave, current and wind forces. Mooring requires multiple anchors spread in a symmetrical pattern. The anchors can be shown to have more redundancy than DP, but requires support vessels and long installation/removal times.

3. Stability and motion theory

3.1 Stability of semi-submersibles

The stability of a floating vessel is simply described as the ability to return to the equilibrium position when disturbing forces are removed. The more forces returning the vessel back to equilibrium position, the better stability the vessel has. The disturbing forces can be waves, wind and live loads. Semi-submersible production platforms generally have great stability because of its wide geometry and ability to alter stability configuration with ballast systems in the pontoon. The column design also generates equilibrium stability. The theory in this chapter describe static stability for relatively small angles of inclination of the vessel. For a more in depth study, the theory for larger inclinations and dynamic stability should be taken into account. The stability equations is described for four column semi-submersible platforms.

3.1.1 Initial stability

Initial stability describes the behavior of a vessel if position is altered slightly from its initial position. A floating vessel can have three different behaviors described in figure 1. The first behavior is stable equilibrium (1), which means that after a small position alteration, the vessel wants to return to its initial position. The other behavior is unstable equilibrium (2), which means that after a small position alteration, the vessel wants to move further away from its initial position. The last behavior is indifferent equilibrium (3), which means that after a small position alteration, the vessel wants to stay at the new position [Gudmestad, 2014]. For a semi-submersible, this means that its intended position always must be in stable equilibrium. This is achieved by having a correct design and continuous monitored ballasting system, which results in a positive GM.

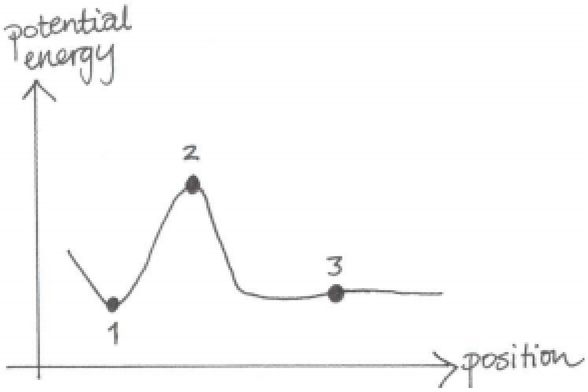


Figure 2 - Potential energy versus position [Gudmestad, 2014].

3.1.2 Stability terms

The general symbol for stability is the GM term. It describes the distance from the metacenter (MC) to the center of gravity (CG). MC is the point where the centerline of the vessel intersects with the vertical line through the center of buoyancy (CB). Dependent on the value of GM, the vessel has the stability behavior described earlier.

- GM > 0 Stable equilibrium
- GM = 0 Indifferent equilibrium
- GM < 0 Unstable equilibrium

Even though a positive GM is wanted, the value should not be too large. Too large GM will affect the roll and pitch motions negatively by generating larger roll and pitch responses. This result in short roll and pitch motions that is very uncomfortable for personnel onboard the vessel. As long as the vessel is in an upright position, the CG and CB should be in the same vertical line. If not, the difference will create a moment around the axis and destabilize the vessel. When the vessel is heeling, CG and CB will be off axis and work in opposite directions. This is caused by the effect of CB moving towards the heeling and away from the vessel centerline. This will generate righting moments by CG and CB which will work towards returning the vessel to its upright position. These moments will increase in force as the heel is increased.

The equation for GM is,

$$GM = KB + BM - KG \qquad (1)$$

GM	*Vertical distance from CG to MC (m)*
KB	*Vertical distance from keel to CB (m)*
BM	*Vertical distance from CB to MC (m)*
KG	*Vertical distance from keel to CG (m)*

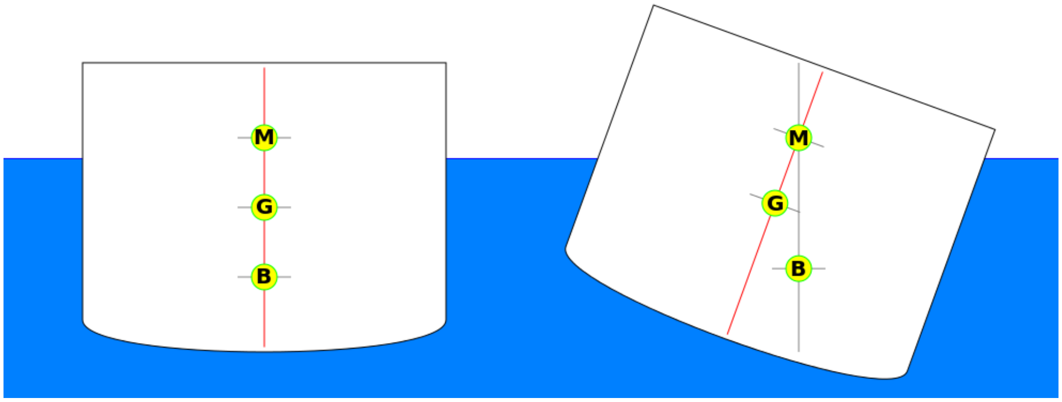


Figure 3 - Stability terms. Initial versus inclined position.

The KB term describing the buoyancy is given by equation (2) and (3).

$$KB = \frac{KB_P \cdot \nabla_P + KB_C \cdot \nabla_C}{\nabla} \tag{2}$$

KB	*Vertical distance from keel to CB (m)*
KB_P	*Vertical distance from keel to center of pontoon (m)*
KB_C	*Vertical distance from keel to center of columns (m)*
∇_P	*Displacement of pontoon (m^3)*
∇_C	*Displacement of column (m^3)*
∇	*Total displacement (m^3)*

The BM term describing the buoyancy is given in equation (4) and (5) [Gallala, 2013]. Equation (5) can describe the second moment of area for all directions because of the platform symmetry.

$$BM = \frac{I}{\nabla} \tag{3}$$

$$I = 4 \cdot \left[\left(\frac{1}{12} \right) \cdot w_c \cdot {l_c}^3 + w_c \cdot l_c \cdot \left(\frac{d_c}{2} \right)^2 \right] \tag{4}$$

BM	*Vertical distance from CB to MC (m)*
I	*Second moment of area for water plane area (m^4)*
∇	*Total displacement (m^3)*
w_c	*Width of column (m)*
l_c	*Length of column (m)*
d_c	*Distance between columns (m)*

The KG term describing the CG is shown in equation (6).

$$KG = \frac{m_h \cdot CG_h + m_{top} \cdot CG_{top}}{m_{total}} \tag{5}$$

KG	*Vertical distance from keel to CG (m)*
m_h	*Mass of hull (kg)*
m_{top}	*Mass of topside (kg)*
m_{total}	*Total mass (kg)*
CG_h	*CG for hull (m)*
CG_{top}	*CG for topside (m)*

3.2 Motion characteristics for semi-submersibles

Motions of a floating vessel are a six degree of freedom system. Three of the motions are rotational and three are translational. Rotation means that the vessel rotates around an axis and translation means that the vessel moves along an axis. The rotational motions are roll, pitch and yaw. The translational motions are heave, sway and surge.

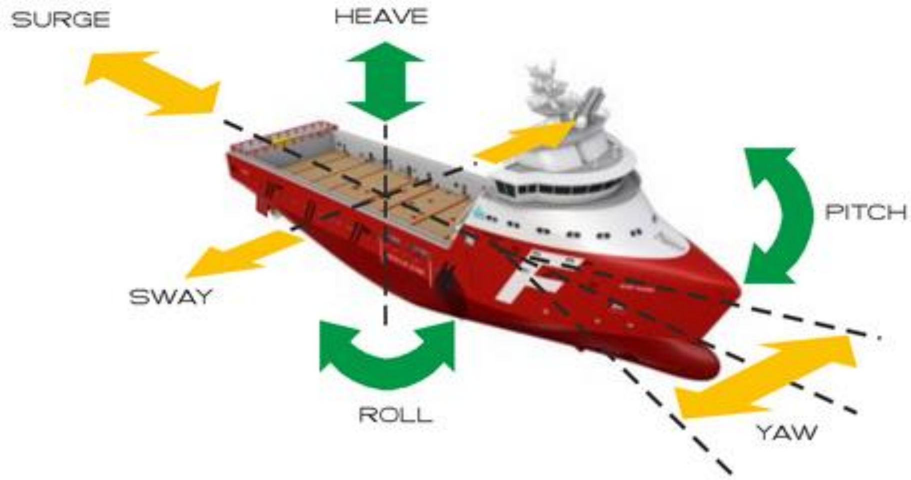


Figure 4 – Floating vessels six degree of freedom [NAUTICADYNAMICS.COM, 2015].

The motions sway, surge and yaw are not important for describing the motion characteristics of the semi-submersibles in this thesis. Production semis will always be fixed on location by anchors or DP, which restrict these motions. The WADAM analysis in HydroD calculates the heave, pitch and roll motions for the semi-submersible models. Because of the hull symmetry, the pitch and roll motions will always be equal for equal wave directions. The natural period equations in this chapter is based on the assumption of uncoupled and undampened motions.

3.2.1 Heave

The heave motion represented by the RAO chart in Postresp are shown in figure 4. The amplitude is calculated based on transfer functions from the WADAM analysis and show vertical displacement for wave height (m/m). There are two important sections of the RAO chart: The natural period in heave, which is the peak at around 26 seconds and the smaller elongated peak at around 14 - 20 seconds. The natural period in heave is calculated by equation (6) [DNV, 2011] and represent one of the critical responses for the semi.

$$T_{heave} = 2\pi \cdot \sqrt{\frac{m}{k}} = 2\pi \cdot \sqrt{\frac{m_v + A_{33}}{\rho_w \cdot g \cdot A_w}} \tag{6}$$

T_{heave}	*Natural period in heave (s)*
m	*Mass (kg)*
m_V	*Mass of vessel (kg)*
k	*Stiffness (kg/s^2)*
A_{33}	*Added mass (kg)*
ρ_W	*Seawater density (kg/m^3)*
g	*Gravitational acceleration (m/s^2)*
A_W	*Water plane area (m^2)*

The mass term consist of the total mass of the semi and the added mass. Added mass is a term describing the additional mass that the semi drags along its vertical motion. The water particles closely adjacent to the submerged hull of a semi will always follow the hull surface as it moves, and the longer away from the hull the water particles are, the smaller the effect will be. Added mass is calculated by equation (7) [DNV, 2011]. This equation uses strip theory to calculate the mass. This means that the added mass is calculated for one vertical section of the pontoon with the length of 1 meter. The mass for this section is then multiplied by the total length of the pontoon.

$$A_{33} = C_A \cdot \rho_w \cdot \pi \cdot \frac{{w_p}^2}{2} \cdot l_p \tag{7}$$

A_{33}	*Added mass (m)*
C_A	*Added mass coefficient*
ρ_W	*Seawater density (kg/m^3)*
w_P	*Width of pontoon (m)*
l_P	*Length of pontoon (m)*

The added mass coefficient depend on the width to height ratio of the pontoon. It is based on empirical data and can be found for example in the standard DNV RP-H103.

The natural period must be far enough away from the wave periods with high energy, if not the response can be severe. The period with high energy waves depend on the location, but a maximum high-energy period of around 16 seconds is normal for severe weather locations. Therefore, a general minimum natural period in heave for a semi is around 24 seconds. The elongated peak at around 14 – 20 seconds is the area that is important for the heave motions of a semi. This is the periods where the waves have high energy and the semi must tolerate these wave energies without causing to large heave motions. The requirement for heave motions in this area depend on the riser system used. Especially steel catenary risers can have fatigue problems in this area.

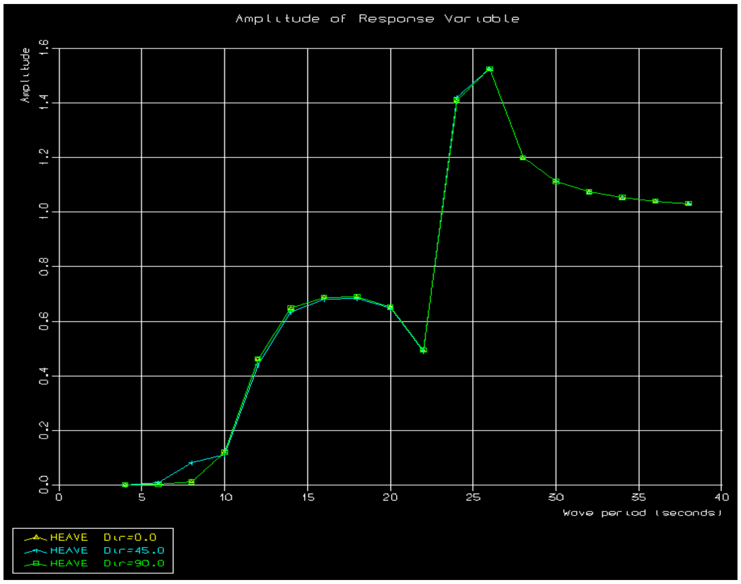


Figure 5 - Heave RAO from Postresp.

3.2.2 Roll and pitch

The roll and pitch motions for semi-submersibles are generally in a range and amplitude that make them non-problematic for the design of the hull. As with the heave motions, the motions are calculated in the WADAM analysis and represented in the roll and pitch RAO. The natural period in roll and pitch are calculated from equation (8) and (9) [DNV, 2011].

$$T_{roll} = 2\pi \cdot \sqrt{\frac{m_v \cdot {r_{44}}^2 + A_{44}}{\rho_w \cdot g \cdot \nabla \cdot GM_t}} \tag{8}$$

$$T_{pitch} = 2\pi \cdot \sqrt{\frac{m_v \cdot {r_{55}}^2 + A_{55}}{\rho_w \cdot g \cdot \nabla \cdot GM_l}} \tag{9}$$

T_{roll}	*Natural period in roll (s)*
T_{pitch}	*Natural period in pitch (s)*
m_V	*Mass of vessel (kg)*
r_{44}	*Roll radius of gyration (m)*
r_{55}	*Pitch radius of gyration (m)*
A_{44}	*Roll added moment* (kg/m^2)
A_{55}	*Pitch added moment* (kg/m^2)
ρ_W	*Seawater density* (kg/m^3)
g	*Gravitational acceleration* (m/s^2)
∇	*Displacement of semi* (m^3)
GM_t	*Transversal GM (m)*
GM_l	*Longitudinal GM (m)*

4. Analysis theory

4.1 Semi-submersible Air Gap

One of the key parameters in the semi-submersible platform design is the air gap. The air gap, also called freeboard, is the vertical distance between sea surface and topside structure. The gap must be sufficient to let waves pass under the platform without causing impact on the topside structure. Unwanted wave impact can cause large damages to equipment and be a risk for environmental pollution and personnel life. However, wave impact may be permitted if accounted for in the design. To fulfil the ULS criteria, the wave heights considered in such calculations should be the waves with a 100-year return period and leave a 1.5 m gap margin [NORSOK, 2007].

The vertical gap between sea surface and topside structure is a function of the wave elevation and the platform motions. The wave elevation is described by a non-linear irregular wave function. When investigating air gap points near the columns or above the pontoon, it is important to take into account that the wave will build up around the columns and on top of the pontoon. Because of this effect, the most critical areas to investigate the air gap are in front of the columns, with respect to the wave direction, and over the pontoon. Wave impact on the columns will cause water jets up along the column. The wave elevation from this effect is hard to calculate and should be based on empirical data. A specified point on the platform will move depending on heave, roll, pitch, sway, surge and yaw motions. The available air gap at a specified time and point on the platform can be written [DNV, 2012],

$$a(t) = a_0 - [\eta_{NET}(t) - \delta(t)] = a_0 - r_t \tag{10}$$

a	*Available air gap (m)*
a_0	*Initial air gap (m)*
η_{NET}	*Vertical wave displacement (m)*
δ	*Vertical platform point displacement (m)*
r_t	*Total response (m)*

The vertical displacement of a point on the platform, δ(t), is dependent on the heave, roll and pitch motions at that specified point and can be written [DNV, 2012],

$$\delta(t) = \xi_3(t) + y \cdot \xi_4(t) + x \cdot \xi_5(t) \qquad (11)$$

δ	*Vertical platform point displacement (m)*
ξ_3	*Heave translation motion*
ξ_4	*Roll rotational motion*
ξ_5	*Pitch rotational motion*

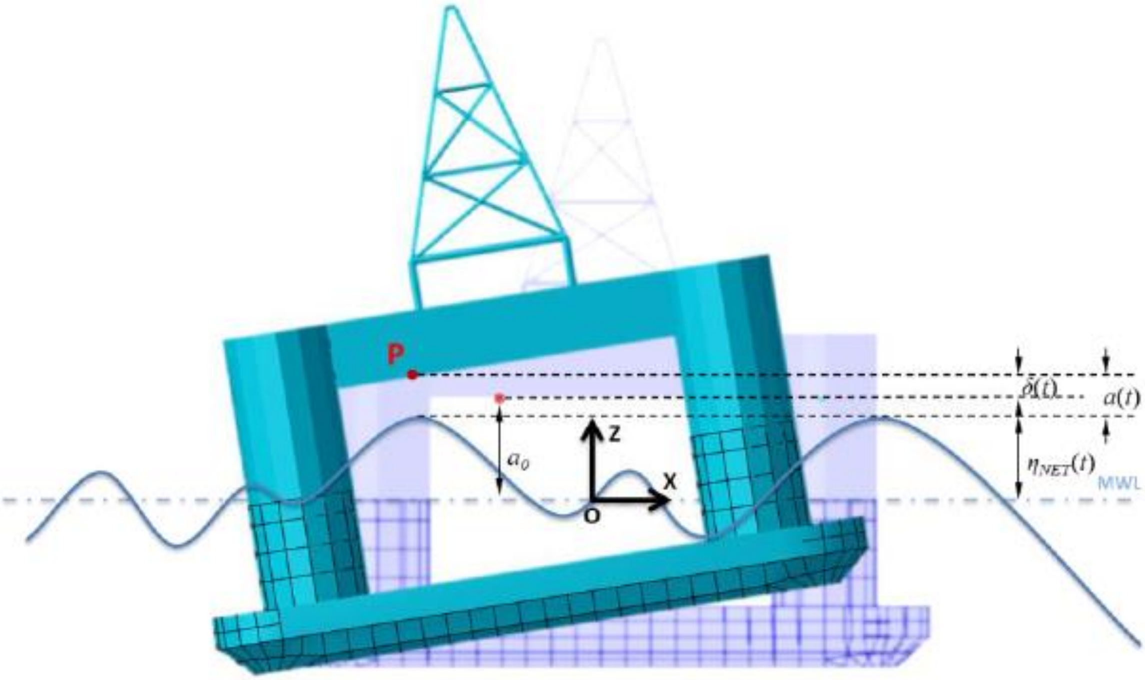


Figure 6 - Air Gap Calculations [DNV, 2012].

The vertical displacement of the waves around the columns, η_{NET}, depend on both first- and second order wave motions for the incident, diffracted and radiated waves, and can be written [DNV, 2014],

$$\eta_{NET} = \eta_i^{(1)}(t) + \eta_{d,r}^{(1)}(t) + \eta_i^{(2)}(t) + \eta_{d,r}^{(2)}(t) \qquad (12)$$

η_{NET}	*Vertical wave displacement (m)*
η_i	*Incident wave displacement (m)*
$\eta_{d,r}$	*Diffracted and radiated wave displacement (m)*

The slowly varying response cannot be found from the Postresp analysis and is therefore estimated by empirical data, which gives a rough factor of 0.1 of the wave frequency response [DNV, 2014]. The slowly varying response of the platform is added to the wave frequency response after the Postresp analysis. The total response is then given by the equation,

$$r_t = r_f + r_s = r_f + [r_f \cdot 0.1] \tag{13}$$

r_t *Total response (m)*
r_f *Wave frequency response (m)*
r_s *Slowly varying response (m)*

4.2 HydroD analysis

To investigate the semi-submersible models motion, stability and air gap, it is necessary to run them through multiple analyses. First, the hull model is created in GeniE. Then, the hull model is used in HydroD to conduct the hydrodynamic analysis with the WADAM wizard. Last, the transfer functions created in HydroD are post-processed in Postresp, to create relevant response data. These analysis software are part of the DNV-GLs Sesam package.

WADAM is a frequency domain hydrodynamic analysis of fixed or floating structures. In the hydrodynamic analyses for this thesis, a panel model is used. This means that only the outer shell of the hull structure is analyzed. Because a Morrison model is not used, damping equations are not included. To run the WADAM analysis and generate transfer functions, these parameters have to be defined: wave directions, wave periods, wave location, hydro model, mass model and offbody points.

4.2.1 Wave directions, periods and location

The direction of the waves are defined in this step. For the motion and air gap analysis, it is necessary to investigate the directions, 0^o and 45^o. For a wave direction of 0^o the wave propagates along the x-axis in the positive direction. The periods necessary to investigate should include the important areas and show the overall RAO. Very low periods give no significant RAO and for large periods, the RAO goes to 1.0. Therefore the range 4 – 38 seconds is chosen. The default parameter values are used for the sea location. It consists of standard physical properties for water.

4.2.2 Hydro and mass model

The model that is analyzed is defined in this step. The hull model generated in GeniE is loaded into the wizard and specified at a correct draft. The next step is to let WADAM calculate the total weight and center of gravity for the platform. It is necessary to define the distance from CG to CB manually. The calculated total weight, displacement and CG is now shown in the wizard, so this is a good time to check the WADAM calculations against your own. WADAM calculates the radius of gyration for the semi, but it is necessary to do these calculations manually to implement the wanted topside weight in the equation.

4.2.3 Offbody points

The general waves generated in WADAM is based on the Airy wave theory, which will not give the correct solutions on the air gap because it does not incorporate the wave build up and diffracted and radiated waves. Therefore, it is necessary to define off body points in the sea surface, for which WADAM will calculate the real response.

In order to investigate the most critical areas around the platform, the air gap will be analyzed in two points for each wave direction. For a wave direction perpendicular (0^o) on the platform, the points are located 5 m in front of the first column and 5 m in front of the second column. For a wave direction diagonally (45^o) on the platform, the points are located 5 m in front of the corner of the first column and 5 m in front of the corner of the second column as seen in figure 6. It will not be necessary to investigate other wave directions because of the symmetry of the hull. The specific points are generated for the sea surface in WADAM, z-axis = 0, and for the semi in Postresp, z-axis = 22.

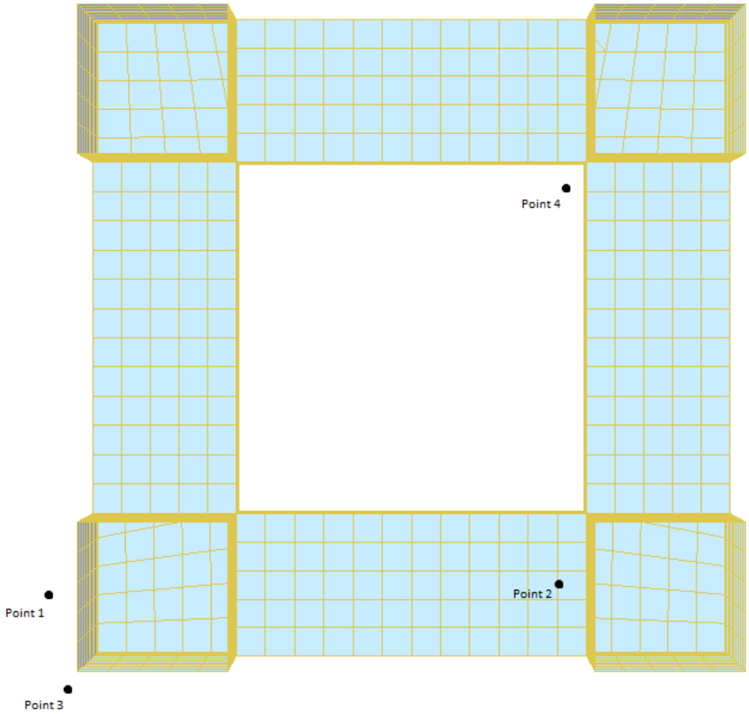


Figure 7 - Air gap analysis points.

4.3 Postresp analysis

Postresp is a graphical post-processor software for frequency and time domain analyzes. The transfer functions generated in WADAM are post-processed in Postresp. The heave, roll and pitch motions are graphically displayed without further processes and can be downloaded as data. To analyze the air gap in Postresp, it is necessary to create: specified points on the platform where the air gap is to be calculated, combined transfer functions with the sea surface elevation and specified point motions, wave spectrums and a defined statistical method.

4.3.1 Specific points

Same definition as for the WADAM analysis, but the points have z-axis coordinates equal to the air gap (22 m).

4.3.2 Wave spectrums

The wave spectrums investigated are single point JONSWAP spectrums, with the variables Hs, T_Z, γ and σ. The JONSWAP spectrum, "JOint North Sea WAve Project", was a joint research program in the North Sea, which was established to take care of the peak enhancement phenomena [Michael, 1999]. To describe the sea states on the Norwegian Continental shelf, the JONSWAP spectrum is a good approximation. This spectrum includes a peakedness factor γ, which can describe more extreme responses than for example the Pierson-Moskowitz spectrum. The Pierson-Moskowitz spectrum is equal to the JONSWAP spectrum when the peakedness factor γ = 1.0. The sigma values describe the width on each side of the peak. A-values for the low frequency side and B-values for the high frequency side. In this thesis we have chosen the peakedness factor γ = 3.0 and the sigma values $\sigma_A = 0.07$ and σ_B 0.09 which is reasonable values for the Norwegian Continental Shelf.

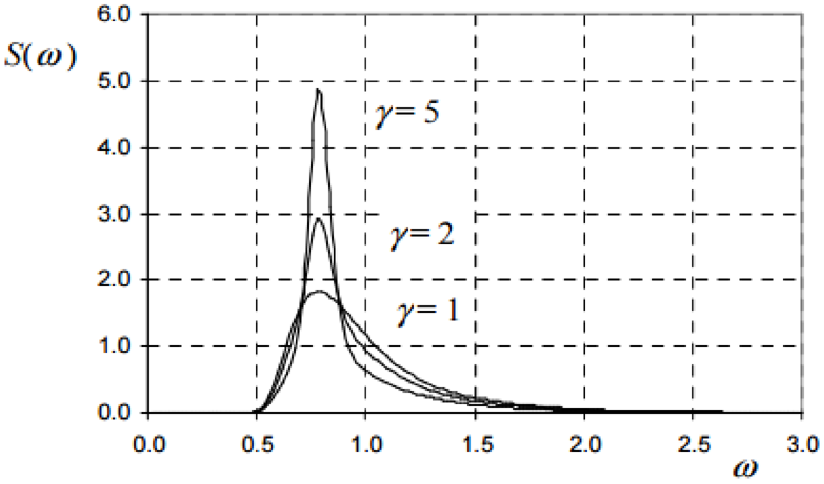


Figure 8 - JONSWAP spectrum. Hs = 4m, Tp = 8s [DNV, 2014].

The variable T_Z is the zero up-crossing period. While T_P describes the period with maximum energy density, T_Z is a measure for the average period between zero up-crossings in a sea state. The zero up-crossing period is found by the relation in equation (14) [DNV, 2011].

$$T_Z(T_P, \gamma) = T_P(0{,}6673 + 0{,}05037\gamma - 0{,}00623\gamma^2 + 0{,}0003341\gamma^2) \qquad (14)$$

4.3.3 Combined transfer functions

The response variables are transfer functions that can be used individually or multiple combined. To analyze the air gap, it is created a response variable for each point specified on the semi earlier. This variable takes into account all the six degrees of freedom and give the absolute vertical motion. The combined response variable combines the response variable from the specific point on the semi-submersible and the elevation of the sea surface. The output is the sum of these vertical displacements, which describes both the negative and positive displacement in the z-direction.

The elevation of the sea surface has a factor of -1.2 and is computed by the off body points in WADAM. The reason for it to have an additional factor of 0.2 is to account for the asymmetry of the wave heights [DNV, 2014]. This transfer function takes into account the column placement and the underlying pontoon for the second column. The rig motion at the specific point has a factor of 1.0.

4.3.4 Statistical method

The statistical method used is a frequency based short-term analysis. To calculate a proper short-term extreme value of the response, the analysis should calculate a high-fractile value (85 – 95 %) of the 3hr extreme value distribution [NORSOK, 2007]. Based on this recommendation, the responses are calculated based on Rayleigh distributed wave heights and depend on the duration of the sea state and a probability of exceedance. The duration will be a 3hr (10800 seconds) sea state and the response will show the 90 % fractile (0.1 prob. of exceedance). It is important that the sea state simulate a sufficient number of frequencies, to assure the randomness of the platform motions. Simulating a typical short-term sea state requires at least 1000 frequencies, but for simulations of floater motions randomness, only approximately 100 frequencies are necessary to get a good simulation [DNV, 2011]. The number of frequencies for each analysis is shown in the analysis tables in the appendix.

4.3.5 Detailed analysis

When simulating a given sea state with peak period, it is important to also implement the periods just below the peak. These periods can have steeper waves and therefore be more critical for the air gap analysis. The recommended periods to investigate with a given peak period and maximum wave height is [NORSOK, 2007],

$$\sqrt{6{,}5\, H_{100}} \leq \; T \leq \sqrt{11\, H_{100}} \tag{15}$$

H_{100} 100-year maximum wave height (m)
T Period (s)

The 100-year maximum wave height for a short-term 3hr sea state is approximated by multiplying the H_S with a factor of 1.9. It is also necessary to check the steepness criteria for the selected H_S and T_P. The average wave steepness for a short-term irregular sea is [NORSOK, 2007],

$$Sp = \frac{2\pi H_s}{g\, {T_p}^2} \tag{16}$$

The steepness limitation for S_P is interpolated between,

$$Tp \leq 8s \rightarrow Sp = 1/15 \tag{17}$$

$$Tp \geq 15s \rightarrow Sp = 1/25 \tag{18}$$

S_P Wave steepness
H_S Significant wave height (m)
g Gravitational acceleration (m/s^2)
T_P Peak period (s)

5. Model Parameters

The design of a semi-submersible hull is a complex task and depend on many design parameters. This complexity is why it would be convenient with a simplified design tool in the early design phase to estimate the hull design. To simplify the model, some parameters are simplified by keeping them constant and others are linearized. This chapter explains the most critical parameters, their influence on the model and how they are treated in the hull estimation.

5.1 Topside layout and weight

The topside of the platform is everything above the hull structure. The layout of the topside on a production platform have some regulations, but can vary greatly in complexity and weight. The topside has generally a layout which requires a VCG around 10-20 meters above the hull structure. The layout often consists of a 10 meter high deck module on the bottom, around 10 meter of processing modules in the middle and smaller modules/piping on the top. Basic stability principles force the designers to locate the horizontal center of gravity for the topside, to be as close to the center as practicable. In this thesis, it is assumed that the horizontal component of the center of gravity is located in the center axis of the hull structure. The vertical component of the topside center of gravity is a major influence on the GM, through the KG term of the stability equation (5). An increase in either the topside weight or VCG will lower the GM and destabilize the platform. The weight of the topside often vary between 15 000 – 50 000 t, depending on processing capacity and complexity.

The topside weight is one of the parameters that is known when concept alternatives are developed. Since it is a known value, it must be one of the input parameters for the spreadsheet.

5.2 Air gap

The air gap is the distance from the sea surface to the lowest point of the topside structure. This distance is one of the major design parameters and will not be altered based on design issues. The air gap must be sufficient to avoid wave impact in severe weather conditions and comply with governing regulations. During operation, the air gap can be adjusted somewhat by changing the ballast weight in the pontoons, but this will affect the stability and motion characteristics of the platform. In the analyses, it is assumed that the air gap will have a fixed distance based on weather conditions for all the cases. The air gap distance will affect the VCG of both the hull and topside, therefore also the KG. This means that the hull design must counter the influence KG has on stability (GM). Stability increasing adjustments can be done by: lower KG by increasing the hull mass, increase BM by increasing the water plane area or/and the column center-center distance, increase KB by increasing the draught (column displacement).

The air gap calculation is based on response analyses for the different models in relevant storm scenarios. The response will be fitted for different designs based on displacement and weather condition.

5.3 Center of gravity

The center of gravity has two components. One in the horizontal plane and one in the vertical plane. The horizontal component of the center of gravity is assumed to be located in the center axis of the hull for both the topside and hull structure. This will simplify the calculations and simulations. In real life, the horizontal component of CG will not be located exactly in the center axis of the platform, nor will the platform be completely symmetrical, but this difference is kept at a minimum and will not influence the total platform stability and motion in a critical way. The vertical component is found from stability calculations based on each case. The VCG for the hull is estimated by the hull design and the assumption that the hull has a uniform distribution of the weight in the columns and pontoon. The topside VCG is not known, but the spreadsheet will generate a value for allowable topside VCG to fulfill the stability requirements.

5.4 Water plane area

In this thesis, we will use a rectangular four-column design, so the water plane area will depend on the width of the columns. The water plane area is a factor for the platform stiffness and indirectly to the added mass, if the pontoon width follows column width, shown in equation (5) and (6). An increased water plane area then results in larger stiffness and added mass. The VCG of the hull depend on the selected column width if displacement is fixed, because the column volume increases and pontoon volume decreases. A larger column width will therefore move the hull VCG upwards and reduce the allowable topside weight and/or VCG. However, the effect is not great as the stability is slightly increased by the increased BM term, shown in equation (3) and (4). The overall philosophy for water plane area design, is to keep it as small as possible.

5.5 Displacement

Displacement is the volume displaced by the pontoon and columns below the mean sea level. This volume is what creates the upwards force (buoyancy) and its design volume is dependent on the total weight from the hull and topside. In the estimations, the displacement is directly related to the topside weight as the total weight is estimated by the topside weight. For deep draft semis, the displacement is largely increased to displace the extra hull weight. The ratio between the displacement in the columns and pontoon often lays in a certain area. For normal draft semis, the columns displace about 25 % and the pontoon about 75 %. For deep draft semis, the columns and pontoon displace about 50 % each. This has not been used to estimate the hull configuration, but is evident for different designs in the spreadsheet.

5.6 Draft

Draft, also called draught, is the distance from the keel of the pontoon (bottom of the hull) to the mean sea level. This value has a strong impact on the heave motions of the platform in the periods below and up to peak period. In figure 5, these periods are expressed by the smaller peak to the left of the natural peak period. The heave motions is a result from the wave forces acting on the pontoon. The longer away from the waves the pontoon is, the smaller the forces and heave motions will be. The dynamic pressure generated by waves decreases exponentially with increased water depth. This means that the ideal design of a semi-submersible has as large draft as possible, while still keeping the platform stable.

To increase the draft, the pontoon displacement must decrease and column displacement increase. There is two ways of achieving this: One way is relevant for the assumptions made in this thesis, which says that the pontoon width must be the same as the column width. This means that a decrease in pontoon width and height will also decrease the column width. The other solution is to keep the column and pontoon width the same, but decrease the pontoon length, but this reduces the allowable topside VCG. For both of these solutions, it is necessary to increase the submerged column length to achieve correct displacement.

5.7 Column dimension and shape

The columns can be either circular or quadratic. With quadratic columns, the pontoon are often the same width as the columns, which will allow the stresses in the structure to spread correctly. The alternative is that the pontoon width is narrowed slightly towards the middle, to get the right motions and displacement ratios. The column width determines the water plane area and when correlated to the pontoon width, it is one of the main parameters for the design. It influences the draught, natural period in heave, hull VCG, KB, BM and the displacement ratio between pontoon and column. Generally, as small column as possible is wanted since this can increase draught and have positive impact on stability and heave motions as mentioned earlier.

5.8 Pontoon dimension and shape

As with the columns, the pontoons can also be circular or rectangular, but circular is a more outdated design. Production platforms generally have a ring pontoon, since this increases overall stability and improves heave motions. Since the width of the pontoon is correlated to the width of the columns, the displaced volume is somewhat dependent on the column design. The height of the pontoon varies generally about half of the width, depending on the stiffness and ballast section requirements. Except from generating more displacement and ballast sections, the height is supposed to generate enough structural integrity as a stiffener between the columns. Ideally, the pontoon would be a flat plate, which would create enough added mass and leave all the displacement to the columns, increasing the draught.

5.9 Distance between columns

When keeping all other parameters constant, the distance between the columns will determine the displacement volume of the pontoon. Altering the pontoon displacement, will determine the displacement of the columns, so by decreasing pontoon displacement the draft must increase. By this relation, it is wanted to make the distance shorter, but it also influence two other parameters negatively. The columns support the topside structure, so a narrower design will restrict the layout. The stability, by the term GM, is also affected negatively by the distance, shown in equations (1), (3) and (4). These two parameters shows that the larger the platform (required topside weight), the larger must the distance be to achieve good stability and support.

5.10 Natural heave period

The natural heave period is a very important factor when considering the motion characteristics of a semi-submersible rig. The closer the wave period is to the semi-submersible's natural heave period, the larger the response motion. The worst case is when the natural heave period of the semi-submersible coincides with the wave period, which results in resonance motions. Resonance motions will increase until either, the acting force (wave period) changes, or the mass of the semi-submersible changes. The natural heave period is described by equation (6), where the important parameters are the total mass, added mass and the stiffness. Total mass and stiffness is known from the geometry of the platform. The added mass is a more complex parameter, dependent on the submerged horizontal hull planes and a mass coefficient. By collection empirical data from the WADAM calculations, the added mass and thereby the natural heave period can be estimated in the spreadsheet.

For semi-submersible production platforms, it is necessary to estimate the heave motions because it determines the fatigue loads on the production risers. Especially for steel catenary risers (SCR), where all the vertical motions is distributed only in the touch down point. This leads to stricter heave motion requirements for SCR than flexible risers.

5.11 Natural roll and pitch period

The natural roll and pitch period are mostly equivalent to each other because of the assumed symmetrical design. Some differences in the periods will occur depending on the riser hang-off arrangements. The roll and pitch motions is generated by the waves, current and wind, but will be somewhat restricted by the mooring system. If the natural periods are too low and with too high amplitude, they will fall into the high-energy area for the sea states of the region. This can lead to resonance and large roll and pitch motions. The motions should be small, to minimize fatigue on risers and increase comfort. This is done by keeping the GM reasonably low.

The natural roll and pitch frequencies for semi-submersibles are generally not an issue for the design. Therefore, it will not be accounted for in this thesis.

5.12 Summary of parameters

Based on these evaluations and their significance for the stability and motion characteristics, some parameters will have a fixed value and other will vary depending on linearization from model analyses. These simplifications is necessary to be able to generate the estimation spreadsheet. Their influence on the accuracy will be discussed in the chapter 13.

To achieve excellent heave motions, some parameters must differ from the normal standpoint. Which parameter who influences the heave motions in a good way is found by a parametric study for the parameters who is suspected to have a positive influence. This is done in chapter 8.

6. The Semi-submersible Model

The semi-submersible models used in the calculations and analyses are simplified models only consisting of the hull structure. The hull model created in GeniE consists of the outer shell, which will be subjected to water forces. Supporting structure, like braces and beams are neglected from the design, as only the outer shell shape will influence the hydrodynamic analyses.

6.1 Assumptions for the semi

To be able to estimate the hull design, some assumptions related to the model must be defined:

- The hull have four columns with quadratic shape.
- Rounded edges on the columns and pontoon are neglected.
- The pontoon is a quadratic ring pontoon.
- The total hull weight includes live loads, riser loads, mooring loads, ballast, equipment in hull and steel weight of hull.
- The semi sections topside, columns, pontoon has symmetrical weight distribution and horizontal center of gravity (HCG) located in the center of each section.
- GM is fixed to 4.0 m.

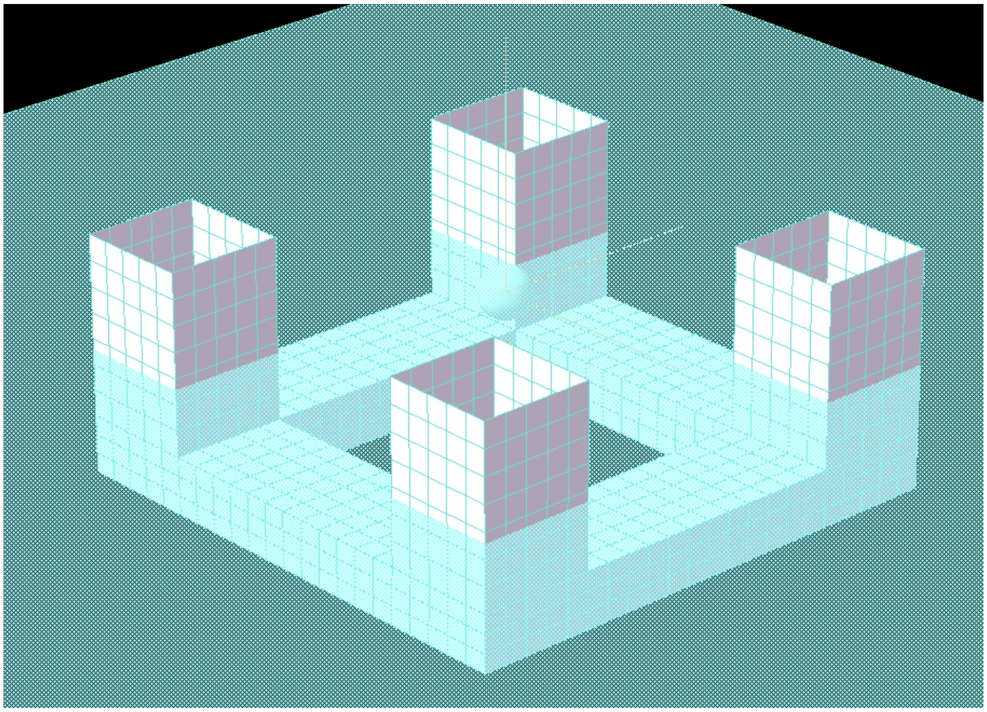


Figure 9 - Hull model of default design in HydroD.

6.2 Default model dimensions

For creating the spreadsheet and initial hydrodynamic analyses, a default model design is provided to set up the correct formulas and calculations. The base model is an already conducted project with good results from the stability, motion and air gap analyses. The generated spreadsheet for estimation of hull design will follow the configuration of the default model and give the default model design output if the topside weight and weather location is equal.

The default model has the following dimensions:

Table 1 - Default model dimensions.

Total hull weight	60 000 000	kg
Hull VCG (KG)	12.0	m
GM	4.0	m
Column spacing c-c	79.5	m
Column width	23.0	m
Pontoon width	23.0	m
Pontoon height	11.0	m
Draught	24.0	m
Air gap	22.0	m

7. Estimation Spreadsheet – Normal Draft

The spreadsheet estimates hull dimensions based on the two inputs, topside weight and 100-year significant wave height. The outputs are hull geometry dimensions, weight and stability. The outputs are based on the default model and alters this model up and down to achieve decent stability and geometry for different input values. The estimation spreadsheet has a topside weight range from 20 000 to 80 000 tonnes. This includes most of today's production platforms.

The reasoning behind the estimations are based on existing platforms, experimentation and general knowledge of decent hull design. Some of the achieved results are compared to relevant existing platforms to show the relevance of the estimates.

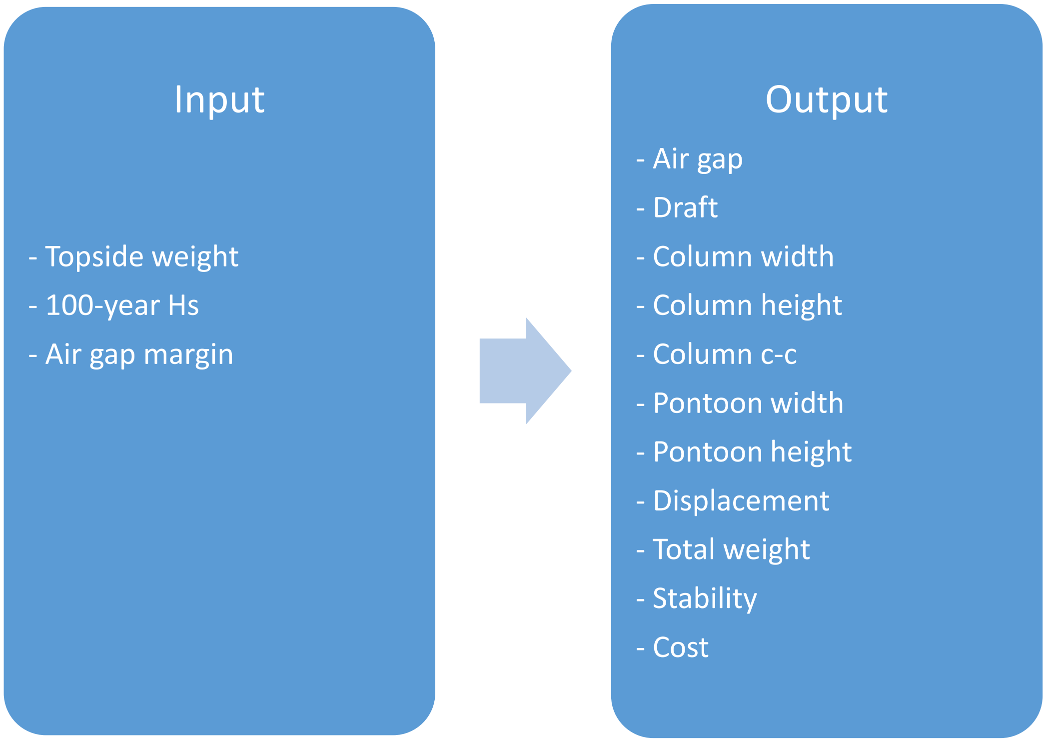


Figure 10 - Estimation process.

7.1 Air gap

The air gap has been fixed at 22.0 meter for all the estimated models in this chapter and for the deep draft estimations. To see the final air gap estimation, see chapter 10. The air gap of 22.0 meter was selected because the dimension of the default model and it would be sufficient for all platforms in all-weather scenarios. The air gap for some of the semis will be decreased from the analyzed 22.0 meter. This will result in a larger available VCG for the topside or the possibility to alter the hull dimensions to improve motions or reduce volume (cost).

7.2 Draft

The draft of the default model is 24.0 meter, which is in the range of normal values for regular platforms. Initially, the draft was a fixed value (24.0 m) for all the estimated platforms. However, this led to some problems with the stability of the platforms, which further generated unreasonable hull dimensions. Therefore, the draft varies from 22.0 – 26.0 meter respectively for small to large platforms. Data from existing platforms shows that this range of draft is common. Comparing the estimated draft with drafts of the example platforms would not give any reasonable knowledge since the draft for these platforms may be selected based on wanted motion characteristics and can vary in a greater way than the other dimensions. The draft of the estimated models should give heave motions in an acceptable range.

The equation that calculates the draft is shown below.

$$d = 22\,m + \frac{W_{top} - 20\,000\,000\,kg}{15\,330\,525\,kg} \qquad (19)$$

d	*Draft (m)*
W_{top}	*Topside weight (kg)*

As many of the estimation equations are build up in the same way, the draft equation will be explained in more detail here. The equation generates a linear increase in draft from the minimum value 22.0 meter. To assign the minimum value to a topside weight of 20 000 000 kg, 20 000 000 is subtracted from the topside weight in the numerator. The fraction will then be zero for this topside weight. If the equation shall generate 24.0 meter for the default model, the numerator must be twice the size of the denominator for this topside weight. The sum in the numerator is 50 661 050 – 20 000 000 which equals 30 661 050. Then the denominator is selected to be 15 330 525 (half) to achieve the 24.0 meter draft. Many of the other equations are build up in the same way, a ratio between the weights in the fraction, added with the minimum value. Some estimation equations will not have a minimum value, but be restricted by the range of the topside weight.

7.3 Displacement and total weight

The topside weight is the main input parameter and decides the total weight and thereby the displacement of the platform. Based on the value of the topside weight, the topside weight percentage of the total weight is calculated.

The topside weight percentage varies based on empirical data from relevant platforms and the default model. It also takes into account to achieve decent stability for the platform. The default model is relatively a medium-large platform and has a topside weight percentage of 45.78 %. Large platforms can achieve a topside weight percentage of about 50 % and the smallest platforms about 35 %. This relationship has been found when investigating existing semi designs. See section about example semis for references to investigated data. The reason behind the variation in topside weight percentage is mainly that additional displacement is achieved with less steel weight, than the increase in topside weight. The internal equipment inside the hull also does not scale in the same way as the hull. From stability experiments and relevant existing platforms, the topside weight percentage is selected to vary from 38.0 % for the smallest platform to 53.22 % for the biggest.

$$W_{\%,top} = 0.38 + \frac{W_{top} - 20\,000\,000\,kg}{394\,100\,899.7\,kg} \tag{20}$$

$W_{\%,top}$ *Topside weight percentage*
W_{top} *Topside weight (kg)*

From the topside weight percentage, the total weigh together with the hull weight is calculated. This also gives the required displacement of the hull. Shown below is the displacement of estimated models based on the topside weight percentage compared with existing platforms. The chart shows that the estimated displacement and total weight is reasonable relative to the topside weight.

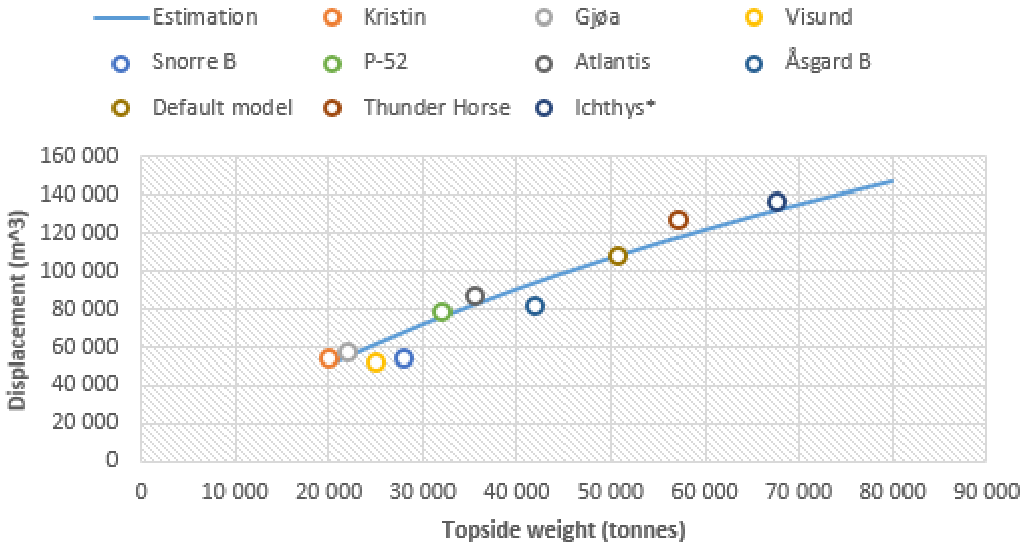


Figure 11 - Topside weight versus displacement, with examples.

7.4 Column width, pontoon width and pontoon height

The column width only varies based on examples of existing rigs. The column width shall add displacement, stability and structural integrity for the platform and is therefore somewhat restricted to a certain range. The column width decides the pontoon width, as they always have the same value. Some platforms has variations of pontoon width relative to column width, but generally, the difference is small and does not alter the behavior of the platform noteworthy.

Small platforms has a column width of about 16.0 – 18.0 meter. The large platforms has a width of about 23.0 – 24.0 meter. There are not many very large platforms to compare against, but as an estimate, the column width for the largest estimated platform is set to 25.0 meter. The smallest platform receives a width of 16 meter. This gives a smaller range of variation for the platforms larger than the default model (2.0 m) than the smaller ones (7.0 m). This has to do with the stabilization of the platforms. Generally, the larger the platform the larger must the deck area be. Therefore, as the platform gets bigger and topside weight increases, the height of the platforms does not change significantly. By reducing the increase in column width, the column c-c can increase more and provide more stability for the wider topside.

To implement this into the spreadsheet, the calculation of column width is different based on whether the topside weight is above or below the default model.

For topside weights below the default model, the calculation of column width follows this relation.

$$C_w = 16\ m + \frac{W_{top} - 20\ 000\ 000\ kg}{4\ 380\ 150\ kg} \tag{21}$$

For topside weights above the default model.

$$C_w = 23\ m + \frac{W_{top} - 50\ 661\ 050\ kg}{15\ 330\ 525\ kg} \tag{22}$$

The pontoon width follows the relationship.

$$P_w = C_w \tag{23}$$

C_w Column width (m)
W_{top} Topside weight (kg)
P_w Pontoon width (m)

The estimation of pontoon height follows the same method as the column width and is based on relevant existing platforms. The height for platforms smaller than the default varies in the range of 8.5 – 11.0 meter. For larger platforms, it varies from 11.0 – 12.0 meter.

Platforms smaller than the default model.

$$P_h = 8.5\ m + \frac{W_{top} - 20\ 000\ 000\ kg}{5\ 110\ 175\ kg} \tag{24}$$

Platforms larger than the default model.

$$P_h = 11\ m + \frac{W_{top} - 50\ 661\ 050\ kg}{30\ 661\ 050\ kg} \tag{25}$$

P_h Pontoon height (m)
W_{top} Topside weight (kg)

Based on topside weight, these values are calculated. The chart below shows the estimated column width compared with relevant examples. The available examples for the larger platforms are non-existent also for this chart, but for the medium to small platforms, the estimations are a reasonable good match with the examples.

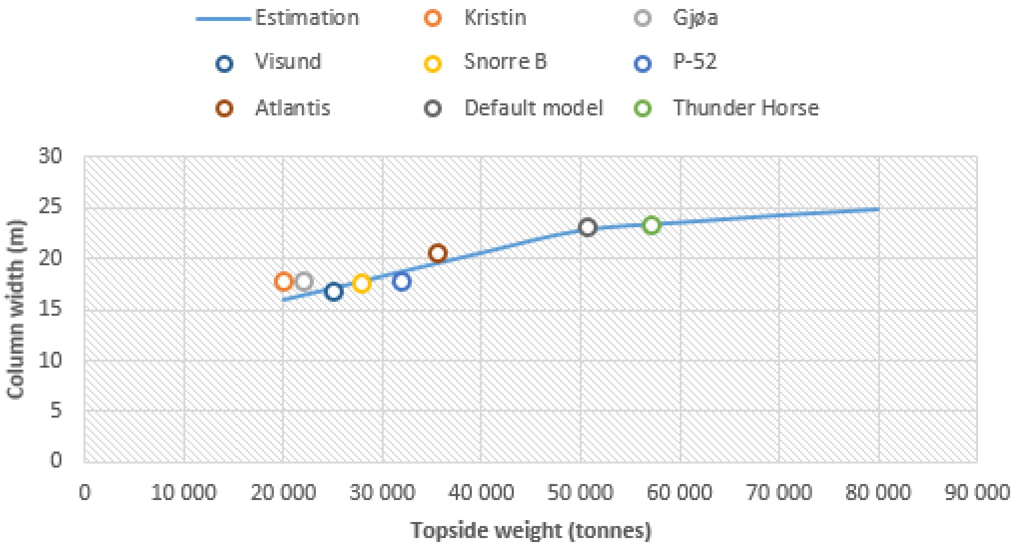


Figure 12 - Topside weight versus column width, with examples.

7.5 Column height and c-c distance

Of the estimation equations, the calculation of column center-to-center (c-c) distance is the only geometrical value that is not directly dependent on the topside weight. The column c-c is calculated to achieve the correct displacement together with the earlier estimated hull dimensions. When experimenting with the variation of the other hull dimensions, a resulting reasonable range for the column c-c was a main factor.

Shown below is the equation for calculating the column c-c.

$$C_{c-c} = \frac{\nabla - \left[4 \cdot {C_w}^2 \cdot (d - P_h)\right]}{4 \cdot P_w \cdot P_h} \qquad (26)$$

The column height is the sum of the air gap and draft. Note that it includes the pontoon height. If not stated else, the column starts at the top of the pontoon for the other parts of the thesis.

$$C_h = A + d \tag{27}$$

$C_{c\text{-}c}$ = Column center to center distance (m)
∇ = Semi displacement (m^3)
C_w = Column width (m)
d = Draft (m)
P_h = Pontoon height (m)
P_w = Pontoon width (m)
A = Air gap (m)

The chart below shows that the range for the column c-c is reasonable. Note that the chart shows the total pontoon length, which includes the column width in addition.

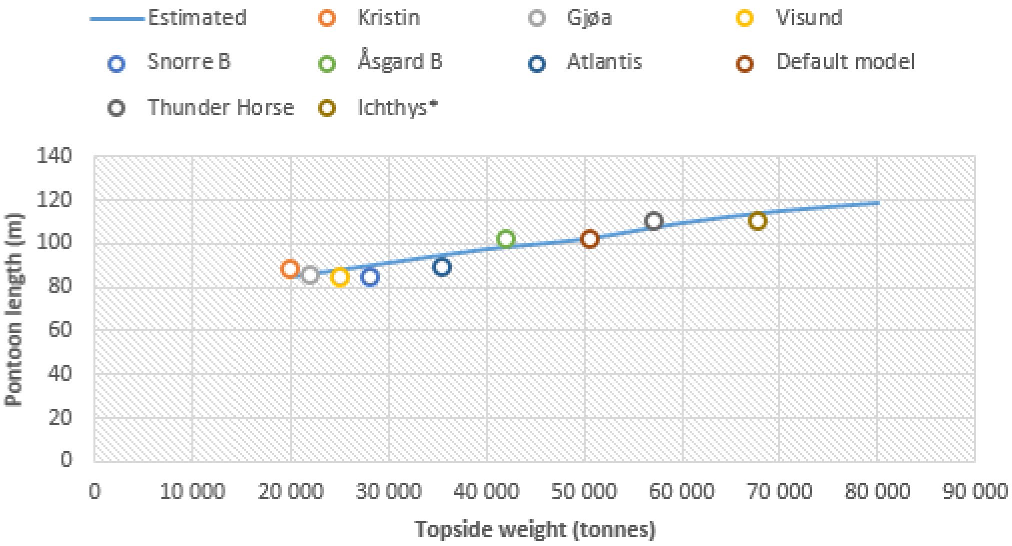


Figure 13 - Topside weight versus pontoon length, with examples.

7.6 Examples

Existing semi designs have been studied to be able to compare the estimations with existing data. This has shown to be valuable when developing the equations as they work well as a guiding parameter. Interesting relationships between topside weight and hull dimensions have been found for many of the dimensions, which have been used in the estimation equations. The data is mainly gathered from “worldwide survey of semi-FPSs and FPUs”, by Mustang Engineering. The data is also quality check with manufacturers where it has been possible.

Table 2 - Semi-submersible production platforms [Wood Group Mustang, 2011], [GVAC.SE, 2013], [Aker Kværner, 2003], [OFFSHORE-TECHNOLOGY.COM, 2015].

Platform	Topside weight (tonnes)	Displacement (m^3)	Column width (m)	Pontoon length (m)
Kristin	20 000	54 600	17.8	88.3
Gjøa	22 000	57 500	17.8	85.3
Visund	25 000	52 600	16.8	84.5
Snorre B	28 000	54 600	17.5	85.0
P-52	32 000	78 000	17.8	n/a
Atlantis	35 500	86 600	20.5	89.6
Åsgard B	42 000	82 000	Circular	102.4
Thunder Horse*	57 100	126 800	23.2	110.0
Ichthys**	67 800	136 600	n/a	110.0

* Thunder Horse: 2 x 22m x 23m and 2 x 22m x 26m. Avr. 23.2m x 23.2m.

** Ichthys: Topside weight is maximum allowable design weight.

7.7 Stability

The estimated hull dimensions generates an estimate on the stability of the platform. The stability is represented by the VCG for the hull, topside and total (KG). KG is calculated based on equation 5 with the assumption of a constant GM of 4.0. The VCG for the hull is more complicated to calculate and depends on the arrangement of mooring, equipment, ballast tanks etc. Therefore, it is very difficult to estimate a reasonable distribution of the weight in the hull. One easy approach could be to assume a uniform distribution of the weight on the hull, but this would generate a too high VCG, as the hull is generally heavier in the lower parts. This is mainly because of ballast and storage tanks in the pontoons and lower columns.

The method chosen to estimate the hull VCG is to assume uniform distribution of the weight, but add a correction factor for the pontoon. Because of uniform distribution of weight, volume can replace the weight term. The default model has a VCG for the hull of 12.0 meter, but with uniform distribution has 16.5 meter. To achieve 12.0 meter, the correction factor must be 2.35. Simulating for other topside weights, this assumption gives reasonable results. The formula for estimating hull VCG is shown below.

$$VCG_{hull} = \frac{\left[V_p \cdot \left(\frac{P_h}{2}\right) \cdot 2.35\right] + \left[V_c \cdot \left(P_h + \frac{C_h}{2}\right)\right]}{V_c + \left(V_p \cdot 2.35\right)} \qquad (28)$$

The VCG for topside is calculated based on KG and hull VCG. The formula for estimating topside VCG is shown below.

$$VCG_{top} = \frac{W_{total} \cdot KG - W_{hull} \cdot VCG_{hull}}{W_{top}} \qquad (29)$$

VCG_{hull}	*Vertical center of gravity for hull (m)*
VCG_{top}	*Vertical center of gravity for topside (m)*
V_p	*Pontoon volume* (m^3)
V_c	*Column volume* $(m^{3)}$
P_h	*Pontoon height (m)*
C_h	*Column height (m)*
W_{total}	*Total semi weight (kg)*
W_{hull}	*Hull weight (kg)*
W_{top}	*Topside weight (kg)*

8. Sensitivity study for deep draft hull configurations

The purpose of a deep draft semi is to minimize the heave motions to allow the use of for example steel catenary risers. When developing the spreadsheet, the focus is first on how the other variables influence the heave motions. Then, the results from those studies are used to study the effects of different draft configurations. The study of the dimensions is done by generating different cases and studying the heave and pitch RAO for those. A good estimation is achieved when the heave and pitch motions are lowered by about 50 % from the normal draft semi. To achieve larger draft, the hull size and thereby its weight must increase. Increased hull size also leads to increased costs. Therefore, the hull size is increased minimally to achieve the wanted response decrease.

For heave RAO, the area around the first peak (about 12 – 18 s) is evaluated. For the pitch RAO, the peak values are evaluated.

8.1 Parametric study of alternative hull designs

Throughout the studies, the draft is constant at 40 meters. Different configurations for column width, c-c and pontoon height are evaluated. All other dimensions are constant from the default case.

Table 3 show the different cases.

Table 3 – Alternative hull designs for case 1 – 10.

	DEFAULT	**CASE 1**	**CASE 2**	**CASE 3**	**CASE 4**	**CASE 5**	**CASE 6**
INCREASED HULL WEIGHT %	0	43.9	56.9	39.9	47.9	33.9	48.6
COLUMN WIDTH	23.0	24.5	26.0	24.5	24.5	24.5	27.0
COLUMN C-C	79.5	79.5	79.5	75.5	83.5	79.5	72.0
PONTOON HEIGHT	11.0	11.0	11.0	11.0	11.0	9.0	9.0

In the default case, the hull weight was governed by equation (20). In these deep draft cases (1 – 6) the first parameter, increased hull weight percentage, describes how much the original weight must increase to accommodate the extra hull displacement. This parameter is wanted as low as possible to minimize cost.

- The objective of case 1 and 2 is to show the effect of increased column width, when keeping all other parameters constant.
- The objective of case 3 and 4 is to show how the semi responds to increasing and decreasing the column c-c.
- Case 5 illustrates the effect of decreasing the pontoon height.
- Case 6 is an extreme case for all the positive configurations and only used for illustrational purposes.

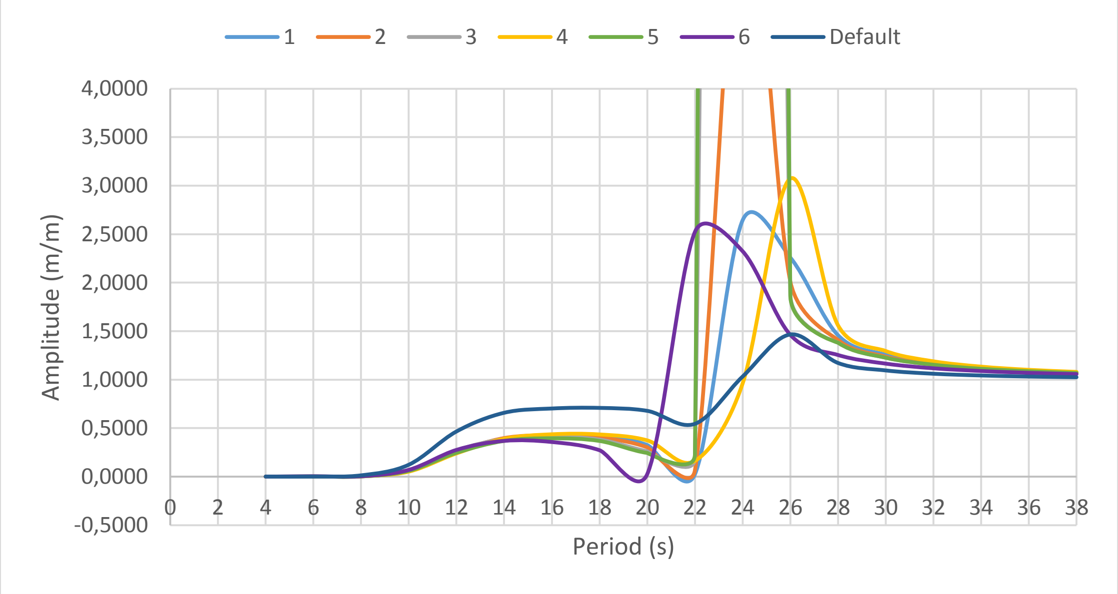


Figure 14 - Heave RAO for case 1 – 6.

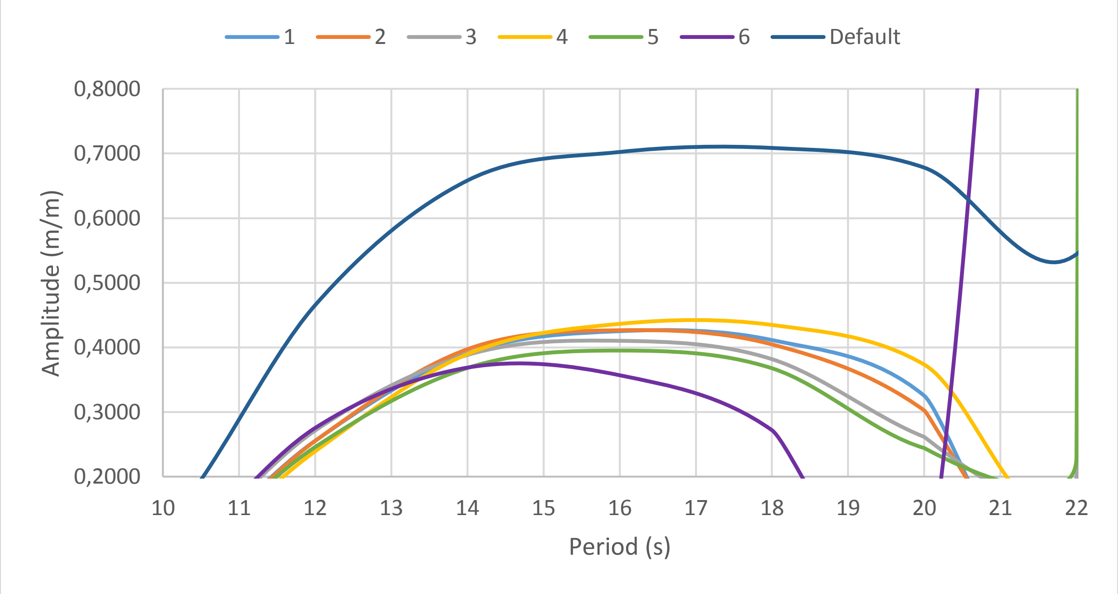


Figure 15 - Heave RAO for case 1- 6. Detailed view.

The first thing to discuss from the studies is the problem with the natural peak period in the amplitude for some of the cases. Normally the peak has an amplitude between 1.5 and 3.0, but here an amplitude of e.g. 50 and 100 are reported. This is not a problem for the results, since it is not this area of the graph that is evaluated. The problem with the peaks is probably caused by something with the dampening of the system and the models does not include Morrison model, which would contribute to damping. This problem should be analyzed if further work is done on the thesis.

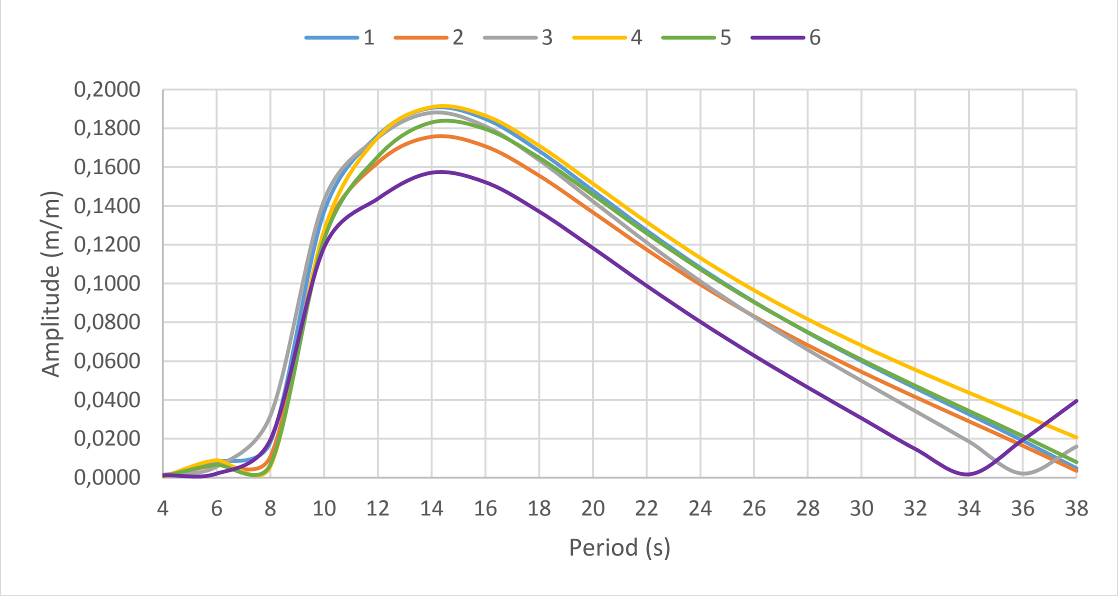


Figure 16 - Roll and pitch RAO for case 1 – 6.

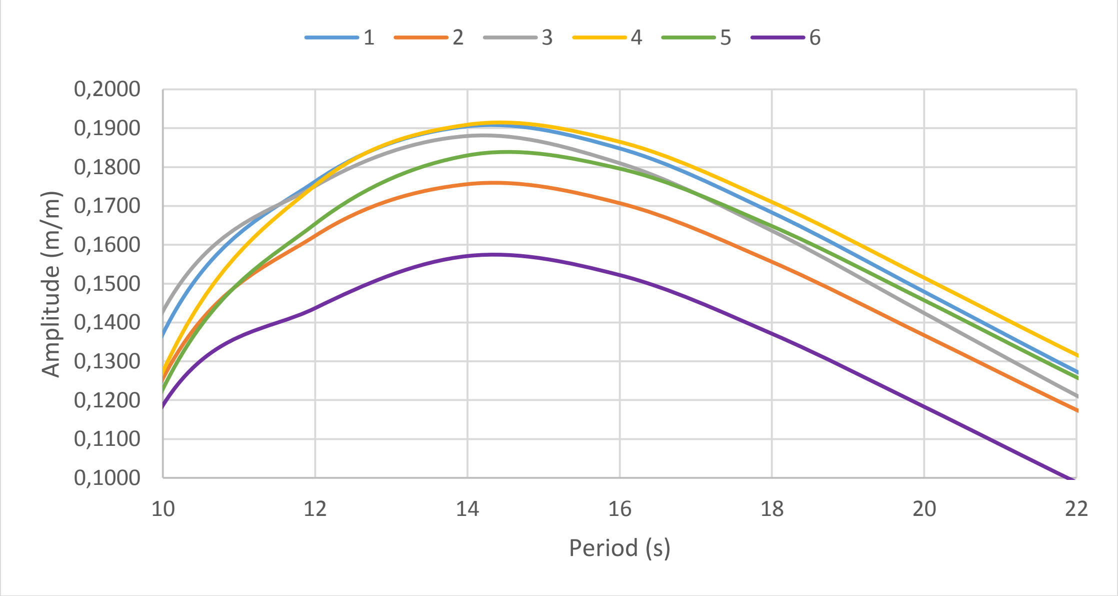


Figure 17 - Roll and pitch RAO for case 1 – 6. Detailed view.

The results from case 1 and 2 shows that the column width has no noteworthy influence on the heave RAO. On the other hand, it is seen that pitch motions is reduced (7.8 %) when increasing column width from 24.5 to 26.0 meters.

Case 3 and 4 evaluates the influence from the column c-c distance. Figure 15, show that a reduction has a positive effect and an increase has a negative effect on the heave RAO. The same applies to the pitch RAO. The effects are very small, when considering that the c-c distance is altered by plus/minus 4 meters, which is a relatively large change. The positive effects for the heave and pitch RAO compared to case 1 are respectively 3.5 % and 1.3 %.

Case 5 shows the effect of reducing the pontoon height and the result show a positive effect. The reduction of both heave and pitch RAO compared to case 1 are respectively 7.0 % and 4.0 %.

The total results from this study is:

Column width:	No results for the heave RAO. Good effect on pitch RAO for increased width.
Column c-c:	Very small positive effect on heave and pitch RAO for reduced distance. Important influence for the heave natural peak period.
Pontoon height:	Small positive effect on heave and pitch RAO when reduced height. Gives negative effect on heave natural peak period.

Compared against the default model, all the 40-meter draft cases gives excellent motions. The worst (case 4) and best (case 5) have respectively a reduction in heave RAO of 38 % and 44 %. The results show that the main contributor to the motions is the draft, which was expected. The next stage for generating the estimation spreadsheet is to configure the equations to increase the draft, while altering the other dimensions as recommended from the study, until 50 % reduction in heave motion is achieved.

Based on these results, a new parametric study is done. This time the draft is varied while the other parameters are kept constant. Three cases are studied with the draft at 40.0, 42.0 and 44.0 meters. The dimensions of the hull is selected based on the data from the previous study.

8.2 Sensitivity study of alternative draft depths

8.2.1 Default model topside weight

Based on the previous sensitivity study, a reasonable hull configuration is selected to accommodate good topside VCG but keep the increased hull weight as low as possible. The draft is the only parameter that will be altered. The objective of this sensitivity study is to achieve about 50 % reduction in heave RAO while keeping a reasonable topside VCG and a minimum weight increase. Exactly how large reduction in heave RAO is needed for excellent heave motions will depend on the individual case. Reductions of less than 50 % could be sufficient e.g. to be able to implement steel catenary risers. To secure decent allowable topside weight and VCG, the minimum VCG for the default model topside weight is selected to be 12.0 meter above the hull structure. The VCG will probably increase, as the air gap probably will be estimated to a smaller value than 22.0 meter. As the draft becomes deeper, the effect on the analyzed peak will become smaller and smaller. Therefore, relatively deep drafts will be needed to achieve 50 % reduction.

Table 4 – Alternative hull configuration for case 7 – 8.

	Default	**Case 7**	**Case 8**	**Case 9**
Topside weight (tonnes)	50 661	50 661	50 661	50 661
Hull weight (tonnes)	60 000	95 168	99 891	104 614
Total weight (tonnes)	110 661	145 829	150 552	155 275
Increased hull weight (%)	0	58.6	66.5	74.3
Topside VCG (m)	19.3	15.9	14.3	12.7
Column width (m)	23.0	24.0	24.0	24.0
Column c-c (m)	79.5	82.0	82.0	82.0
Pontoon width (m)	23.0	24.0	24.0	24.0
Pontoon height (m)	11.0	9.0	9.0	9.0
Air gap (m)	22.0	22.0	22.0	22.0
Draft (m)	24.0	40.0	42.0	44.0

Figure 17 and 18 show the results from the sensitivity study.

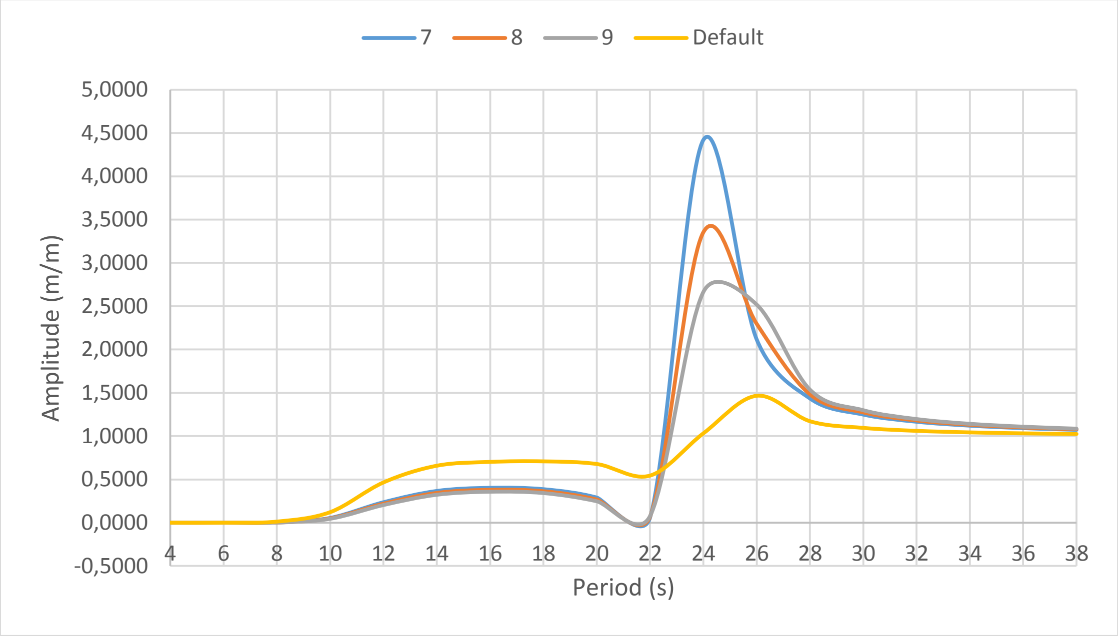


Figure 18 - Heave RAO for case 7 -9.

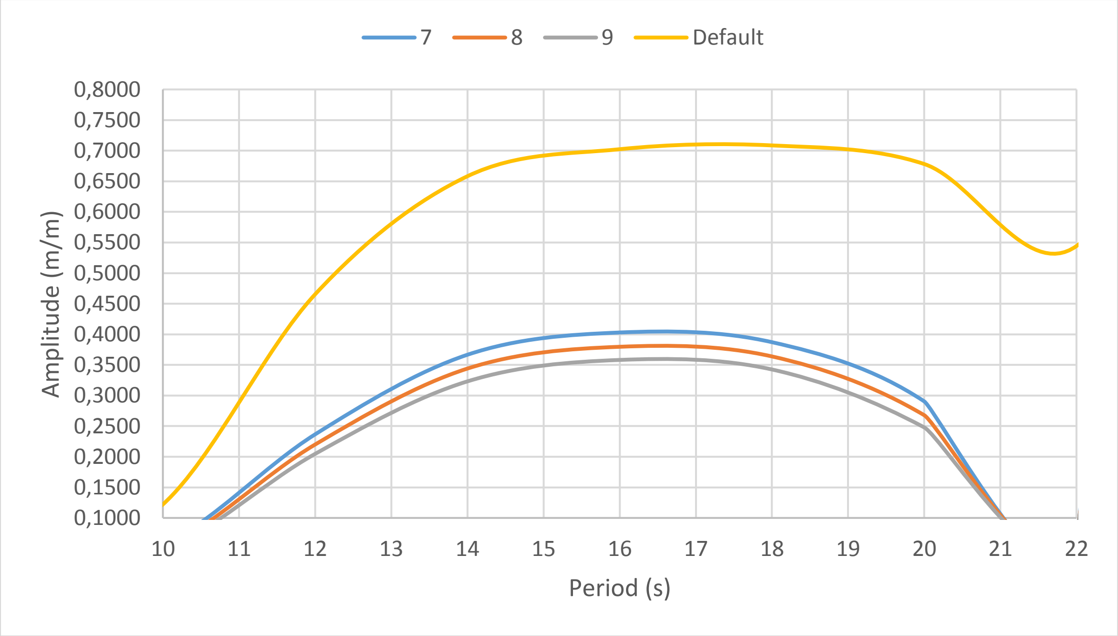


Figure 19 - Heave RAO for case 7 – 9. Detailed view.

The charts show that the natural peak period for heave is reduced from 26 to 24 seconds for the deep draft models. This is a compromise to achieve excellent motions for the semi, but is acceptable as the wave energy is limited around these periods. The total reduction in heave RAO for the three cases are respectively 43.1, 46.4 and 49.4 percent. The achieved heave RAO for case 9 is considered a good result and will govern the estimation spreadsheet for the deep draft semis.

8.2.2 20 000 tonnes topside weight

With the results from case 9, a hull configuration for a semi with topside weight of 20 000 tonnes is made. The objective is to evaluate if the hull configuration of case 9 is transferable to a semi with this topside weight.

Table 5 – Hull configuration for case 10.

	Normal	Case 10
Topside weight (tonnes)	20 000	20 000
Hull weight (tonnes)	32 632	65 313
Total weight (tonnes)	52 632	85 313
Increased hull weight (%)	0	62.1
Topside VCG (m)	10.6	12.1
Column width (m)	16.0	17.0
Column c-c (m)	69.0	76.5
Pontoon width (m)	16.0	17.0
Pontoon height (m)	8.5	8.0
Air gap (m)	22.0	22.0
Draft (m)	22.0	44.0

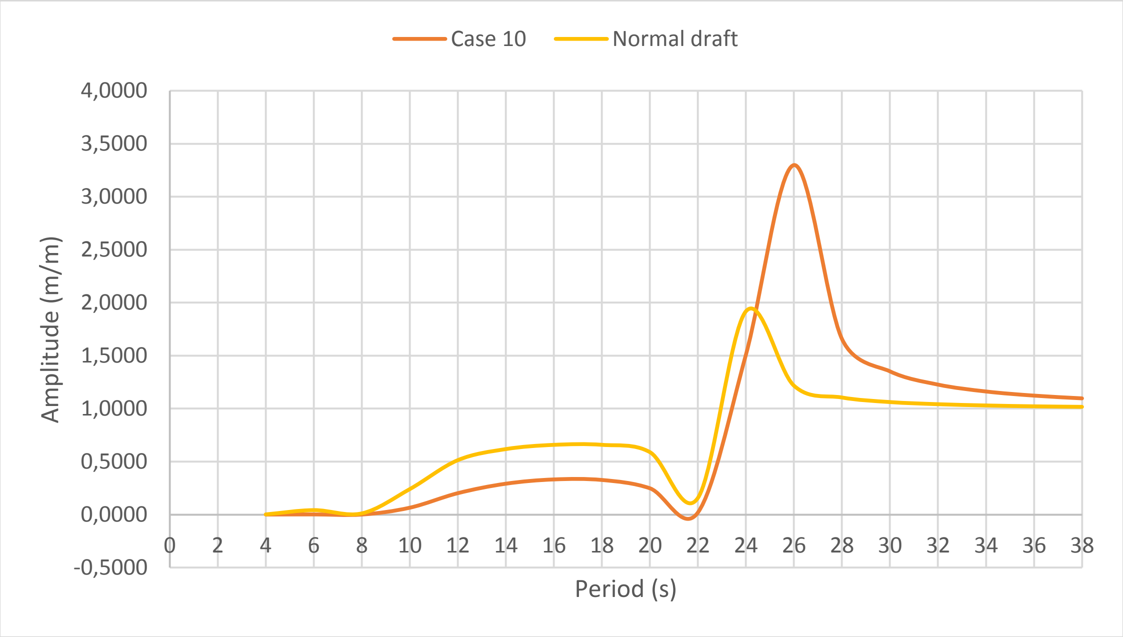


Figure 20 - Heave RAO for case 10.

The results from the alternative hull configuration in case 10 show a reduction of heave RAO of 49.6 %. This prove good motions and show that the results from case 1 to 9 can be used to generate the estimation spreadsheet for all the variable topside weights.

8.3 Summary

The results show that the heave RAO is mainly dependent on the draft of the semi. A reduced column c-c distance also showed small positive effects on the RAO, but will influence the natural peak period negatively. When developing the estimation spreadsheet for deep draft semis with excellent motions, the main parameter will be the draft. The other dimensions will only follow the recommendations given in the earlier results to achieve good stability and natural peak period.

These results show the same recommendation as a sensitivity study conducted by a joint industry project by Statoil, Hydro, Shell, BP and Marintek in 2006. Their study took into account more hull configurations, but the conclusion was the same. *"The sensitivity study has shown that from all the geometric variations that have been tested, very few if any gave sufficient effect on the vertical riser porch in fatigue sea states"*[Arnesen, et al., 2006]. Based on these findings the verdict was that a more drastic change to the design parameters must be implemented to reduce heave motions for the riser porch, by increasing the draft.

9. Estimation spreadsheet – deep draft

The estimation spreadsheet for deep draft semis is based on the same principles as for the normal draft. The spreadsheet will estimate hull dimensions from the inputs topside weight and 100-year H_S. The spreadsheet can estimate hull configurations for topside weights between 20 000 and 51 000 tonnes. To achieve the excellent vertical motions, the draft was found to be 44 meter for both the default model and the 20 000 tonnes topside model. From this, it is assumed that the draft is fixed at 44 meter for all the estimations. This chapter describes the estimation equations that have been changed from the normal draft estimations.

9.1 Displacement and total weight

The displacement for normal draft semis was dependent on the total weight. The displacement of the deep draft semis is only dependent on the hull dimensions and is the sum of all the estimated dimensions. From this, the total weight is calculated based on the displacement output and gives a weight/displacement increase in percent for the deep draft.

$$\nabla = 4 \cdot \left((d - P_h) \cdot {C_w}^2 + C_{c-c} \cdot P_w \cdot P_h \right) \tag{30}$$

$$W_{total} = \nabla \cdot \rho_w \tag{31}$$

∇	*Semi displacement (m^3)*
d	*Draft (m)*
P_h	*Pontoon height (m)*
C_w	*Column width (m)*
C_{c-c}	*Column center to center distance (m)*
P_w	*Pontoon width (m)*
W_{total}	*Total semi weight (kg)*
ρ_w	*Seawater density (kg/m^3)*

9.2 Column width, pontoon width and pontoon height

The column width for the deep draft is dependent on the width of the normal draft columns. The width is basically just increased 1 meter to achieve increased stiffness for the system and allow a smaller c-c distance. Pontoon width follow the column width as for the normal draft. The pontoon height is reduced in comparison to the normal draft estimations. This is to indirectly increase the draft and reduce the total weight increase of the hull. For normal draft semis, the height varied in the range 8.5 – 12.0 meter. For deep draft semis, the range is reduced to 8.0 – 9.0 meter for the smallest and largest topside respectively.

The pontoon height varies linearly and is described by the equation below.

$$P_h = 8\,m + \frac{W_{top} - 20\,000\,000\,kg}{30661050\,kg} \tag{32}$$

P_h *Pontoon height (m)*
W_{top} *Topside weight (kg)*

9.3 Column height and c-c

The data from the sensitivity study of deep draft hull configurations governed the column c-c distance. As the normal draft semis c-c distance completes the total displacement, the deep draft semis c-c distance varies linearly in four intervals. This is done to secure acceptable topside VCG.

The interval ranges are shown in the table below.

Table 6 – Column c-c equation range for deep draft.

Topside weight (tonnes)	c-c distance (m)
20 000 – 25 000	76.5 – 79.0
25 000 – 30 000	79.0 – 80.3
30 000 – 40 000	80.3 – 81.6
40 000 – 51 000	81.6 – 82.0

Equation for calculating topside weight for 20 000 – 25 000 tonnes topside weight. The other ranges are calculated in the same way but different fixed parameters.

$$C_{c-c} = 76.5\,m + \frac{W_{top} - 20\,000\,000\,kg}{2\,000\,000\,kg} \tag{33}$$

$C_{c\text{-}c}$ *Column center to center distance (m)*
W_{top} *Topside weight (kg)*

The column height is estimated with the same method as for normal draft.

Below is a chart showing the differences in displacement, column width and draft between the normal and deep draft semi estimations.

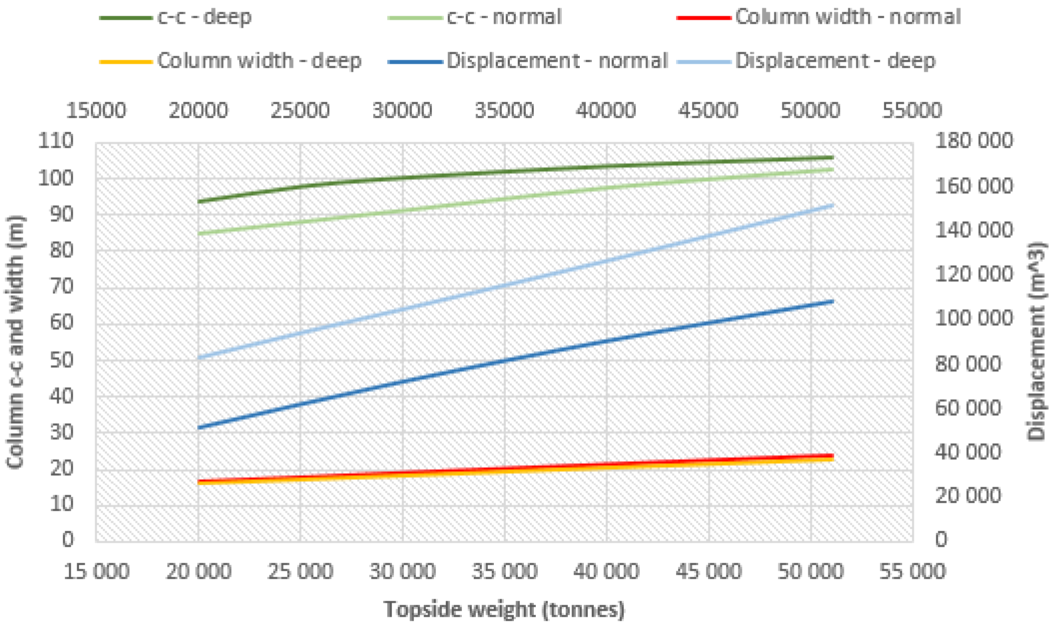


Figure 21 - Hull dimensions. Normal versus deep draft.

10. Air gap analysis

The air gap is analyzed for normal and deep draft semis with 20 000, 50 000 and 80 000 tonnes topside weight with the standard 22.0 meter air gap. The analysis is done in the Postresp software. A single point Jonswap wave spectrum is generated for each storm scenario and together with the air gap location and wave direction merged as a response spectrum The response spectrums are analyzed with a storm duration of 3 hours (10 800 s) and a probability of exceedance of 0.1. After the responses are generated, they are increased by 10 % to include slowly varying motions in the rig. The detailed analysis investigates some of the periods just below the peak period for the given H_S, which is expected to give greater response.

It is assumed that the minimum design air gap will be 12.0 meter and increase in increments of 2.0 meters. The response is allowed to overrun the air gap by about 2.0 meters as described earlier.

10.1 Storm scenarios

To investigate the required air gap, four typical 100-year storm scenarios for relevant locations were analyzed [Swail, et al., 2000], [NORSOK, 2007]. The 100-year storm for the Norwegian Sea is also analyzed in more detail for the three normal draft semis (20’, 50’ and 80’ tonnes topsides) to highlight the effect of analyzing periods below the peak period.

The selected locations give an evenly increase in severity of the storm conditions. The locations selected are Gulf of Mexico, Mid-Atlantic, Norwegian Sea and West Africa.

Table 7 – 100-year storm situations [Swail, Ceccacci, Cox, 2000], [NORSOK, 2007].

	Significant wave height, H_S (m)	Peak period, T_P (s)	Zero-up crossing period, T_Z (s)
West Africa	4.0	16.0	12.2
Mid-Atlantic	8.0	14.0	10.7
Gulf of Mexico	12.0	15.0	11.5
Norwegian Sea	16.0	18.0	13.8

10.2 Detailed analysis

To investigate the wave spectrum for the Norwegian Sea in more detail, it is necessary to check the critical wave periods below T_P and their wave steepness.

The most critical periods for a storm condition with $H_S = 16.0$ and $T_P = 18.0$ are found by using equation (15). This result in the period range $14.05 \leq T \leq 18.28$. Periods with 1s increments will be used, which gives four additional periods to the original. The steepness for these periods and correlated wave heights must then be checked against the NORSOK criteria with equation (16), (17) and (18). The results are shown in table 8.

Table 8 – Wave steepness for detailed analysis.

T_P (s)	H_S (m)	T_Z (s)	S_P (limit)	S_P	Corrected H_S (m)
18,0	16,0	13,9	0,0517	0,0316	-
17,0	15,6	13,1	0,0478	0,0345	-
16,0	15,0	12,3	0,0439	0,0375	-
15,0	(14,2)	11,6	0,0400	**0,0404**	14,0
14,0	(13,4)	10,8	0,0361	**0,0439**	11,0

The correlated wave height to the additional periods are found by extrapolating the contour diagram for Norwegian Sea. As seen in table 8, H_S for the two lowest periods was too steep and needed to be corrected to fulfill the steepness criteria.

10.3 Results

The air gap response was investigated at four points around the semi for two wave directions. The results show the maximum response from one of the points for each storm scenario. The available air gap is described as the initial air gap minus the response.

Table 9 – Respons data for analyzed semis.

	20' - normal	20' - deep	50' - normal	50' - deep	80' - normal
West Africa	4,8	5,5	5,9	5,5	6.6
Mid Atlantic	11,4	12,0	14,1	13,3	15.7
Gulf of Mexico	15,5	17,1	19,3	18,9	21.4
Norwegian Sea	17,1	21,5	20,6	24,0	22.2
Norwegian Sea (Detailed Analysis)	+ 0.8 + 4.6 %		+ 1.6 + 7.7 %		+ 2.4 + 10.8 %

Detailed analysis for the Norwegian Sea conditions indicates that a detailed analysis becomes more important as the semi becomes heavier. A response increase of up to about 10 % could make an air gap insufficient for the selected location and result in unwanted damage to structure and equipment.

Table 9 show that the response is worsened for the deep draft semis. This is because the increased draft reduces the vertical motions of the semi and thereby prevents the semi from following the wave motions. The increased response for the heavier semis come from the same principle, but here the weight reduces vertical motions.

10.3.1 West Africa (4m, 16s)

For the West Africa conditions, the variations and response are relatively small for all the semis. This leads to the air gap calculation for this condition and semis can follow the same estimation without giving to large source for error. For this condition, the semis will have the minimum air gap of 12.0 meter, which will allow enough air gap under all conditions.

10.3.2 Mid-Atlantic (8m, 14s)

For the Mid-Atlantic conditions, the response is varying around the minimum air gap. The air gap estimates when assuming linear response variations is shown below.

Table 10 – Air gap estimation for Mid-Atlantic.

	Normal draft		Deep draft
Topside weight (tonnes)	20’ - 50’	50’ - 80’	20' - 50'
Interpolated response (m)	11.4 – 14.1	14.1 – 15.7	12.0 – 13.3
Air gap (m)	12.0	14.0	12.0

10.3.3 Gulf of Mexico (12m, 15s)

For the storm scenario typical for the Gulf of Mexico, the response and variation are not continuous. For the small semis, the response is negatively affected by increasing the draft and the opposite for the large. With linear increase in response, the air gap will be as tabled below.

Table 11 – Air gap estimation for Gulf of Mexico.

	Normal draft			Deep draft	
Topside weight (tonnes)	20’ - 40’	40’ - 60’	60’ - 80'	20' - 35'	35' - 50'
Interpolated response (m)	15.5 – 18.0	18.0 – 20.0	20.0 – 21.4	17.1 – 18.0	18.0 - 18.9
Air gap (m)	16.0	18.0	20.0	16.0	18.0

10.3.4 Norwegian Sea (16m, 18s)

The semi response in Norwegian Sea locations is the most severe of the analyzed scenarios. The variations is somewhat linearly and predictable with roughly a 2.0 meter increase between the normal draft semis and about 4.0 meters between normal and deep draft semis. If assuming linearly response increments between the semis, the distribution of the selected air gap is as follows for normal and deep draft semis.

Table 12 – Air gap estimation for Norwegian Sea.

	Normal draft			Deep draft	
Topside weight (tonnes)	20’ - 35’	35’ - 50’	50’ - 80'	20' - 30'	30' - 50'
Interpolated response (m)	17.9 – 20.1	20.1 – 22.2	22.2 – 24.6	21.5 – 22.3	22.3 – 24.0
Air gap (m)	18.0	20.0	22.0	20.0	22.0

10.4 Summary

When considering the detailed analyzed responses, the additional response tilted the selected air gap for the larger semis from 20.0 to 22.0 meter. This show the importance of analyzing the significant wave height for periods below the peak period when doing detailed engineering.

As all the analyses in this thesis is done with an air gap of 22.0 meter, the lower recommended air gap will for many of the semis give a possibility to alter the design and/or allow a higher VCG for the topside.

11. Cost Estimation

The cost estimation is calculated from the hull volume. It uses the fixed parameters density of hull (kg/m^3) and hull cost (NOK/kg). These values are provided by the supervisor and are based on earlier design cases. The reason for not using the estimated hull weight and calculate the weight from the hull density parameter, is that the estimated hull weight takes into account all loads acting on the hull. E.g., ballast will not add any production cost. The density of the hull takes into account both steel weight and equipment weight. Cost estimation is shown in equation (34).

$$Cost_h = \rho_h \cdot V_h \cdot C_h \tag{34}$$

$Cost_h$	*Total hull cost (NOK)*
ρ_h	*Density of hull (kg/m^3)*
V_h	*Volume of hull (m^3)*
C_h	*Unit cost of hull (NOK/kg)*

12. The Spreadsheet

Here follows a guideline for using the spreadsheet. The spreadsheet estimates hull dimensions for topside weights between 20 000 and 80 000 tonnes. A figure of the spreadsheet user panel is provided in Appendix D.

12.1 Input data

These parameters can be altered to generate the hull estimations.

Topside weight: This value is in kilograms. The data range possible to use in this field is from 20 000 000 kg to 80 000 000 kg.

Weather condition: It is possible to select four different weather conditions from a drop down menu. They represent the most common weather situations in relevant areas. They are called: Norwegian Sea, Gulf of Mexico, Mid-Atlantic and West Africa.

Air gap margin: An estimated air gap margin can be selected from a drop down menu. The margin varies from -2.0 to 2.0 meter.

12.2 Variable parameters

These values are based on equations and therefore not possible to change. They express the 100-year storm parameters based on the selection of weather condition in input data.

12.3 Fixed parameters

These values are possible to change. Keep in mind that the equations are generated based on the original values, so changing them can result in imprecise estimations.

12.4 Output hull data

These data are based on equations and therefore not possible to change. They express the estimated hull dimensions together with the weights and center of gravity for each platform section.

13. Discussion

13.1 The models and assumptions

The models generated by the estimation spreadsheet have a symmetrical quadratic four-column design with a ring pontoon. This is a good assumption for modern semi-submersible production platforms, which usually have four columns. In special cases, the semi can have six columns or more. The quadratic column shape is also a general trend for modern production semis. Some older production semis have the cylindrical column design, but this is becoming more seldom, see [Wood Group Mustang, 2011]. This also apply to the quadratic ring pontoon.

One of the assumptions for the models is that rounding of column and pontoon corners are neglected. For real design situations, the columns and pontoon will always be designed with rounded corners to smoothen out flow around the hull and add to structural integrity. These are not issues for the studies in this thesis, but rounded corners would reduce the displacement and water plane area some. With a reasonable rounding of 3m radii on the columns of the default model, the water plane area will reduce by 1.5 %. This is not enough to alter the behavior of the semi noteworthy. The rounding radii of pontoons are generally smaller, e.g. 1m. The total displacement effect with rounded columns and pontoon would therefore be negligible.

The topside weight is a fixed input parameter. During the lifetime of a production facility, requirements can change, which results in modifications and maybe new modules in the process area. This generates additional weight and movement of the total center of gravity. Because of this, it is important to allow some margin in the topside VCG, which is implemented in the estimations in the spreadsheet.

The hull weight estimated for the semi-submersibles includes live loads, riser loads, ballast, equipment and steel weight. This generates some uncertainty about the distribution of weight in the hull and the real hull weight. As stated in the thesis, the weight is assumed uniformly distributed but with an additional factor for the pontoons. This assumption obviously generates a source for error as the VCG of the hull is not only dependent on its volume, but will vary depending on the design and production situation. Some variance in the height of the hull VCG will not alter the KG severely enough that the allowable topside weight and VCG becomes unsuitable. The estimated allowable VCG for the topside should have a large enough margin in all the cases to tolerate some variance. When comparing with the default model, the estimated hull VCG with the pontoon added factor is reasonable. The change in hull VCG for increased/decreased draft and hull size have been evaluated with the supervisor and found to give reasonable values.

The total weight of the hull has some uncertainty. The weight includes e.g. riser loads, which is not only dependent on hull size, but depend mostly on the selected riser material and water depth. The number of production risers will influence the total riser weight and the number depend on the reservoir size. The larger the reservoir/production, the more risers. A larger production leads to a larger topside weight, which again leads to a larger hull, so this weight factor will follow the sizing of the semi. The total weight of a riser system is generally in the area around 2000 tonnes, which means it will often not have a significant impact on the total hull weight. As mentioned about the margin for the topside VCG, altering ballast weight will not generate trouble with the allowable weight and VCG.

The GM is fixed at 4.0 meters for all the models. In real final design studies, the GM is normally in the area from 3.0 to 4.0 meter. Fixing the GM at 4.0 will not generate any problems with the design, but it can hinder the possibility to exploit all the potential of a design. E.g. reducing GM slightly could allow for a small reduction in hull size, resulting in reduced cost or the possibility to increase the allowable topside weight and VCG.

13.2 Estimations and example semis

Some of the estimated hull dimensions for normal draft semi-submersibles are compared to existing semis in chapter 7. The comparison shows that the estimations is reasonable in line with existing semis. Since all the hull dimensions influence each other, this means that the dimensions not compared should also be reasonable. It was not found enough data to compare deep draft semis.

Many of the equations are based on linear relationships with topside weight or on empirical data from existing rigs. This will not always give the most fitting value for a dimension, but as estimated values, they are shown to generate decent values. The purpose of the thesis is only the estimate the dimensions to make early phase design comparison and decisions easier, not to give exact final design dimensions. One way of getting more accurate estimations could be to use other forms of equation fitting than linear.

Some of the dimension values for the existing semis have been difficult to quality check, and therefore the comparison can be misleading. This is only for a small amount of the data and the values should not be way off if they are wrong. The dimension comparisons include many example semis to minimize this source of error.

One of the important sources of error in the analysis of different draft configurations is the lack of damping in some of the models, which generates severe peaks around the natural period in heave. The source of the problem is unknown. The important area for the study, which is the first elongated peak, showed correct values for the default model and reasonable values for the estimated cases. This means that the damping problem does not affect the conclusions from the study.

One of the objectives of the thesis was to estimate a hull with minimum weight while still having good stability, motions and air gap. This objective is not implemented in the spreadsheet as a factor, as it has not been enough time to do the required analyses. However, during experimentation of different hull dimensions and estimation equations, the results giving the lowest hull weight have been chosen.

The deep draft hull estimations assumes the necessity of 50 % heave RAO reduction. How large reduction is necessary obviously depend on each individual case. Especially water depth is a factor. Because the reduction effect of increased draft reduces as draft increases, the assumption of 44 meter draft could be many meters too deep, to achieve the required reduction. In what range the required reduction percentage varies is not known, but it could be interesting to study the range and correlation to other parameters.

14. Conclusion

The developed estimation equations for normal draft semis have been shown to give reasonable results when compared to existing semi designs. The hull design estimated for 20 000 and 80 000 tonnes topside weight for the air gap analysis in chapter 10, show good stability and motion characteristics. In an overall view, the results with the normal draft estimations are very good and can possibly work as the intended objective of the thesis, a design decision support tool.

The estimation equations for deep draft semis showed the ability to reduce the heave motions considerably while having good stability. With the lack of comparable data, it is difficult to know if the estimations give recommended design solutions, but the objective of reduced heave motions is fulfilled.

Recommended air gap for all the possible hull configurations is provided for the most common weather situations. Depending on requirements and client requests, the wanted air gap margin can be set. This function can save much time during early phase design decisions, because the air gap analysis requires modelling, analyses and post-processing to get comparable values.

During the development work with the estimation equations, interesting findings for semi design have been identified. E.g., topside weight percentage was shown to have a strong relationship to the total semi weight. Many other design parameters also followed strong trends, which means that estimation of the hull parameters can be reasonable precise.

The estimation spreadsheet combines the presentation of estimated hull dimensions, weight, stability and cost in a good and user-friendly way. With only three simple input parameters, the estimations give relatively accurate data and may indicate that the spreadsheet will be used.

15. References

Arnesen, G., Aker Kværner; Dalane, J. I., Statoil; Aramanadka, S. S. B., Shell; Herfjord, K., Norsk Hydro; Snell, R., BP; Stansberg, C. T., Marintek (2006). *Integrated Semi and Steel Catenary Risers (SCRs) in Deep Water and Harsh Environment Conditions.* OTC 18259. OTC, Texas, USA.

DNV (2011). *Modelling and Analysis of Marine Operations*. Recommended practice DNV-RP-H103. DNV-GL, Oslo, Norway.

DNV (2012). *DeepC - Improved Confidence in Deep Water Concepts*. DNV Software Seminar, pp. 5. DNV-GL, Oslo, Norway.

DNV (2014). *Environmental Conditions and Environmental Loads.* Recommended practice DNV-RP-C205. DNV-GL, Oslo, Norway.

Gallala, J. R. (2013). *Hull Dimensions of a Semi-Submersible Rig.* Master thesis. Norwegian University of Science and Technology, Trondheim, Norway.

Gudmestad, O. T. (2014). *Lecture material – Stability.* OFF580 Marine Technology and Design. University of Stavanger, Stavanger, Norway.

GVAC.SE (2013). *Floating Production Units.* Link: http://www.gvac.se/Products/Semisubmersibles/Floating-Production-Units/. Link verified 9th June 2015.

Michael, W. H. (1999). *Sea Spectra Revisited.* Marine Technology, Vol. 36, No. 4, pp 211-227.

NAUTICADYNAMICS.COM (2015). *Dynamic positioning.* Link: http://nauticadynamics.com/Home.php. Link verified 9th June 2015.

NORSOK (2007). *Actions and Action Effects.* NORSOK Standard N-003, Rev. 2. Norsk Standard, Lysaker, Norway.

Nygård, M., Aker Kværner (2003). *Column Structure Design.* OGP Marine Risks Workshop Proceedings, No. 344, pp. 59 - 79. IOGP, London, United Kingdom.

OFFSHORE-TECHNOLOGY.COM (2015). *Visund Project.* Link: http://www.offshore-technology.com/projects/visund/. Link verified 9th June 2015.

OFFSHORE-TECHNOLOGY.COM (2015). *Gjøa Project.* Link: http://www.offshore-technology.com/projects/gjoa/. Link verified 9th June 2015.

OFFSHORE-TECHNOLOGY.COM (2015). *Thunder Horse Project.* Link: http://www.offshore-technology.com/projects/crazy_horse/. Link verified 9th June 2015.

OFFSHORE-TECHNOLOGY.COM (2015). *Atlantis Project.* Link: http://www.offshore-technology.com/projects/atlantisplatform/. Link verified 9th June 2015.

Swail, V. R.; Ceccacci, E. A.; Cox, A. T. (2000). *The AES40 North Atlantic Wave Reanalysis: Validation and Climate Assessment.* 6th International Workshop on Wave Hindcasting and Forecasting. Monterey, California, USA.

Wood Group Mustang (2011). *Worldwide survey of Semi-FPSs and FPUs.* Link: http://www.mustangeng.com/NewsandIndustryEvents/Publications/Publications/2011%20WW%20Semi%20Production%20Survey.pdf. Link verified 9th June 2015.

Appendix A

Amplitude response for case 1 - 10

Table 13 – Amplitude response for case 1 – 6.

	Period (s)	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Heave RAO	2	0,0000	0,0001	0,0000	0,0000	0,0000	0,0001
	4	0,0018	0,0019	0,0033	0,0001	0,0015	0,0036
	6	0,0020	0,0023	0,0024	0,0049	0,0020	0,0042
	8	0,0598	0,0569	0,0686	0,0518	0,0594	0,0693
	10	0,2557	0,2554	0,2715	0,2394	0,2460	0,2755
	12	0,3907	0,3973	0,3884	0,3898	0,3683	0,3688
	14	0,4252	0,4266	0,4103	0,4365	0,3952	0,3570
	16	0,4114	0,4047	0,3819	0,4348	0,3678	0,2720
	18	0,3253	0,3026	0,2616	0,3735	0,2444	0,0256
	20	0,0241	0,0652	0,1945	0,1622	0,2314	2,5230
	22	2,6440	6,1060	56,3900	0,9606	100,6000	2,3240
	24	2,2590	2,0120	1,8790	3,0740	1,8700	1,4620
	26	1,4580	1,4090	1,3820	1,5600	1,3810	1,2540
	28	1,2570	1,2370	1,2260	1,2950	1,2260	1,1650
	30	1,1700	1,1580	1,1530	1,1890	1,1540	1,1170
	32	1,1230	1,1150	1,1120	1,1340	1,1120	1,0890
	34	1,0940	1,0880	1,0870	1,1010	1,0870	1,0700
	36	1,0740	1,0700	1,0690	1,0800	1,0690	1,0570
	38	0,0000	0,0001	0,0000	0,0000	0,0000	0,0001
Pitch RAO	2	0,0009	0,0006	0,0015	0,0004	0,0007	0,0012
	4	0,0082	0,0067	0,0057	0,0090	0,0066	0,0020
	6	0,0182	0,0108	0,0319	0,0058	0,0068	0,0196
	8	0,1371	0,1256	0,1429	0,1274	0,1229	0,1187
	10	0,1763	0,1623	0,1751	0,1753	0,1654	0,1437
	12	0,1905	0,1756	0,1880	0,1909	0,1830	0,1571
	14	0,1848	0,1707	0,1810	0,1865	0,1796	0,1522
	16	0,1683	0,1556	0,1636	0,1710	0,1648	0,1371
	18	0,1479	0,1367	0,1424	0,1515	0,1457	0,1183
	20	0,1274	0,1175	0,1212	0,1317	0,1259	0,0989
	22	0,1081	0,0995	0,1012	0,1132	0,1073	0,0803
	24	0,0906	0,0831	0,0828	0,0965	0,0904	0,0629
	26	0,0747	0,0682	0,0658	0,0816	0,0749	0,0465
	28	0,0600	0,0545	0,0498	0,0681	0,0607	0,0306
	30	0,0462	0,0416	0,0343	0,0556	0,0473	0,0148
	32	0,0326	0,0290	0,0186	0,0437	0,0344	0,0017
	34	0,0190	0,0164	0,0021	0,0322	0,0214	0,0194
	36	0,0048	0,0035	0,0160	0,0207	0,0080	0,0395
	38	0,0009	0,0006	0,0015	0,0004	0,0007	0,0012

Table 14 – Amplitude response for case 7 – 10.

	Period (s)	Case 7	Case 8	Case 9	Case 10
Heave RAO	2	0,0000	0,0000	0,0000	0,0002
	4	0,0006	0,0005	0,0004	0,0016
	6	0,0029	0,0025	0,0022	0,0003
	8	0,0554	0,0505	0,0460	0,0651
	10	0,2367	0,2201	0,2048	0,2022
	12	0,3667	0,3441	0,3232	0,2916
	14	0,4030	0,3797	0,3582	0,3319
	16	0,3872	0,3639	0,3426	0,3268
	18	0,2905	0,2679	0,2480	0,2483
	20	0,0593	0,0705	0,0773	0,0194
	22	4,4200	3,3540	2,6640	1,5090
	24	2,1170	2,2970	2,5190	3,2990
	26	1,4350	1,4830	1,5360	1,6580
	28	1,2490	1,2740	1,2990	1,3520
	30	1,1660	1,1810	1,1970	1,2270
	32	1,1210	1,1310	1,1420	1,1620
	34	1,0920	1,1000	1,1090	1,1230
	36	1,0730	1,0800	1,0860	1,0970
	38	0,0000	0,0000	0,0000	0,0002

Appendix B

Detailed air gap analysis

Table 15 – Detailed response analysis for 80 000 tonnes topside weight.

Response spectrum	Standard Deviation (m)	Duration (s)	Number of frequencies	Response Level (m)	Corrected Response Level (m)
1	3,9	10800	1081	16,9	18,6
2	4,1	10800	1107	17,8	19,6
3	4,4	10800	1126	18,8	20,7
4	4,5	10800	1142	19,2	21,2
5	3,9	10800	1162	16,9	18,5
6	4,7	10800	1055	20,2	22,2
7	4,9	10800	1085	21,2	23,3
8	5,1	10800	1111	22,1	24,3
9	5,2	10800	1132	22,4	24,6
10	4,5	10800	1158	19,4	21,3
11	4,6	10800	970	19,5	21,4
12	4,8	10800	984	20,7	22,7
13	5,1	10800	996	21,8	24,0
14	5,2	10800	1007	22,1	24,3
15	4,5	10800	1023	19,1	21,0
16	3,9	10800	867	16,4	18,0
17	4,0	10800	895	16,9	18,6
18	4,1	10800	918	17,4	19,2
19	4,1	10800	938	17,4	19,1
20	3,5	10800	961	14,9	16,4

Table 16 – Detailed response analysis for default topside weight.

Response spectrum	Standard Deviation (m)	Duration (s)	Number of frequencies	Response Level (m)	Corrected Response Level (m)
1	3,6	10800	987	15,6	17,2
2	3,7	10800	1031	16,0	17,7
3	3,8	10800	1062	16,6	18,3
4	3,9	10800	1081	16,8	18,5
5	3,4	10800	1099	14,7	16,2
6	4,3	10800	969	18,6	20,5
7	4,4	10800	1019	19,0	20,9
8	4,5	10800	1058	19,4	21,4
9	4,5	10800	1086	19,4	21,4
10	3,8	10800	1115	16,7	18,4
11	4,2	10800	955	18,2	20,1
12	4,4	10800	982	19,1	21,0
13	4,6	10800	1001	19,9	21,9
14	4,7	10800	1013	20,2	22,2
15	4,0	10800	1027	17,5	19,2
16	4,2	10800	949	18,1	19,9
17	4,3	10800	996	18,4	20,3
18	4,4	10800	1035	18,8	20,7
19	4,3	10800	1062	18,8	20,7
20	3,7	10800	1089	16,2	17,8

Table 17 – Detailed response analysis for 20 000 tonnes topside weight.

Response spectrum	Standard Deviation (m)	Duration (s)	Number of frequencies	Response Level (m)	Corrected Response Level (m)
1	3,3	10800	1095	14,1	15,5
2	3,3	10800	1149	14,4	15,9
3	3,4	10800	1196	14,8	16,3
4	3,4	10800	1231	14,9	16,3
5	3,0	10800	1266	12,8	14,1
6	3,6	10800	1036	15,5	17,0
7	3,7	10800	1092	15,8	17,3
8	3,7	10800	1144	16,1	17,7
9	3,7	10800	1185	16,0	17,5
10	3,1	10800	1229	13,6	14,9
11	3,5	10800	1058	15,0	16,5
12	3,6	10800	1099	15,5	17,1
13	3,7	10800	1132	16,1	17,7
14	3,8	10800	1156	16,3	17,9
15	3,3	10800	1180	14,1	15,5
16	3,4	10800	921	14,4	15,8
17	3,4	10800	971	14,5	15,9
18	3,4	10800	1017	14,6	16,1
19	3,3	10800	1054	14,4	15,8
20	2,8	10800	1093	12,1	13,3

Appendix C

Air gap analysis – normal draft

Table 18 – Response analysis for 80 000 tonnes topside weight.

Wave spectrum	Standard Dev. (m)	Duration (s)	Number of frequencies	Response Level (m)	Cor. Response Level (m)
Gulf of Mexico	3,9	10800	1144	16,7	18,4
Mid-Atlantic	2,9	10800	1165	12,4	13,7
Norwegian Sea	4,0	10800	1085	17,0	18,7
West Africa	1,2	10800	1129	5,1	5,6
Gulf of Mexico	4,5	10800	1136	19,4	21,4
Mid-Atlantic	3,3	10800	1161	14,3	15,7
Norwegian Sea	4,7	10800	1059	20,4	22,4
West Africa	1,4	10800	1114	6,0	6,6
Gulf of Mexico	4,5	10800	1008	19,2	21,1
Mid-Atlantic	3,3	10800	1025	14,1	15,5
Norwegian Sea	4,6	10800	972	19,7	21,6
West Africa	1,4	10800	997	5,9	6,5
Gulf of Mexico	3,5	10800	941	15,1	16,6
Mid-Atlantic	2,6	10800	964	10,9	12,0
Norwegian Sea	3,9	10800	871	16,5	18,2
West Africa	1,1	10800	921	4,7	5,2

Table 19 - Response analysis for default topside weight.

Wave spectrum	Standard Dev. (m)	Duration (s)	Number of frequencies	Response Level (m)	Cor. Response Level (m)
Gulf of Mexico	3,4	10800	1084	14,6	16,0
Mid-Atlantic	2,5	10800	1101	10,8	11,9
Norwegian Sea	3,7	10800	994	15,7	17,3
West Africa	1,0	10800	1065	4,5	4,9
Gulf of Mexico	3,9	10800	1090	16,9	18,5
Mid-Atlantic	2,9	10800	1118	12,3	13,5
Norwegian Sea	4,4	10800	976	18,7	20,6
West Africa	1,2	10800	1062	5,2	5,8
Gulf of Mexico	4,1	10800	1015	17,5	19,3
Mid-Atlantic	3,0	10800	1029	12,9	14,1
Norwegian Sea	4,3	10800	959	18,4	20,3
West Africa	1,3	10800	1002	5,4	5,9
Gulf of Mexico	3,8	10800	1066	16,3	17,9
Mid-Atlantic	2,8	10800	1092	11,9	13,1
Norwegian Sea	4,3	10800	956	18,2	20,0
West Africa	1,2	10800	1040	5,1	5,6

Table 20 - Response analysis for 20 000 tonnes topside weight.

Wave spectrum	Standard Dev. (m)	Duration (s)	Number of frequencies	Response Level (m)	Cor. Response Level (m)
Gulf of Mexico	3,0	10800	1236	12,9	14,2
Mid-Atlantic	2,2	10800	1270	9,4	10,4
Norwegian Sea	3,3	10800	1102	14,1	15,5
West Africa	0,9	10800	1202	4,0	4,4
Gulf of Mexico	3,2	10800	1191	13,8	15,2
Mid-Atlantic	2,3	10800	1234	10,0	11,0
Norwegian Sea	3,6	10800	1043	15,6	17,1
West Africa	1,0	10800	1150	4,3	4,8
Gulf of Mexico	3,3	10800	1159	14,1	15,5
Mid-Atlantic	2,4	10800	1183	10,4	11,4
Norwegian Sea	3,5	10800	1063	15,1	16,6
West Africa	1,0	10800	1136	4,3	4,8
Gulf of Mexico	2,9	10800	1059	12,4	13,7
Mid-Atlantic	2,1	10800	1097	8,9	9,8
Norwegian Sea	3,4	10800	927	14,4	15,9
West Africa	0,9	10800	1022	3,9	4,3

Air gap analysis – deep draft

Table 21 – Response analysis for deep draft default tonnes topside weight.

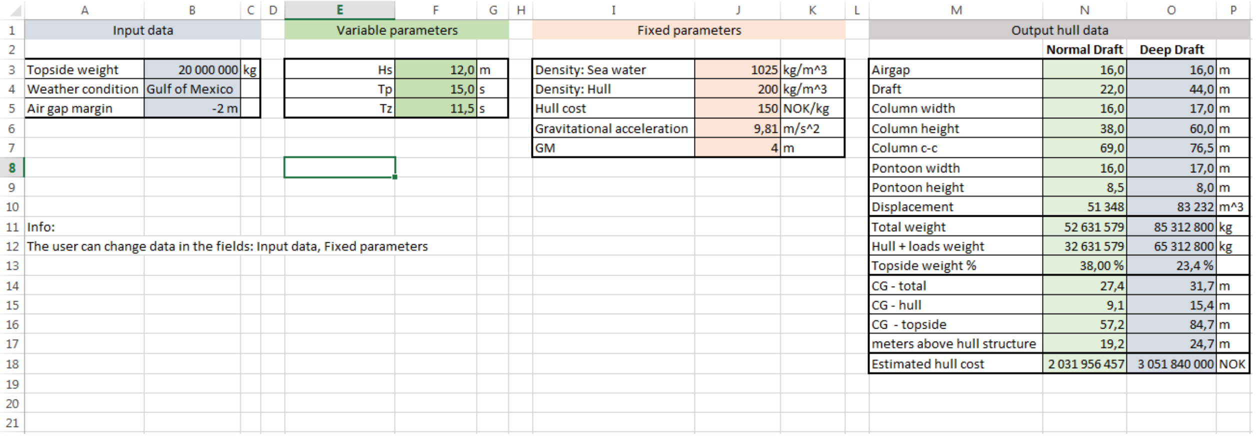
Wave spectrum	Standard Dev. (m)	Duration (s)	Number of frequencies	Response Level (m)	Cor. Response Level (m)
Gulf of Mexico	3,8	10800	1056	16,4	18,1
Mid-Atlantic	2,8	10800	1089	11,9	13,1
Norwegian Sea	4,7	10800	889	20,0	22,0
West Africa	1,2	10800	1018	5,2	5,7
Gulf of Mexico	4,0	10800	996	17,2	18,9
Mid-Atlantic	2,8	10800	1045	12,1	13,3
Norwegian Sea	5,2	10800	825	21,8	24,0
West Africa	1,3	10800	951	5,5	6,1
Gulf of Mexico	3,8	10800	970	16,0	17,6
Mid-Atlantic	2,7	10800	1000	11,5	12,7
Norwegian Sea	4,6	10800	833	19,6	21,5
West Africa	1,2	10800	939	5,1	5,6
Gulf of Mexico	4,0	10800	993	17,0	18,7
Mid-Atlantic	2,8	10800	1041	12,0	13,1
Norwegian Sea	5,1	10800	822	21,6	23,8
West Africa	1,3	10800	949	5,5	6,0

Table 22 - Response analysis for deep draft 20 000 tonnes topside weight.

Wave spectrum	Standard Dev. (m)	Duration (s)	Number of frequencies	Response Level (m)	Cor. Response Level (m)
Gulf of Mexico	3,5	10800	1090	15,0	16,4
Mid-Atlantic	2,5	10800	1140	10,6	11,7
Norwegian Sea	4,3	10800	906	18,5	20,3
West Africa	1,1	10800	1041	4,8	5,3
Gulf of Mexico	3,6	10800	1040	15,6	17,1
Mid-Atlantic	2,5	10800	1096	10,9	12,0
Norwegian Sea	4,6	10800	862	19,5	21,5
West Africa	1,2	10800	991	5,0	5,5
Gulf of Mexico	3,5	10800	1048	14,9	16,4
Mid-Atlantic	2,5	10800	1095	10,6	11,6
Norwegian Sea	4,3	10800	881	18,3	20,1
West Africa	1,1	10800	1005	4,7	5,2
Gulf of Mexico	3,6	10800	1018	15,2	16,8
Mid-Atlantic	2,5	10800	1072	10,7	11,7
Norwegian Sea	4,5	10800	844	19,3	21,2
West Africa	1,2	10800	970	4,9	5,4

Appendix D

Spreadsheet user panel



Input data

Topside weight	20 000 000	kg
Weather condition	Gulf of Mexico	
Air gap margin	-2 m	

Variable parameters

Hs	12,0	m
Tp	15,0	s
Tz	11,5	s

Fixed parameters

Density: Sea water	1025	kg/m^3
Density: Hull	200	kg/m^3
Hull cost	150	NOK/kg
Gravitational acceleration	9,81	m/s^2
GM	4	m

Info:

The user can change data in the fields: Input data, Fixed parameters

Output hull data

	Normal Draft	**Deep Draft**	
Airgap	16,0	16,0	m
Draft	22,0	44,0	m
Column width	16,0	17,0	m
Column height	38,0	60,0	m
Column c-c	69,0	76,5	m
Pontoon width	16,0	17,0	m
Pontoon height	8,5	8,0	m
Displacement	51 348	83 232	m^3
Total weight	52 631 579	85 312 800	kg
Hull + loads weight	32 631 579	65 312 800	kg
Topside weight %	38,00 %	23,4 %	
CG - total	27,4	31,7	m
CG - hull	9,1	15,4	m
CG - topside	57,2	84,7	m
meters above hull structure	19,2	24,7	m
Estimated hull cost	2 031 956 457	3 051 840 000	NOK

Figure 22 - Spreadsheet user panel.