FLOATOVER BARGE RESPONSES FOR RANDOM WAVES

by

Lim Eu Shawn

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
UniversitiTeknologi PETRONAS
in partial fulfilment of the requirement for the
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(CIVIL ENGINEERING)

Approved by,

(Professor Dr. Kurian V. John)
Project Supervisor

UniversitiTeknologi PETRONAS

Tronoh, Perak

Dec 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LIM EU SHAWN

ABSTRACT

Floatover method was a novel method of topside installation introduced in the 70s to overcome the limitations of the conventional crane lifting method. This was due to the increasing weight of topsides which made it physically impossible currently to install complex & heavy topsides. It is also compounded by the fact that most of the heavy lift crane vessels are mostly located in the Gulf of Mexico, thus preventing installation works in African & Asian regions from being carried out in a timely & economical manner. The floatover process itself is a unique method in which it allows the limitations of the conventional crane lifting method to be overcome on top of it being easily implemented as barges could be easily refurbished for the floatover process.The floatover process is however not without its faults, the nature in which it installs the topside by ballasting makes it particularly susceptible to environmental loads such as waves. Therefore, this experiment was setup to study into the effects of random waves affecting the floatover barge.The experiment will focus on identifying the governing parameters which affect the motion of the barge & this will be measured by understanding the resultant RAO values. The experiment will study the effects of significant wave height, peak period & drafts on the barge motions. The methodology will employ theoretical analysis which involves the use of Froude-Krylov theories to study the theoretical RAOs. It will be then be compared against the model test values which will be transformed using the model RAO formula of $\sqrt{S_R/S(f)}$ to check for the validity of our theoretical analysis.Findings of the experiment indicated that the governing factor of the barge RAO is the barge draft that is adjusted during the installation phase. Factors such as significant wave height & peak period played an almost non-existent role in affecting the barge's RAO. Thus as such, it is imperative that further research be done to fine tune the barge draft values as it greatly reduces barge motions if properly deployed.

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1.0 Introduction

1.1 Background of Study

Before the advent of floatover technology in the 70s, most of the topside installation processes were done via crane lifting vessels which were however mostly unavailable in most parts of the world as they were mostly operating in Europe or the Gulf of Mexico (GOM), (Technip, 2011). Typical crane vessel loadouts were limited to approximately 14,000 tonnes as of year 2000 (SPE, 2000). This is attributed by the need to stabilize the crane's center of gravity as well as resulting dynamic effects which makes it harder for installation of larger topsides to be feasible. This has resulted in topsides become modularized in larger sized installations due to crane lift limitations. This is further compounded by the unavailability of large sized cranes in more remote regions of the world (as mentioned earlier, they mostly operate in Europe & GOM). The need to wait for the availability of these cranes has put additional burden on the overall life cycle costing of the project (especially with regards to mobilization costs).

In overall, this has made offshore installations in Africa (West Africa) & Asia (South China Sea) more favourable as it reduces mobilization costs & man hours spent hooking up the topside on to the jackets. Although floatover installations have been implemented since the 70s, continuous research has been conducted by the like of floatover pioneers such as Technip& Worley-Parsons to continuously provide more efficient & safer methods of floatover installations. One of the main concerns related to the implementation of floatovers is that they are more sensitive to environmental loads in open waters, resulting in smaller favourable weather windows for installation (SPE, 2000). Nonetheless the cost-effectiveness of this method has allowed rapid growth of research to continuously find ways of improving floatover barge installations. Among the many areas of research aimed at improving this method of installation involves improving the fender systems, LMU's, DMU's & understanding better barge responses during loading phases.

1.2 Problem Statement

1.2.1 Problem Identification

While floatover installation is the method of choice for most installations in shallower West African & South East Asian regions, there are many inherent risks related to the installation process itself. It is known that most of the 250 platforms in Malaysian waters mainly consist of shallow water jacket platforms where heavy crane lifting is not permissible for much heavier topsides. With increasing floatover facilities available, this has allowed oil & gas operators to implement heavier topsides in shallower waters where cranes requiring approximately 20m hull depth were previously not allowed to enter. However, the installation phase has poses much risk to the floatover process as it is sensitive to environmental loadings & as such, elements pertaining to the installation phase should be analyzed & studied to allow mitigating measures to be taken in future.

1.2.2 Significance of Project

Technip is currently designing & constructing the Owez Drilling Platform A (ODP-A which is located at the Owez Field in Block 1B, Caspian Sea located approximately 70km south-west of Kiyanly. Challenges posed by the sea state of the Caspian seas requires that theoretical analysis, software analysis as well as model tests be run in order to further understand the extent of environmental loads acting upon the floatover barge that is to operate in the area. While Technip had previously appointed DHI Sdn. Bhd. To perform detailed analysis of the MCR-A platform within the same vicinity, the task has now fallen upon the hands of UniversitiTeknologiPetronas (UTP) to continue the research within this area of floatover installation. The provided metocean data will give valuable insight into the responses of the barge & its mooring lines in the Caspian Sea.

1.3 Objective & Scope of Study

Based upon the background research listed above, several objectives are listed out to demarcate the direction of this research project:

a) To determine the dynamic responses of the floatover barge subjected to random waves in the JONSWAP spectrum through RAO spectrums & Motion Spectrums
b) To validate the dynamic responses that occur as a result of conducting model tests on a model barge within UTP's offshore engineering facilities such as the wave tank (model analysis).

Scope of study of this project have been revised to encompass the following parameters

a) Fixed parameters:
    i. Unidirectional waves at 180° heading
    ii. Random waves at the significant wave height, Hs=2.0m
    iii. 2 degrees of freedom are studied, surge & heave
b) Varying parameters
    i. Barge draft of **2.0m& 4.0m**
    ii. Varying peak period, **Tp=7s &Tp=8s**

These parameters will then be studies for the following outputs:

a) Wave Energy Spectrum (JONSWAP)
b) Time Series of Wave Profile
c) Motion RAO

1.4 Relevancy of Project

This research project will focus very much on the understanding of metocean data & its dynamicity upon floating structures. As such, valuable output from the research of barge's responses will tie back the theoretical concepts & theories previously conceived in the Design of Offshore Structures. Further research could possibly include the utilization of experiences gained on this project to develop a Regional

Annex on how to deal with floatover installations in Malaysian waters (with respect to the South China Sea).

1.5 Feasibility

The feasibility of the project is very positive as much of the needed data, facilities & resources have been provided for either by sponsors of an existing grant, facilities available within the campus as well as valuable metocean data provided by the parties interested.

a) Metocean Data – Provided for by Technip (M) Sdn. Bhd. as per needed to complete the barge analysis
b) Facilities – Utilization of the 1m deep wave tank within UTP in the Offshore Engineering labs as well as all related equipment, models & hardware.
c) Support & technical expertise – Provided for by the supervisor of the project who is a professor that has had more than 40 years of experience in the offshore research area as well as research engineers from Technip
d) Referencing material – Readily available from the Information Resource Center (IRC) of UTP which stocks materials such as "Hydrodynamics of Offshore Structures" by Chakrabarti which provides fundamental theories & concepts to be utilized in the analysis of the floatover barge.

2.0 Literature Review

2.1 Background of Topside Installation

The following is a summary of the evolution of topside installation. This section will help understand better the current need for new & innovative solutions to installing topsides (hence the current popularity of floatover systems).

2.1.1 Lift Installed Decks

2.1.1.1 Modular Deck Installation

Early days of topside construction saw an average module of 250t being fabricated before being towed out to sea by lifting cranes. This fabrication limit was due to the technology available back then which only allowed such carrying loads by the cranes. However, the development of newer fabrication methods as well as larger cranes (bigger capacity) saw installation of larger modularized topsides such as the North Rankin A platform in the North West Shelf of Australia in 1984 which consisted of 20 modules with the largest being 1,300t (SPE, 2000).

Modular installation required skid beams to be deployed to enable the deck modules lifted from the transport by the crane to be slid in position on top of the substructure (jacket). This method proved to be costly especially when module counts increased with larger topside weights. On top of that, modularized topsides required more steel then necessary for the installation process of the modules.

2.1.1.2 Integrated Deck Installation

Integrated decks became popular in the 80s with the introduction of Heavy Lift Construction Vessels (HLVC) in the market with construction recording singular topside installations of up to 12,000t (Shearwater, North Sea – 2000). As of 2000, HLVC forms have formed the majority of topside installation methods.

This process however had become less than desirable as more platforms were constructed due to the following factors:

a) Crane availability – Most of the HLCVs operate within the GOM & the North Sea rendering operations in areas such as the Arabian Gulf & West Africa having to wait long times for vessel to mobilize to their area.

b) Crane suitability – HLVCs require an operating draft of approximately 20m & this could pose a challenge in shallow water construction such as Mobile Bay in GOM (SPE, 2000) & West Africa (Nigeria) where water depths are limited to around 20-30m depending on location.

c) Crane capacity – Certain installations require integrated decks of up to 21,800t (Lunskoye – Sea of Okhotsk) & this is not possible using HLVCs.

2.1.2 Floatover Decks

2.1.2.1 Inshore Installation

This method was implemented as early as the 1970s in the North Sea inshore deep-water sites (fjords) for Concrete Gravity Based Structures (CGBS). This method involved ballasting down the GBS to a certain draft before the deck is then transported over it. The GBS is then de-ballasted until it supports the deck entirely before finally towing it to the installation site. This was done in 1973 for Mobil Beryl A & future implementations saw deck installations of up to 50,000t (SPE, 2000).

2.1.2.2 Offshore Installation

First commenced in 1981 in Ekoundou, Cameroon (for 1600t topside), the successful installation at sea states of 13s swells at 1m wave height proved that floatover installations are viable for open water applications. 90% of floatover installations have been performed on steel jackets with GBS & TLP applications becoming more popular as of 2000.

Offshore floatover has proven to be vastly superior to crane lifting methods; this is attributed to its ability to support large payloads that usually have to be implemented in modules by HLCVs. This gives the process an economical advantage in terms of lower hookup times, no need for modular installations (longer construction process) & savings in steel redundancies usually associated with modular installations.

It is however noted that due to volatile sea states in open waters, barges play a very crucial role in ensuring the feasibility & operability of this installation method.

Below is a diagram depicting the floatover process from barge approach, barge approach in floatover position, ballasting of barge, load transfer of topside, withdrawal of barge through ballasting & finally the barge's removal from between the jacket legs.

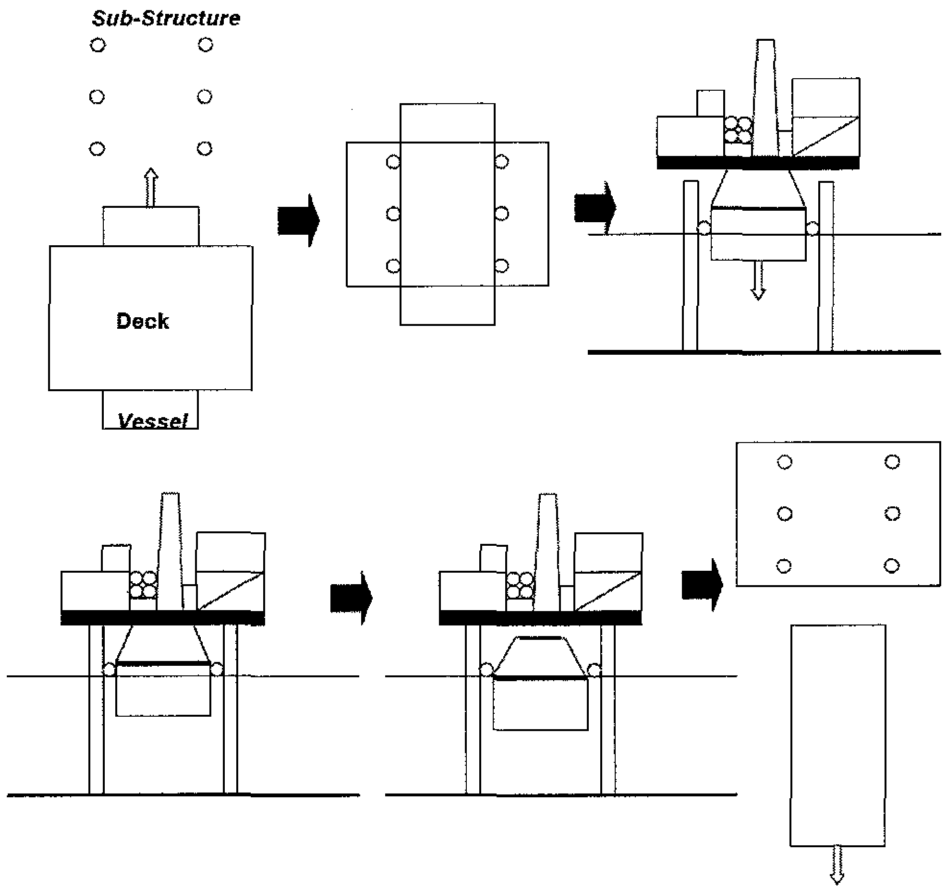

Figure 2.1: Typical floatover process for offshore installations

2.2 Critical Factors Affecting Barge Stability & Jacket Integrity

2.2.1 Motion Controls During Mating

Forces induced by waves during the installation phase can create motions that yield large impact loads upon the ship. Roll motion particularly induce high impact loads upon the structure accompanied along with other motions such as heave, surge, & pitch. The magnitude of such forces is attributed to the proximity of the roll periods of the combined deck/vessel to the peak spectral period (G.Gros& A. Lescurat, 1982).

These favourable conditions are monitored using specialized equipment fitted at the LMUs or stabbing cones where force actions are critical during installation or at barge fenders during floatover mating. These will allow engineers to predict favourable weather windows that are correspond with the expected resultant forces that the jacket, deck & barge is designed for. This process can be better predicted using barge models where controlled test parameters can model motion reactions that will help engineers predict the best weather window for installation given the designed strength of the structures or vice verca.

Vessel drift & diffraction can be critical in large structures such as GBS (OTC, 1996) where fluid interactions are significant. There are 3 common methods in which topside mating is conducted, each with differing installation rate (which affects the length of the favourable weather window) as well as differing costs:

a) Passive mating – elastomeric pads, rapid ballasting

b) Partially active mating – elastomeric pads, rapid ballasting, mechanical rapid lowering

c) Active mating – elastomeric pads, rapid ballasting, mechanical rapid lowering with hydraulic positioning

The methods from a) to c) provide increasing speed of installation, thus permitting a weather window for installation but comes with increased cost with active mating costing twice as much as passive installation (OTC, 1996). The following table shows the comparison of permissible wave heights in correlation with different mating systems:

	Beam Seas (m)	Quartering Seas (m)	Head Seas (m)
Passive mating	0.5	0.7	0.9
Partially active	0.9	1.4	1.8
Active mating	1.1	1.7	2.3

Figure 2.2: Relationship between different mating systems & allowable wave heights.

Although significantly more costly, it can be crucial in certain projects to implement active mating as barge motions induced during the 8-month study in the Gulf of Guinea has rendered operability less than 50% for passive while active mating gave a rating of up to 90% (OTC, 1996).

2.2.2 Allowable Sea States

Allowable sea states or operability window period is determined very much by the strength of the substructure with the interfacing on the deckside as well as the strength of the substructure to withstand the interfacing of the installation barge. This will allow engineers to understand whether the current floatover system as well as the utilized barge can yield workable weather windows. Reassessment & redesign is required if an acceptable weather window cannot be achieved with current conditions.

The calculation of allowable sea states should be based on the following criteria:

a) Seasonal conditions

b) Tidal ranges

c) Direction of Swells

d) Wave Height & Period (Regular & Irregular)

It is essential to maintain a factor safety in predicting weather windows & therefore a 24-48 hour time frame for prediction is required for operations to commence. It is useful to run model tests on the substructure & barge during installation via model tests & numerical simulations to allow prediction of suitable weather windows prior to operations.

2.2.3 Floatover Vessel Selection

Vessel selection plays a prominent role in affecting the design of the jackets as well as determination of favourable windows (as it affects the barge motions). In general, the width of the vessel is dictated by the height of the deck loaded above it as an acceptable center of gravity (CG) must be maintained to ensure barge stability. For an example, a 10,000t deck loadout would require a vessel width of 42m (OTC - Houston, 1997). The floatover motions are also sensitive to mass distributions on top of it & as such it is important to have a good placement of topside to ensure optimum stability & minimal barge motions.

Such parameters & considerations ultimately affects the design of the jackets as the width between jackets is determined by the width of the barge passing through it into floatover position. It is however more favourable to have smaller barge dimensions without compromising safety & therefore a model study of barge motions should be carried out to study the extent to which barge motions can be considered unsafe (optimization of barge width with respect to safety & sea states).

The following diagram illustrates the correlation between ship width, ship height & ship stability

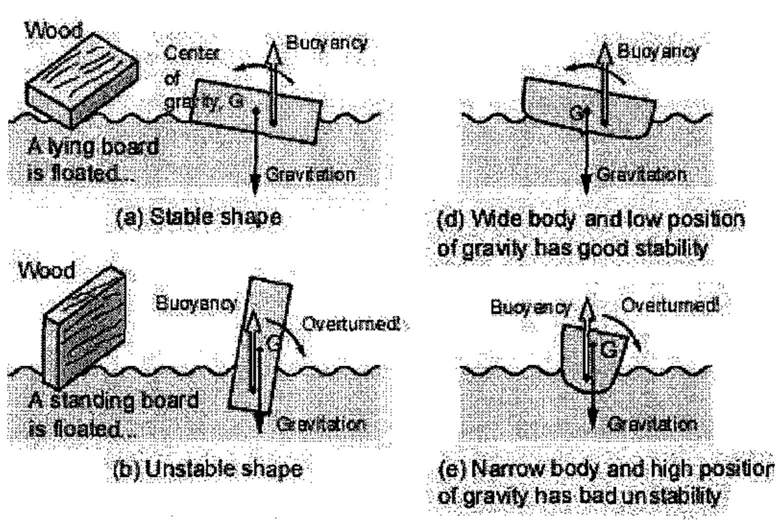

Figure 2.3: Relationship between barge width, height & how it affects stability

2.3 Role of Model Testing in Optimizing Platform Design & Installation Process

Over the years since the inception of floatover installation systems, improvements to model testing (in terms of accuracy of equipment used & methods) has seen actual designs of platforms approaching the limit of the predicted sea states. Likewise for prediction of barge motions based on deck mass distribution as well as barge dimensions, model testing has proven to be a useful tool in identifying suitable & longer weather windows for installation.

Kvaerner O&G Australia in 2000 published in SPE journals & had made a study on the trend of platforms over the years from 1992 – 1997 on how the improvement to model testing has brought significant savings in platform design as it now can be modeled closer to actual wave heights (less overdesigning). This is similarly applied to floatover installations where improved floatover techniques can extend the weather window for barges (due to less barge motions).

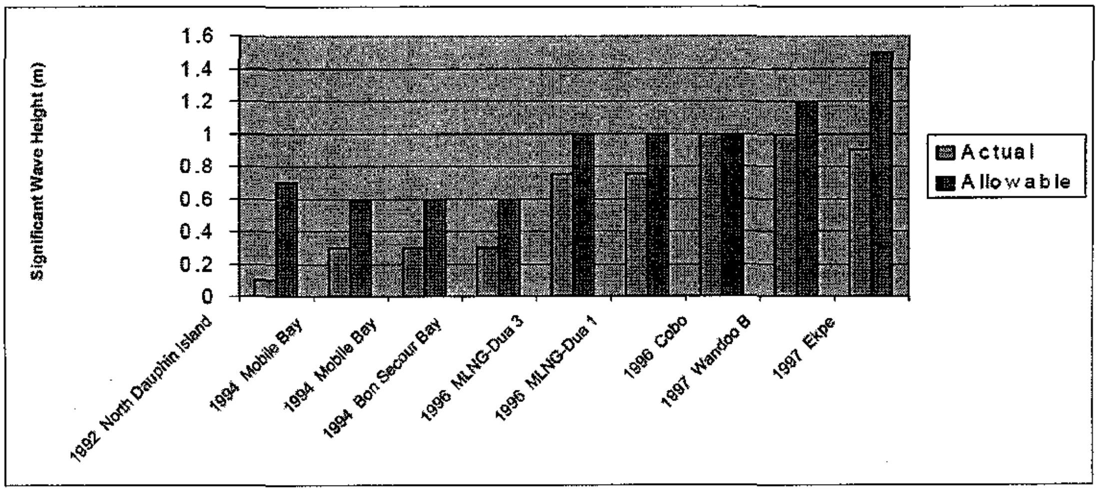

Figure 2.4: Allowable significant wave height for installation vs actual wave height

3.0 Research Methodology

3.1 Research Methods

2 methods will be employed throughout the course of this research:

a) Theoretical Analysis – Wave energy densities using JONSWAP spectrum, Motion RAOs using Froude – Krylov Theory & barge Motion Spectrums will be calculated
b) Experimental/Modeling – This method will be employed at the end to verify the assumptions & methods used in the calculation of the above outputs

3.2 Theoretical Analysis

3.2.1 Wave Energy Spectrum (JONSWAP)

Joint North Sea Wave Project (JONSWAP) spectrum was developed by Hasselman (1973) during a joint North Sea wave project (Chakrabarti, 1987) & was designed to be a fetch-limited version of the Pierson-Moskowitz Spectrum, which better describes the partially developed sea conditions in the Caspian Sea.

The following formula will be used to derive an approximate expression for the JONSWAP spectrum in terms of H_s& ω_0 (Goda, 1979).

$$S(\omega) = \alpha^* H_s \frac{\omega^{-5}}{\omega_0{}^{-4}} \exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right] \gamma^{\exp[-(\omega-\omega_0)^2(2\tau^2\omega_0{}^2)]} \quad (3.1)$$

Whereby,

$$\alpha^* = \frac{0.0624}{0.230 + 0.0336\gamma - 0.185(1.9 + \gamma)^{-1}} \quad (3.2)$$

Whereby spectral peak response, $\gamma = 3.3$, & $\tau = 0.07$ ($\omega \leq \omega_0$), 0.09 ($\omega \geq \omega_0$)

This modified formula will allow the calculation of the energy spectrum while taking into consideration H_s& ω_0 as factors contributing to the spectral plot.

3.2.2 Time Series of Wave Profile

The time series of the wave motion is generated from the JONSWAP spectrum based on the following formula,

$$H(f_1) = 2\sqrt{2S(f_1)\Delta f}(\mathbf{3.3})$$

$$\eta(x,t) = \sum_{n=1}^{N} \frac{H(n)}{2} \cos\left[k(n)x - 2\pi f(n)t + \varepsilon(n)\right] (\mathbf{3.4})$$

Formula (4.3) allows the calculation of wave height associated with a particular frequency within the spectrum while formula (4.4) enables the computation of the vertical displacement based on horizontal coordinate, x & moment in time, t.

3.2.3 Motion RAOs

Response Amplitude Operators (RAO) is written relating the dynamic motion of the structure to the wave-forcing function on the structure. RAOs are critical in identifying wave frequencies that can cause resonance in the structure by the motion it induces. In RAO analysis, waves are deemed to be of regular range & cover a sufficient number of critical frequencies in the wave spectrum (Chakrabarti, 1987). The RAOs or dynamic-motion spectrum is constructed from the wave spectrum & can be assembled using the following formula

$$x(t) = \left[\frac{F_1/\left(\frac{H}{2}\right)}{\left[(K - m\omega^2)^2 + (C\omega)^2\right]^{0.5}}\right]^2 S(\omega) \quad (\mathbf{3.5})$$

Whereby, x(t) is the RAO depending on direction (Fx for surge &Fy for heave). The forces Fx&Fy can be computed from the Froude – Krylov Theory for rectangular shapes.

Following the Motion RAO Spectrum, The Motion Spectrum of the respective surge & heave motions can be calculated & correlated with the Wave Energy Spectrum through the following relationship

$$S_R = RAO^2 S(f)(\mathbf{3.6})$$

3.2.4 Froude – Krylov Theory

The numerical analysis of the barge will be done by utilizing the Froude – Krylov Theory in Excel spreadsheets to obtain the projected results. These results will then be compared against model results & actual barge responses in the Caspian Sea in which this project is modeled after.

Froude–Krylov force is the force introduced by the unsteady pressure field generated by undisturbed waves. The Froude–Krylov force does, together with the diffraction force, make up the total non-viscous forces acting on a floating body in regular waves (Chakrabarti, 1987).

This theory will be essential in accounting for the forces acting on the ship based on the geometry of the barge. Since the different motions such as heave & surge have different surfaces in which forces act upon, they are accounted for by the Froude – Krylov equations:

a) Surge:

$$F_x = C_H \rho V \frac{\sinh(\frac{kL_3}{2})}{kL_3/2} \frac{\sinh(\frac{kL_1}{2})}{kL_1/2} \dot{U}_o \quad (3.7)$$

b) Heave:

$$F_y = C_V \rho V \frac{\sinh(\frac{kL_3}{2})}{kL_3/2} \frac{\sinh(\frac{kL_1}{2})}{kL_1/2} \dot{V}_o \quad (3.8)$$

For this project, the barge is considered as rectangular block. The rectangular block is assumed to have the dimensions l_1, l_2 and l_3 where l_3 is the height and l_2 is perpendicular to the wave direction. Volume of the block is noted as $V=l_1 l_2 l_3$. However, some adjustments need to be done as the barge is not completely a rectangular block and the dimensions are also varies from bow to stern.

3.3 Model Tests

The model that is to be utilized in this project is based on a 1:50 scale which is to imitate the barge dimensions & geometry as that used in the installation of the ODPA Platform in Turkmenistan. The barge model's center of gravity, it is located

161.7cm from the bow or 303.35cm from the forked stern & weighs in at 60kg. The barge will be tested at 6-degrees of freedom by utilizing the optical tracking system to detect the barge's movements. However for the purpose of this research, we will be only considering 3 degrees of freedom in the direction of surge, heave & pitch in one wave direction (180 degrees). This research will be conducted using random waves & analyzed in the JONSWAP & Pierson – Moskowitz Spectrum.

Tension in the mooring lines will also be analyzed to find the responses related to stabilizing the barge after sailing in between the jacket legs (DHI, 2009). By having these model tests, we are able to predict the barge responses under expected metocean conditions & how they affect the installation phase. All this data will however be tied back to actual data in the Caspian Sea to validate that these models can be applied for real-life predictions.

3.3.1 Model Test Setup

The model is setup in a wave tank with 4 different types of equipment to record critical data with relations to barge motions:

a) Wave probe – Records wave height to generate the time series of the particular wave frequency
b) Accelerometers – To record the acceleration components (u dot & v dot) of the barge motions
c) Load cells – To record the resultant forces caused by barge motions with respect to the fixed draft & wave periods
d) Optical track sensors (Optitrack) – high precision devices meant to detect the 6 degrees of freedom of the barge via sensing reflective bulbs attached to the barge (motion targets)

The following is the typical setup of the experiment:

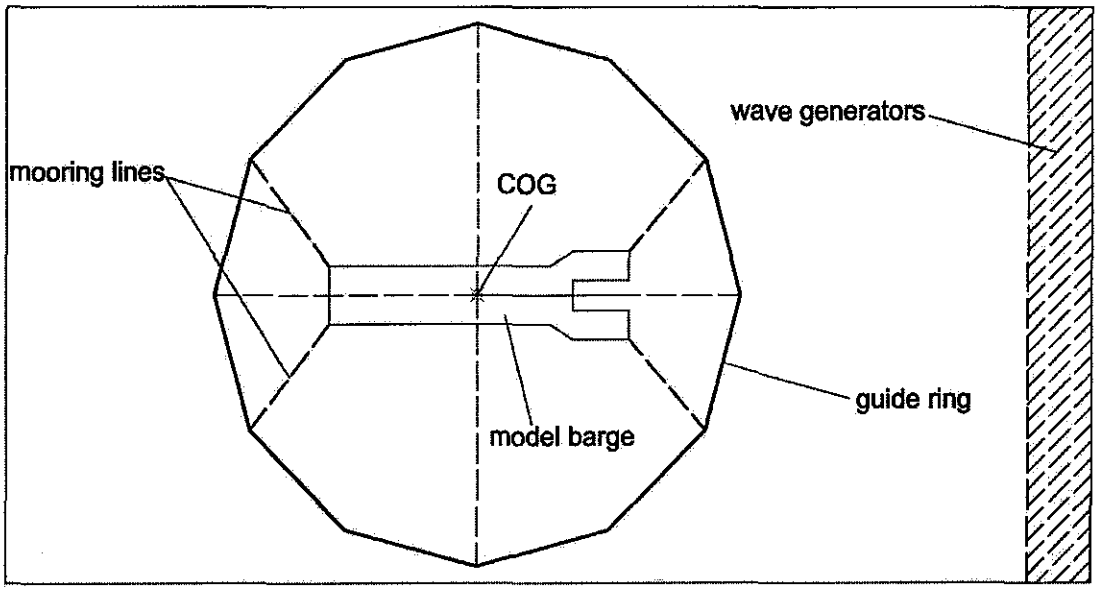

Figure 3.1: Typical experiment setup for 180° wave direction

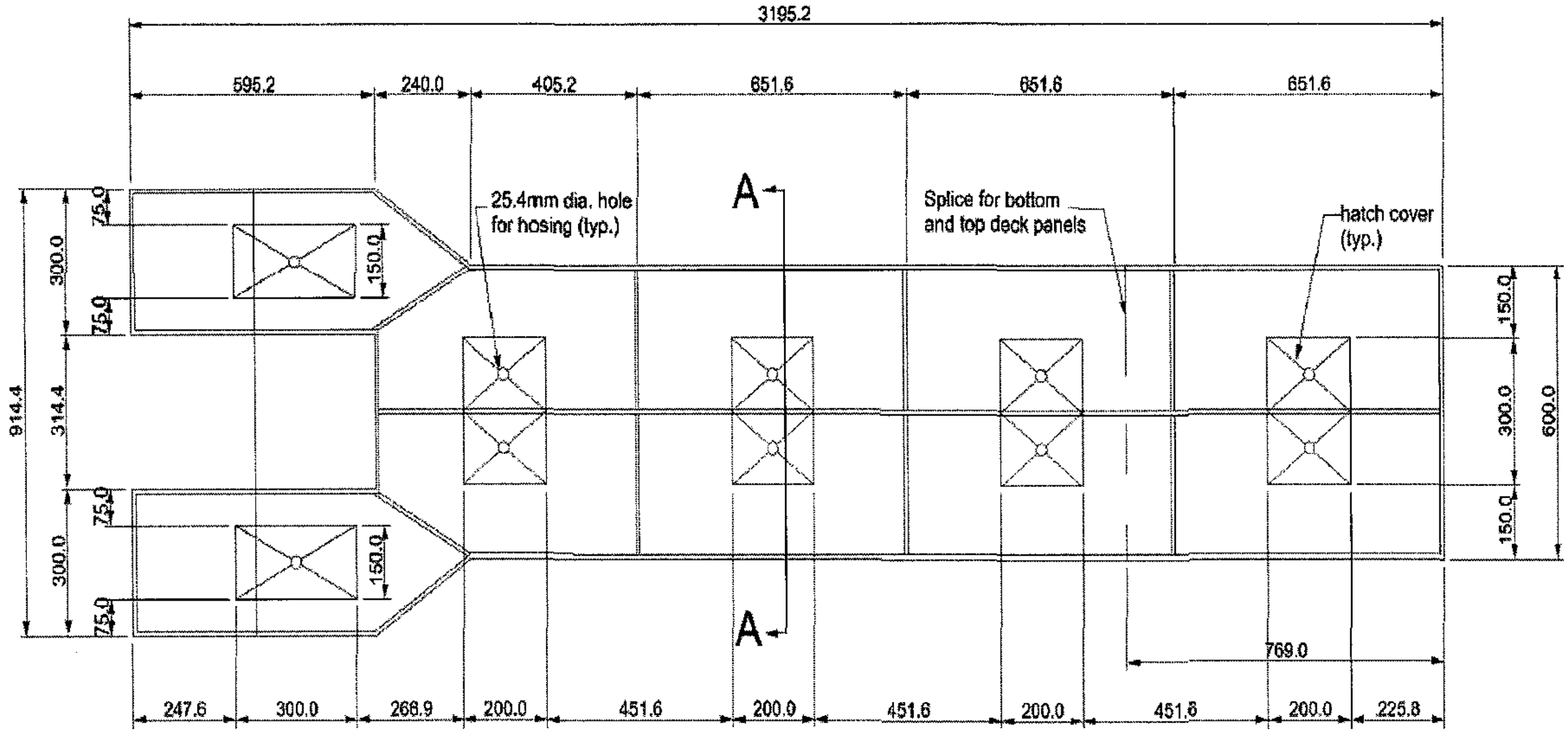

Figure 3.2: Plan view of the 1:50 scaled barge model with compartments for draft adjustment (to simulate deck loadings)

3.4 Gantt Chart

Week Number / Activities/Milestones	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Experimental set up	■			■				■							
Model testing (0˚, 4m water draft)	■	■						■							
Analysis of data from model (random waves)	■	■	■	■	■	■	■	■							
Submission of progress report								■	■						
Numerical analysis			■	■	■	■	■	■	■	■	■				
Pre-EDX								■				■			
Submission of draft report								■					■		
Submission of dissertation (soft bound)								■						■	
Submission of technical paper								■						■	
Oral presentation								■							■
Submission of project dissertation (hard bound)								■							■

3.5 Tools required

In the course of this research project, we will be utilizing the various resources &softwares available in UTP which are tabulated below:

Equipment / Software	Purpose
1m deep Wave Tank & Wave Generators	Conduct & simulate model tests on the barge & collect the corresponding dynamic responses
Wave Probes	Record wave heights with relation to time
Velocimeters	Records the velocity of the barge in motion
Accelerometers	Records the acceleration of the barge in motion
Load Cells	Records the tension in the mooring lines of the barge
Optical Tracking Sensors	Records the positioning of the barge with respect to its motion in time
Model barge	1:50 scale model barge that will be subjected to various test parameters to understand the resulting responses
Microsoft Excel	To compute mass amounts of data with respect to the various mathematical models implemented

Table 3.1: Tools required for project completion

4.0 Results & Discussion

4.1 Results

Based on extensive analysis, the experimental & theoretical components of the experiment shall be analyzed & be compared using the following parameters. Discussions will be made for each individual section:

a) Varying significant wave heights
   i. JONSWAP Model
   ii. RAO Spectrums (model & experimental)
b) Varying peak periods
   i. JONSWAP Model
   ii. RAO Spectrums (model & experimental)
c) Varying barge drafts
   i. RAO Spectrums (model & experimental)

4.1.1 Varying Significant Wave Height

4.1.1.1 JONSWAP Model

The following diagrams will illustrate the spectral density of various significant wave heights.

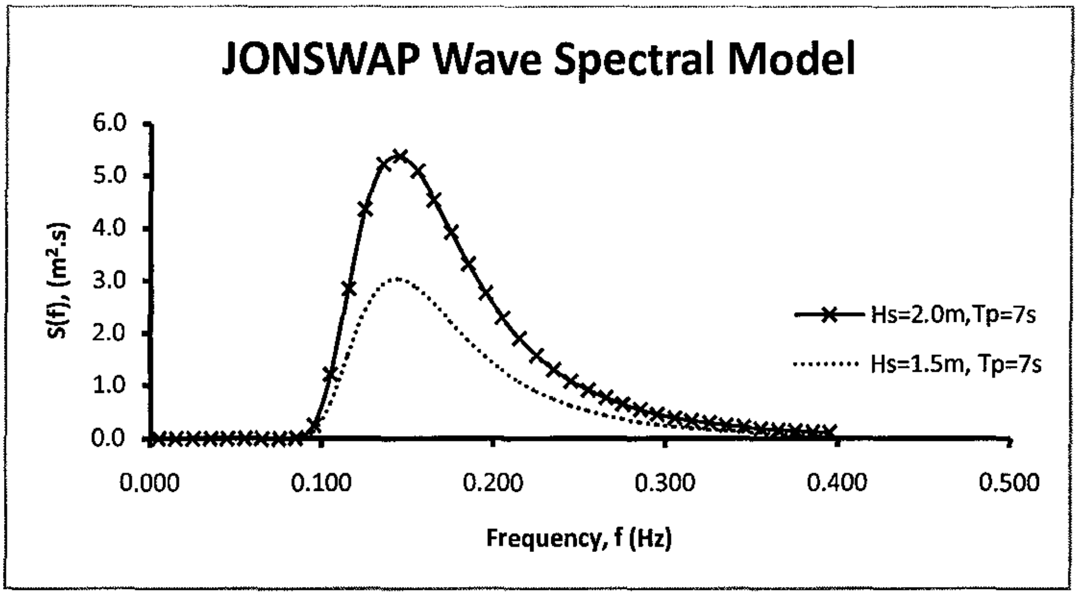

Figure 4.1: JONSWAP spectrum for varying wave heights at Tp=7s

Based on the Goda formula for JONSWAP spectrums, it is noticed that the change in significant wave height does not affect the critical range of the spectrum but only serves to increase the spectral density content of the waves in the critical frequency range. The increased wave height does not serve to affect the RAO in any way. Changes in wave peak period will only cause a shift spectral critical frequencies maintains the same relationship of increasing spectral peaks as the significant wave height increases.

4.1.1.2 RAO Spectrum (Theoretical)

Based on the prescribed formula for RAO computation:

$$x(t) = \left[\frac{F_1/\left(\frac{H}{2}\right)}{[(K - m\omega^2)^2 + (C\omega)^2]^{0.5}}\right]^2 S(\omega) \quad \mathbf{(4.1)}$$

The diagram below shows the effect of increasing wave heights. Values are taken at a 2m draft

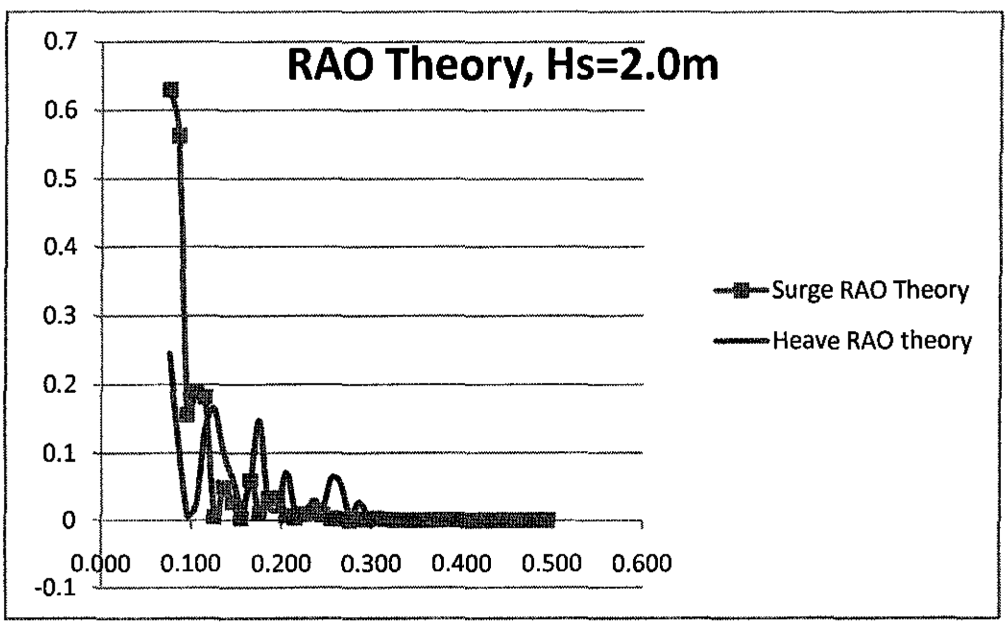

Figure 4.2: Theoretical RAO for 2m significant wave height

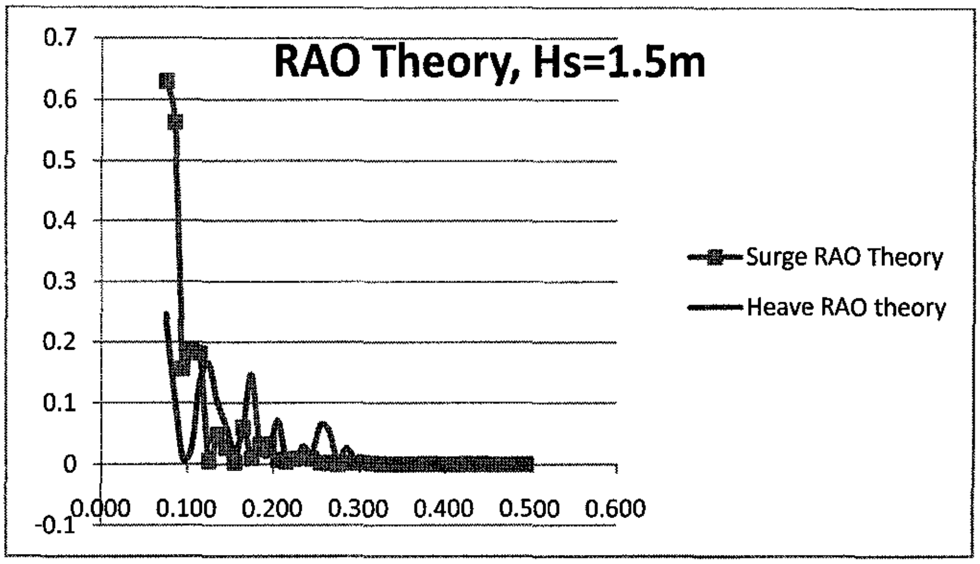

Figure 4.3: Theoretical RAO for 1.5m significant wave height

It is found that there is no change in the RAO peak values as the significant wave height increases. This is due to the force, F_1 term in the aforementioned formula which is proportionally cancelled out as the wave height increases. It can be seen that the RAO peak values are ranging in the 0.1Hz range for surge motions as well as heave motions & are consistent in value when changing from Hs=2.0m to Hs=1.5m. Thus we can make initial conclusions from the theoretical analysis that change in significant wave heights has no impact on the barge's RAO.

4.1.1.2 RAO Spectrum (Model Test)

The validate the findings, model tests are conducted to verify the extent of the theoretical accuracy.

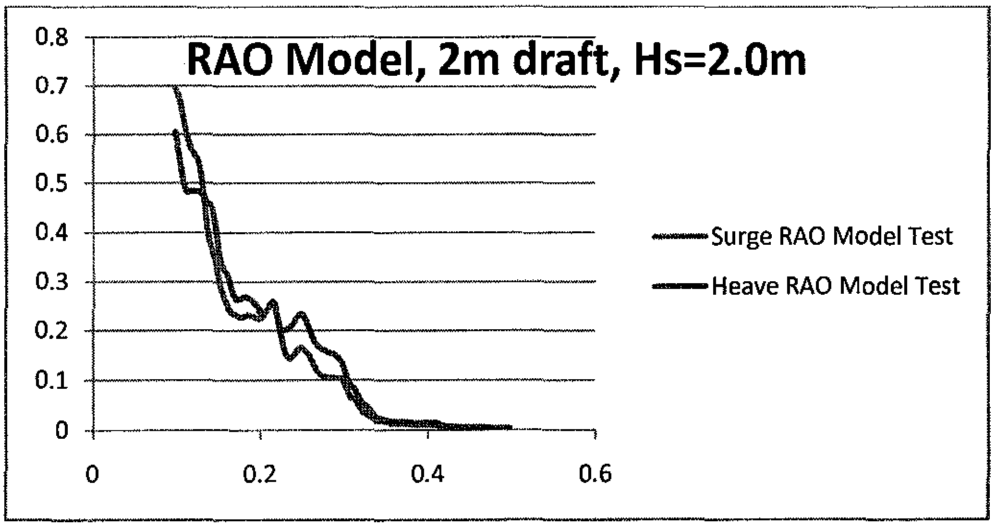

Figure 4.4: Model Test RAO for 2.0m significant wave height

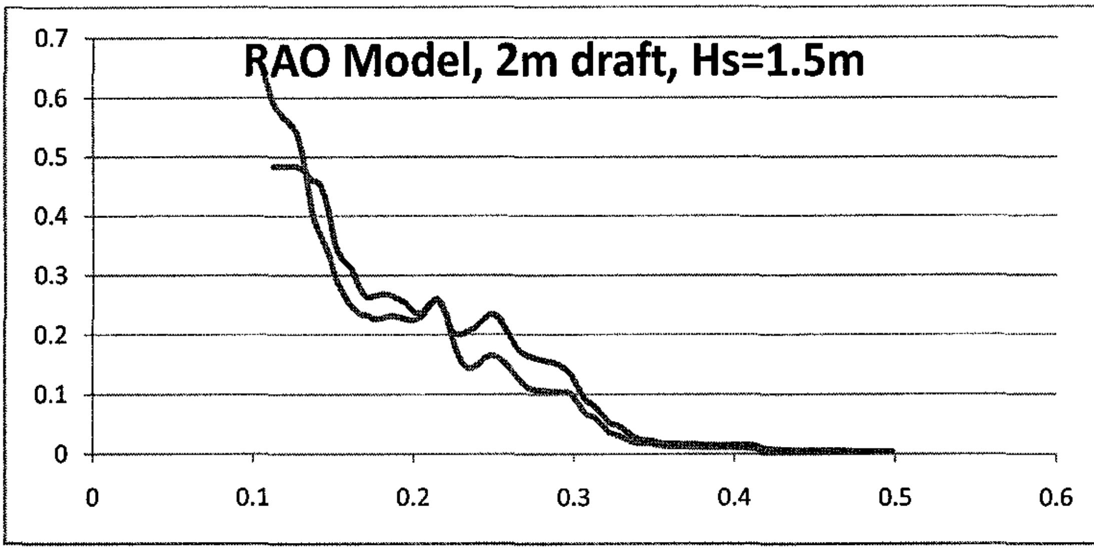

Figure 4.5: Model Test RAO for 1.5m significant wave height

The above chart concludes that there is no change in RAO spectrum as it changes from 2m to 1.5m draft thus concluding that significant wave height does not affect barge RAOs.

4.1.2 Varying Peak Periods

4.1.2.1 JONSWAP Model

The following diagrams will illustrate the spectral density of various peak periods:

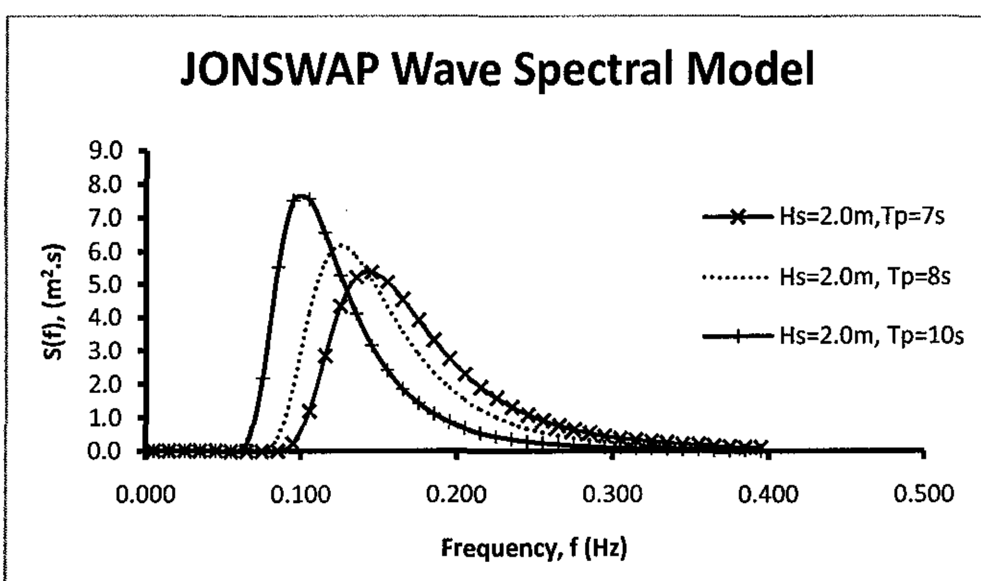

Figure 4.6: JONSWAP spectrum for varying peak periods at Hs=2.0m

Theoretical findings using the JONSWAP model indicates that increase in wave height causes a shift in the peak spectral frequency to the lower region (approx. 0.1Hz at Tp=10s). There is however a trend that indicates an increase in the peak spectral density at the expense of a reduced critical frequency range (narrow band). Calculations of the area below the graph will yield the same values for varying peak periods even though the peak has changed its location & width as the significant height of the wave is the governing factor in determining the energy content of the spectrum.

4.1.2.2 RAO Spectrum (Theoretical)

The effect of varying peak periods at a fixed 2m draft on a theoretical scale are shown below

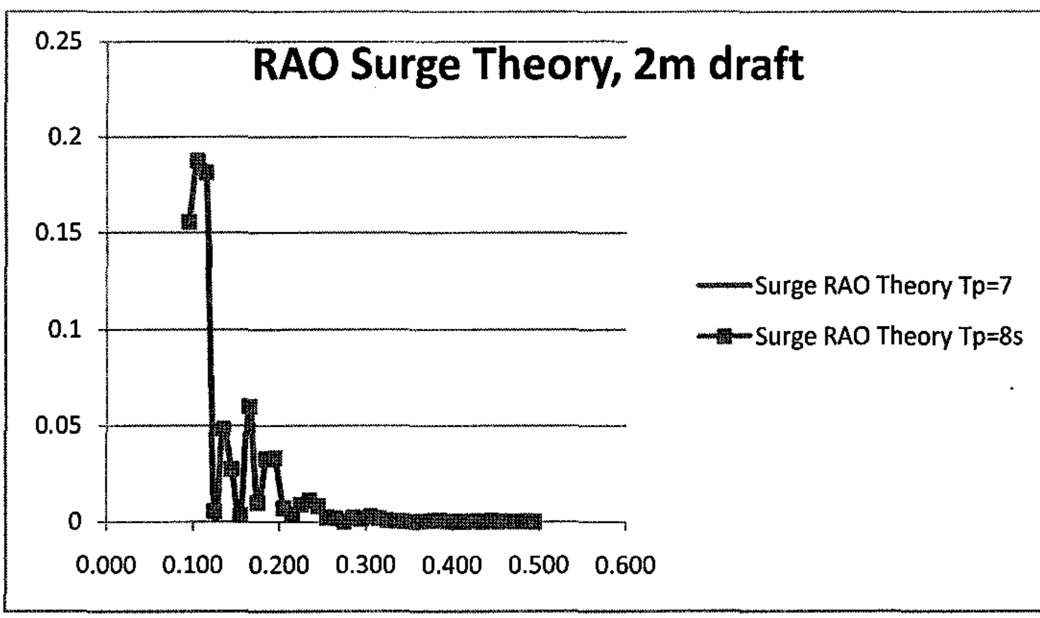

Figure 4.7: Theoretical Surge RAO Spectrum varying peak period at 2m draft

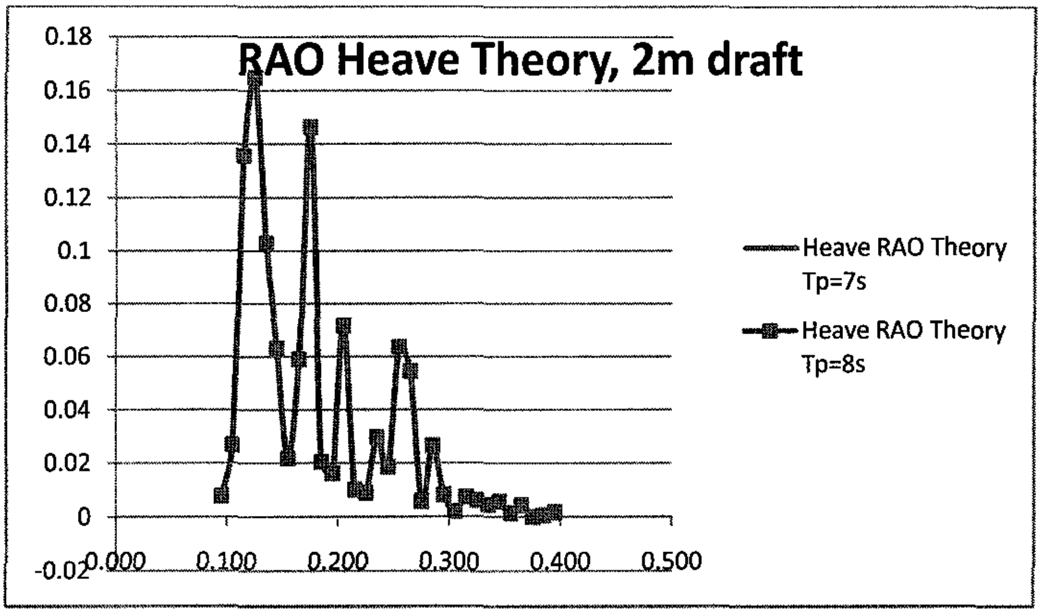

Figure 4.8: Theoretical Heave RAO Spectrum varying peak period at 2m draft

Similar to the variation in significant wave height, the change in peak period does not yield any difference theoretically in the calculation of RAOs as the change in peak period values will cause an adjustment in the peak frequency, ω thus resulting in a change of force values, F_1. The combined effect of both will offset each other theoretically, thus yielding the exact same RAO spectrum for both Tp=7s &Tp=8s.

The calculations are then repeated for a different barge draft of 4.0m to validate the theoretical findings of a 2.0m draft.

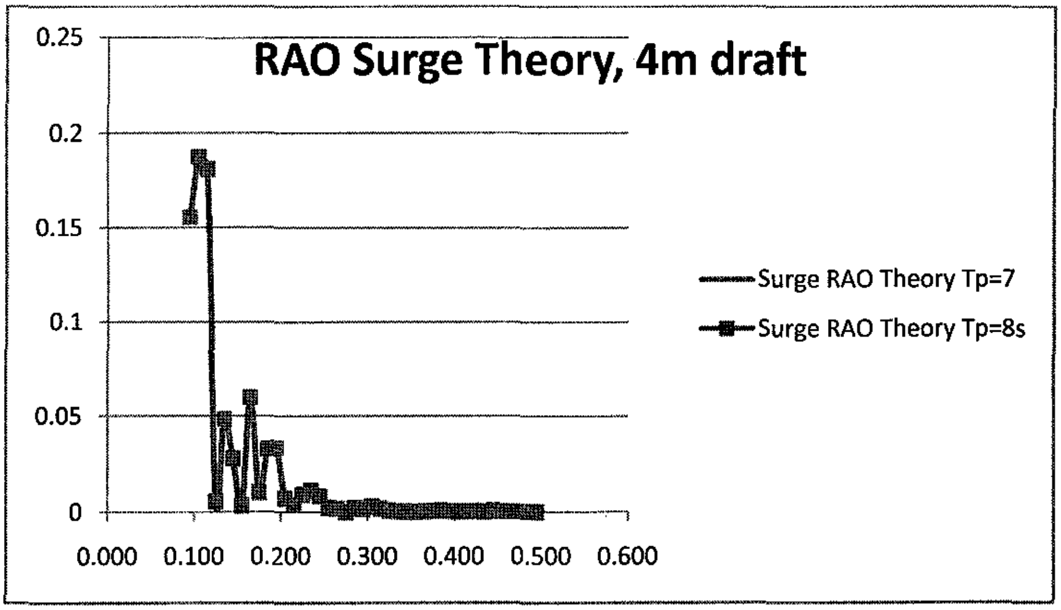

Figure 4.9: Theoretical Surge RAO Spectrum varying peak period at 4m draft

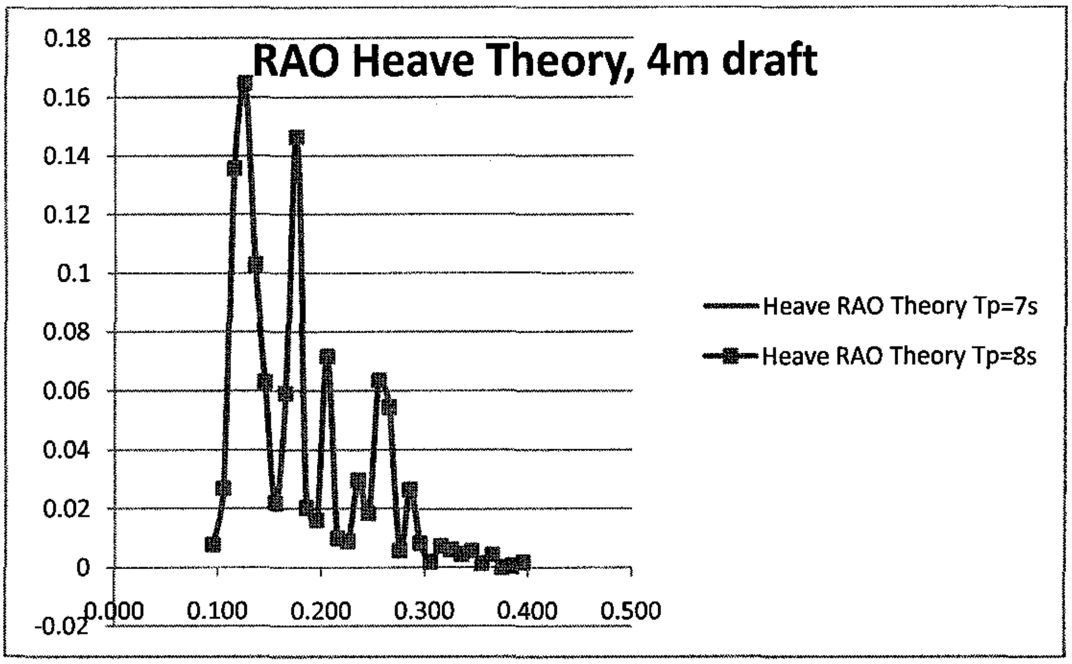

Figure 4.10: Theoretical Heave RAO Spectrum varying peak period at 4m draft

The theoretical analysis of RAOs at barge draft of 4m yields the same results when variation of peak period is applied. This further reinstates the point that change of peak period, Tp does not result in a change of theoretical RAO Spectrums.

There is however an anomaly observed in the plotting of the Heave RAOs for the barge draft. This phenomenon of having multiple peaks of almost the same amplitude will be attempted to be explained in the Discussion section as it is not in the scope of this subtopic.

4.1.2.2 RAO Spectrum (Model Test)

To verify the validity of the above initial conclusions based on theoretical data, the model test results are presented below:

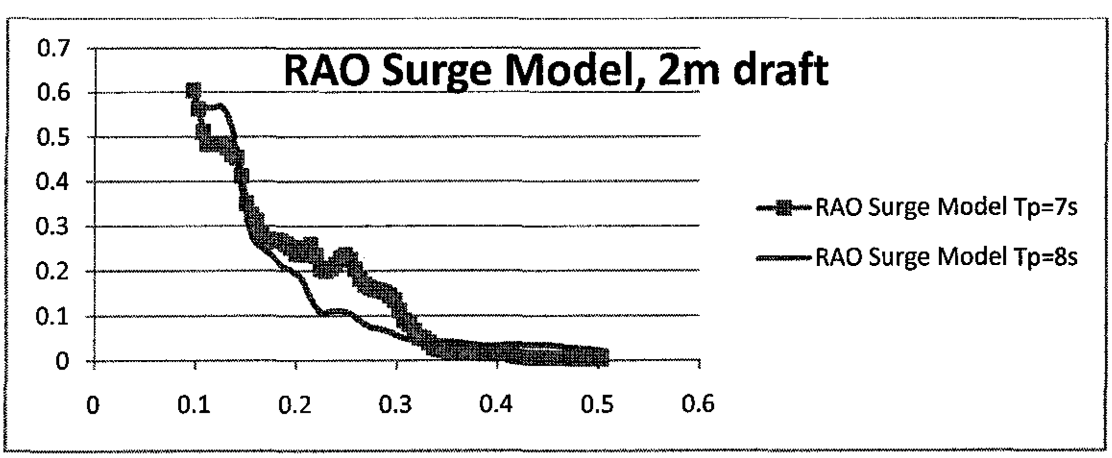

Figure 4.11: Model Surge RAO Spectrum varying peak period at 2m draft

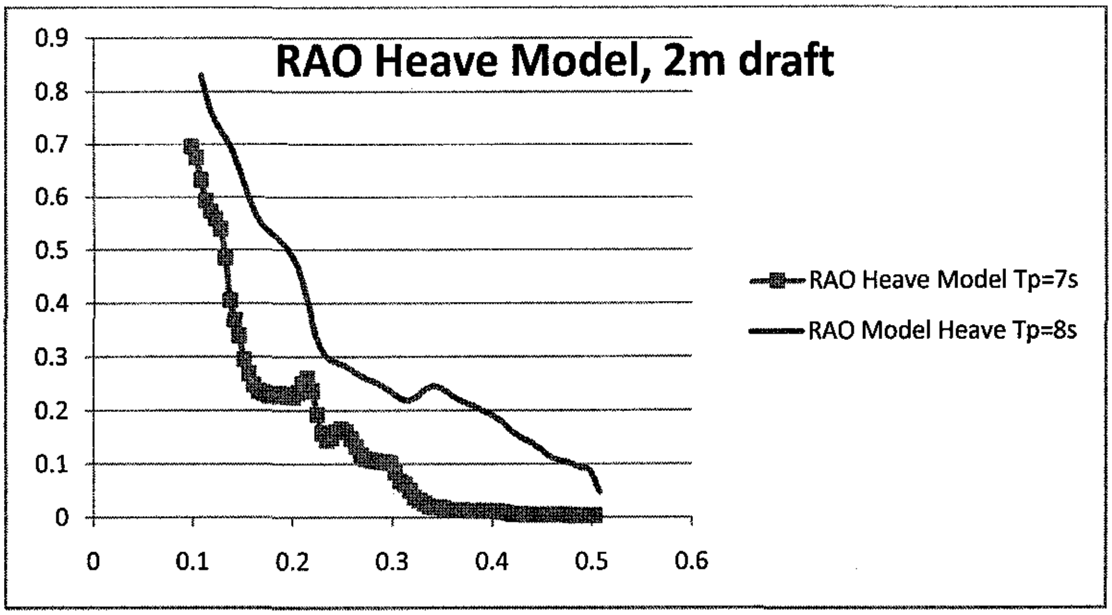

Figure 4.12: Model Heave RAO Spectrum varying peak period at 2m draft

The results above show that model test comparison between Tp=7s &Tp=8s for a barge draft of 2.0m yield nearly the same peak values. The slight differences could possibly arise from uncontrollable variables which will be explained in the Discussion. To further consolidate the findings, there is no correlation between the increase in peak period, Tp value & the RAO values due to (1) Increase in Tp value caused an increase in heave RAO, however (2) increase in Tp value caused a decrease in surge RAO value. Thus we can conclude that there is a very high likelihood that the slight variation in peak RAO values for both Tp values are due to that for both uncontrollable variables in the experiment. It can however be concluded that for both surge & heave motions, the critical RAOs are located within the 0.1Hz frequency range.

To further prove the findings, the experiment is repeated for a barge draft of 4.0m& the following are the findings:

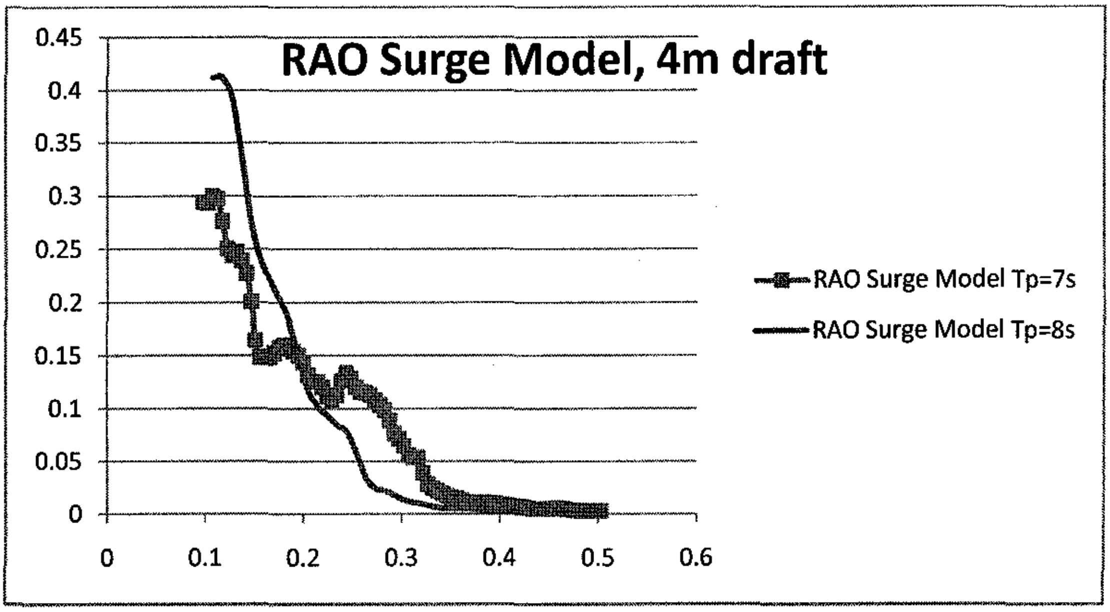

Figure 4.13: Model Surge RAO Spectrum varying peak period at 4m draft

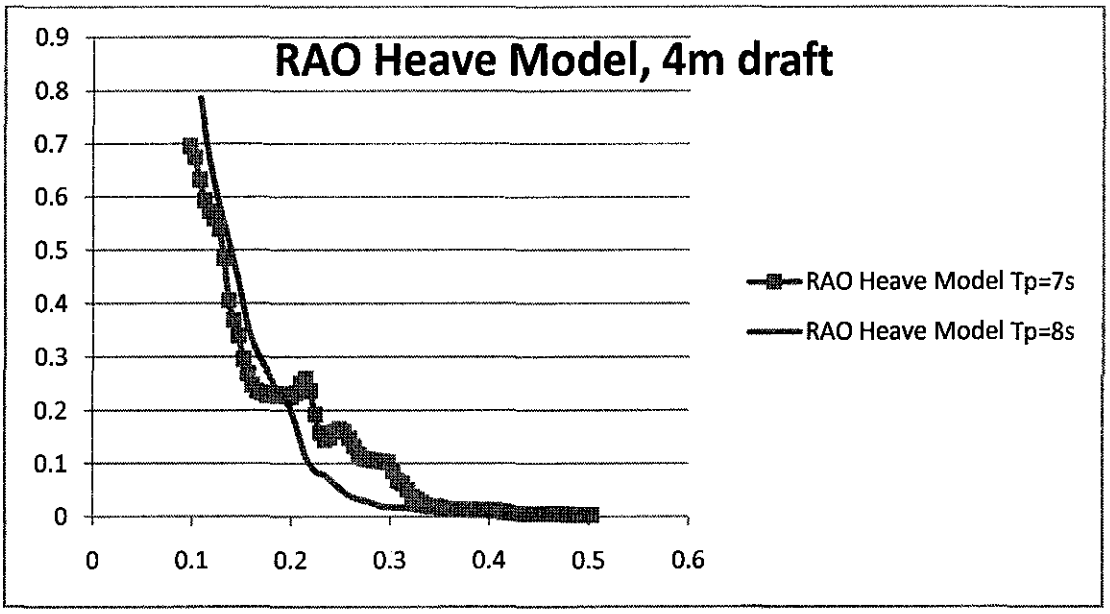

Figure 4.14: Model Heave RAO Spectrum varying peak period at 4m draft

In similar trend with the 2m draft, the 4m model test displays much similarity in peak values between the Tp=7s &Tp=8s model tests& peaks approximately in the 0.1Hz frequency range.

4.1.3 Varying Barge Drafts

4.1.3.1 RAO Spectrum (Theoretical)

The graph below shows that plotting of theoretical surge & heave RAOs for different barge drafts:

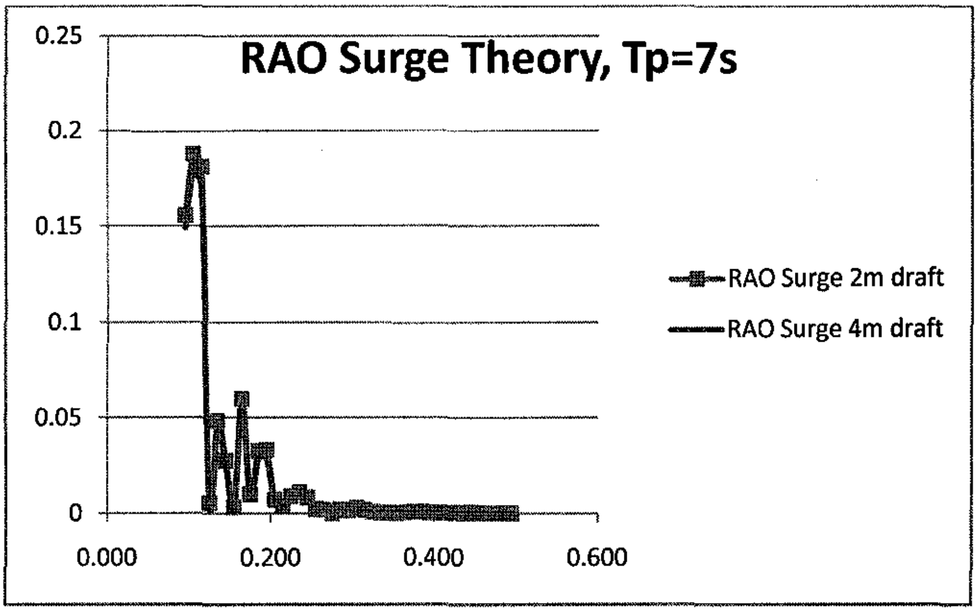

Figure 4.15: Theoretical Surge RAO Spectrum for varying barge draft at Tp=7s

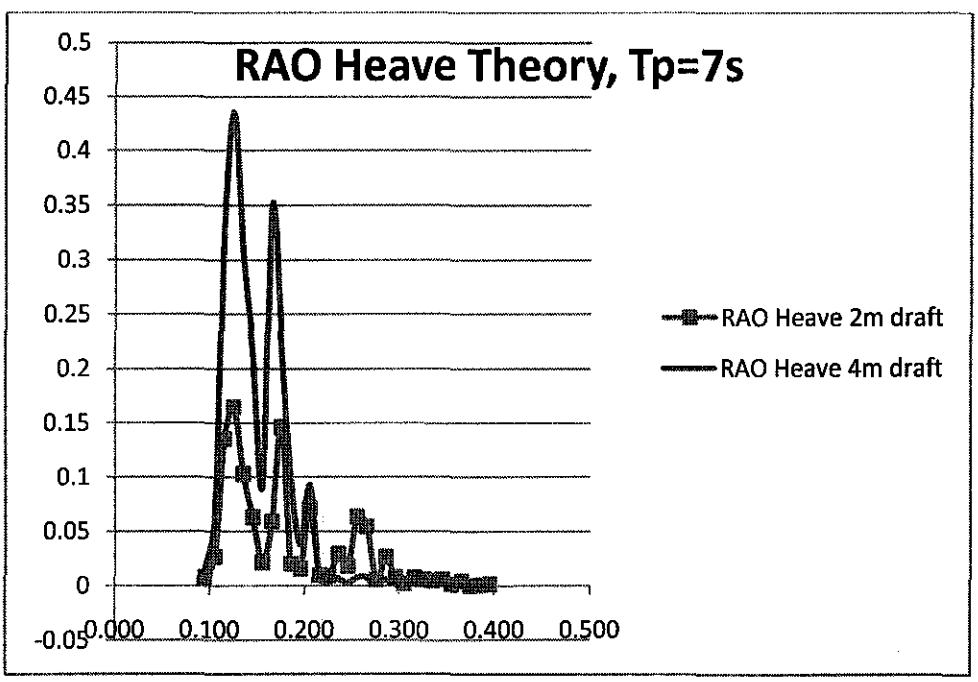

Figure 4.16: Theoretical Heave RAO Spectrum for varying barge draft at Tp=7s

Based on the graph above, it can be observed that the theoretical RAO for a draft of 2m is marginally higher than the 4m draft at most points. This is due to the mass, M in the RAO formula which is associated with barge drafts. A larger barge draft would result in the barge being immersed deeper in the water body, thus providing added mass to the barge & ultimately providing more stability towards motions. In contrast, a smaller barge would leave the barge with a higher moment arm (more surface area exposed above water) on top of the reduced mass provided by the water body.The graphs also show a trend of critical peak RAO frequencies of between 0.1 – 0.15Hz.

A graph is plotted for Tp=8s for validation that this trend is consistent even for other peak periods. Aside from that, it is also noticed again that there is an anomaly in the heave RAO spectrum whereby there is a sudden spike in RAO values compared to surge RAO spectrum. This will be explained later in the Discussion.

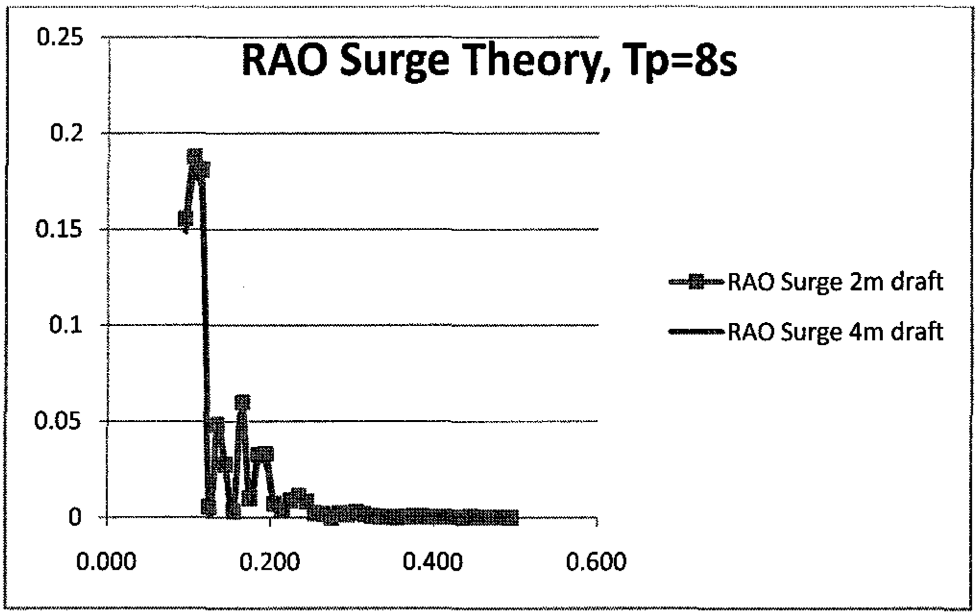

Figure 4.17: Theoretical Surge RAO Spectrum for varying barge draft at Tp=8s

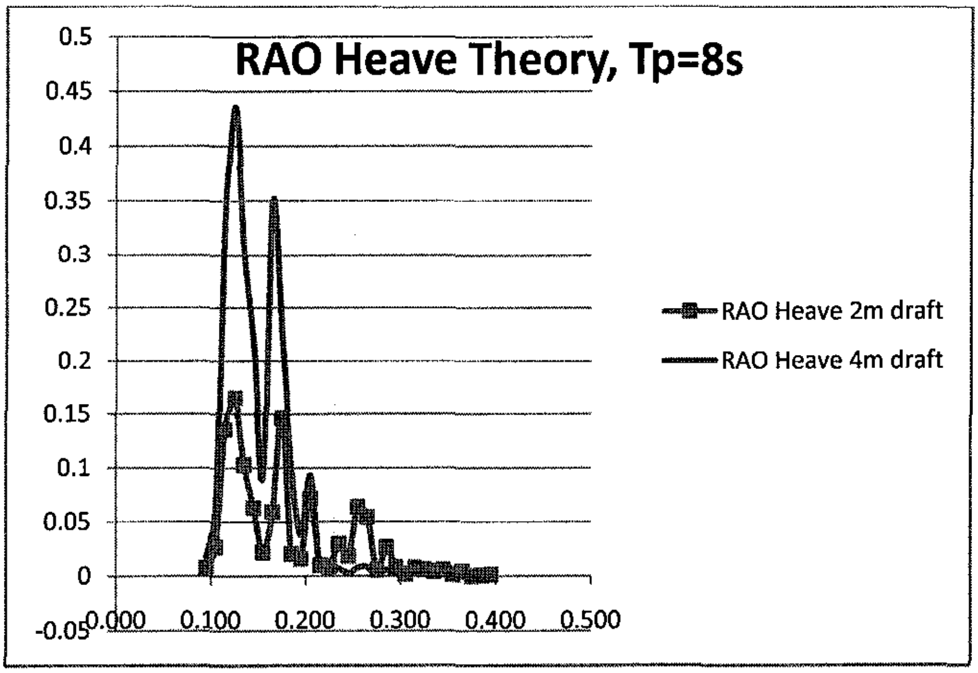

Figure 4.18: Theoretical Heave RAO Spectrum for varying barge draft at Tp=8s

As per discussed in Section 4.1.2 regarding varying peak periods, the theoretical RAO for both Tp=7s & 8s are the same & thus as such, the above graph depicts such similar conditions.

4.1.3.2 RAO Spectrum (Model Test)

The following graph illustrates the RAOs for model tests in heave & surge motions:

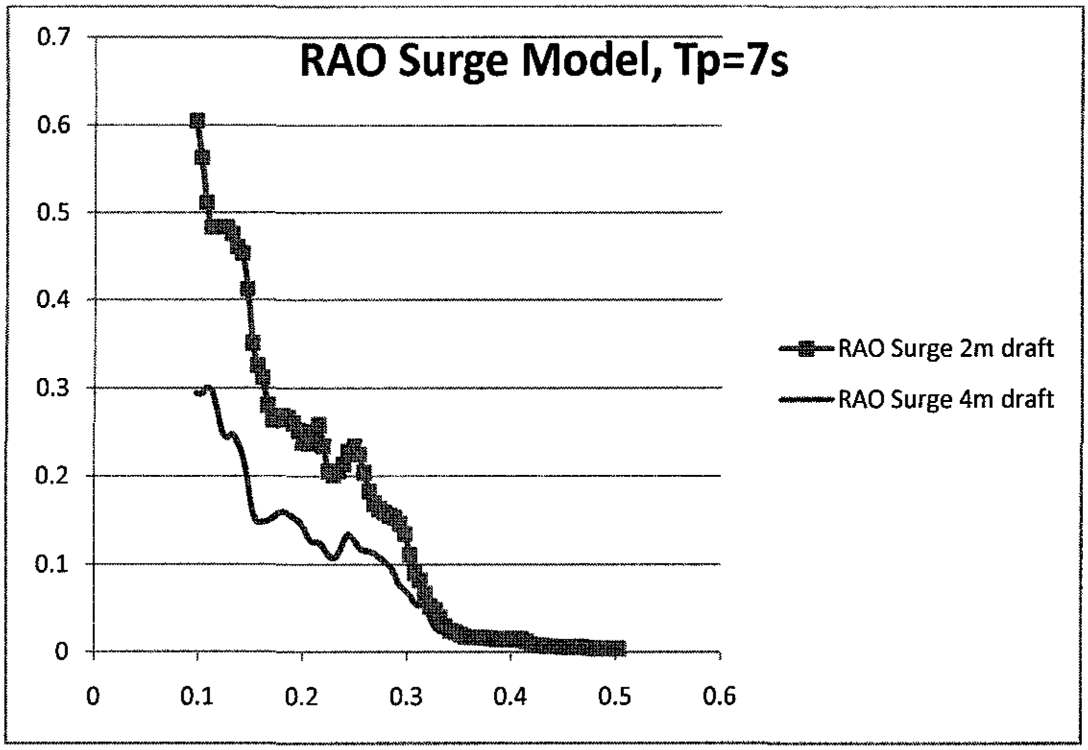

Figure 4.19: Model Test Surge RAO Spectrum for varying barge draft at Tp=7s

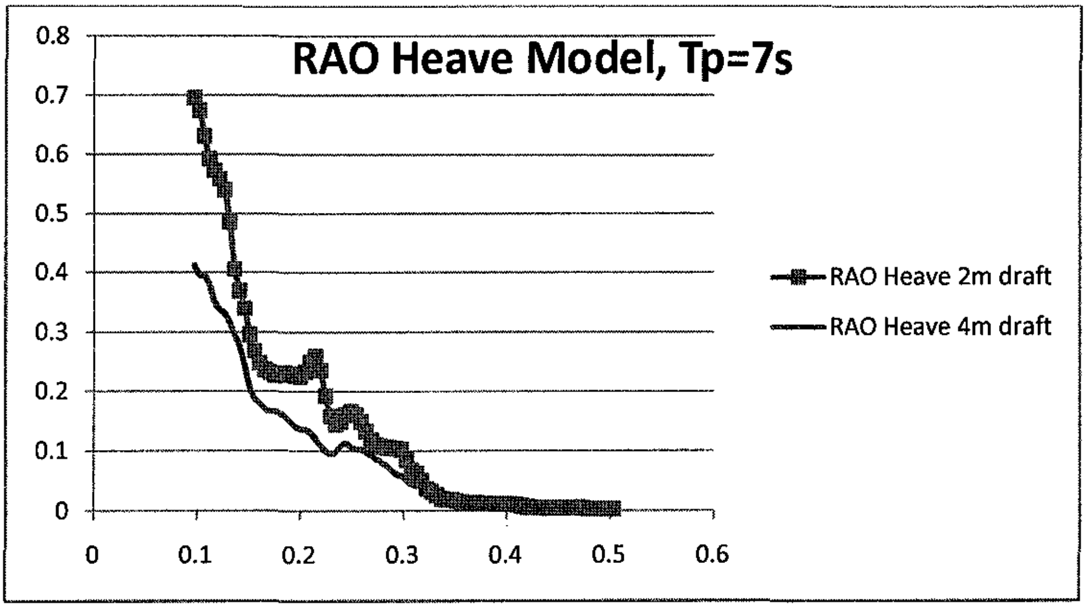

Figure 4.20: Model Test Heave RAO Spectrum for varying barge draft at Tp=7s

Based on observation of the graphs above, it can be seen that model tests are able to validate the theoretical analysis which indicate that the RAOs for surge & heave for 2m barge drafts are higher than that of 4m drafts. As explained before, the mass contribution of the water body to the barge improves the stability as the draft increases. Critical peak frequencies of the RAOs once again show consistency of falling in the 0.1 – 0.15Hz region.

The analysis is repeated for a Tp=8s to verify the consistency of the results which indicate that 2m draft should yield a higher RAO than 4m drafts

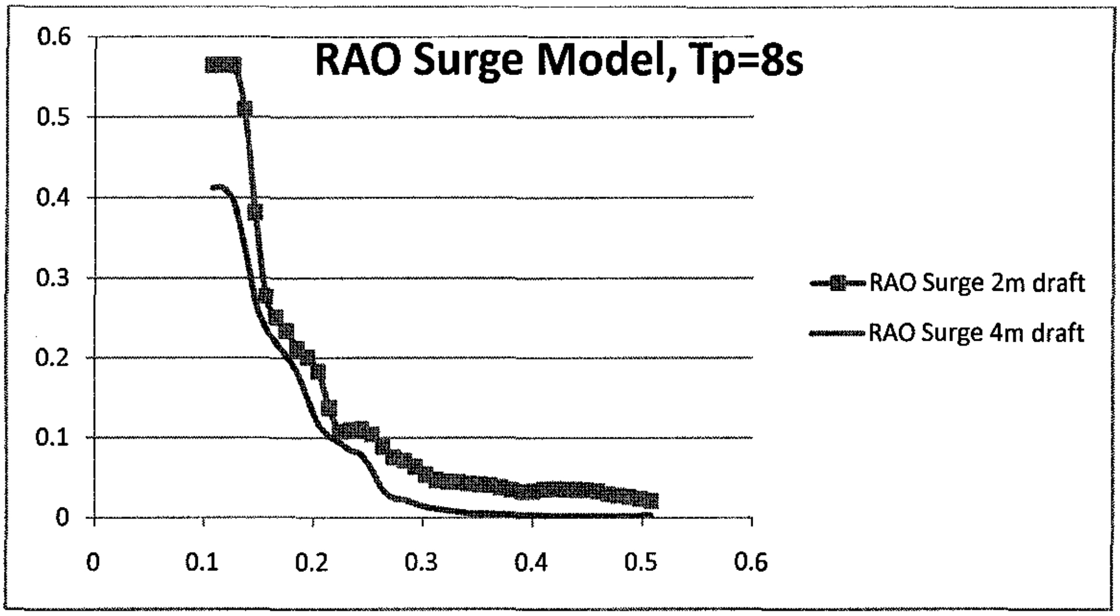

Figure 4.21: Model Test Surge RAO Spectrum for varying barge draft at Tp=8s

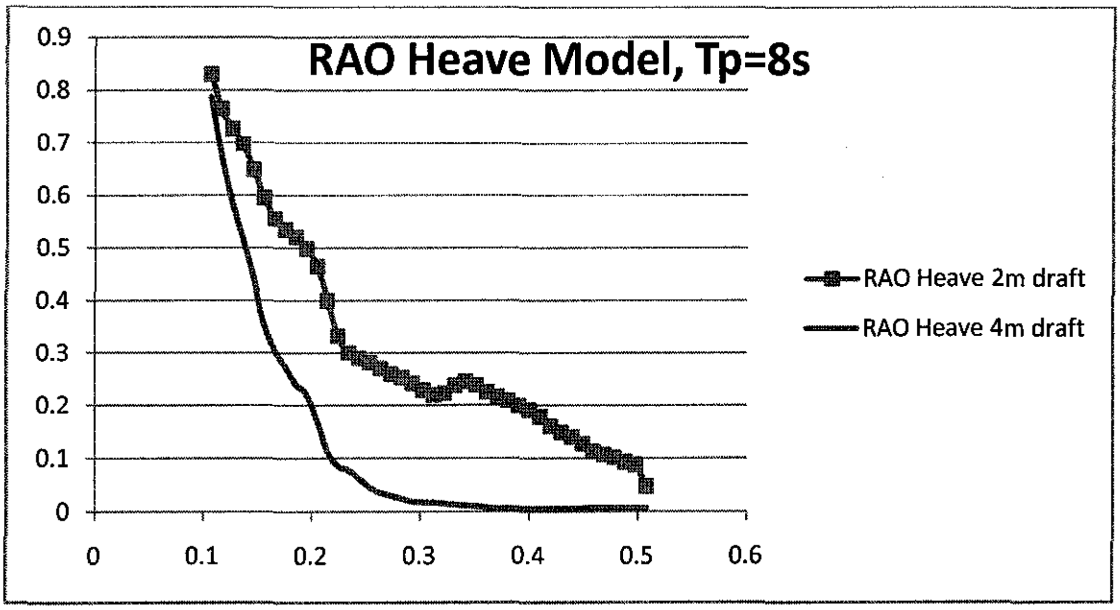

Figure 4.21: Model Test Heave RAO Spectrum for varying barge draft at Tp=8s

Similarly as predicted, the RAOs for 2m drafts are larger than that of 4m drafts. It is also observed that peak RAOs for differing barge drafts still maintains itself in the 0.1Hz region.

4.2 Discussion

Based on the theoretical results obtained above we can infer the following:

4.2.1 Varying Wave Heights

a) The increase in significant wave height, Hs increases the energy density of the JONSWAP spectrum (higher peak energy density). However it is noticed that the critical/peak frequency range is similar across the wave heights (considering the same peak period, Tp)

b) Due to the nature of the model RAO formula which is $\sqrt{S_R/S(f)}$ the increased wave height is which contributes to the *S(f)* component is offset proportionally by the barge motions S_R, thus resulting in no change to the RAO values. This proves the theoretical RAO analysis correct whereby it predicted zero change in spectrum shape as wave height increases, thus concluding that wave height does not play a role in affecting the barge's RAO.

4.2.2 Varying Peak Periods

a) Increment in peak periods, Tp will results a shift of the spectrum further into the lower frequency region but will however have higher energy density peaks but at smaller frequency ranges (narrow band). The total energy density is the same for similar significant wave heights

b) RAOs which reflect the ratio of the motion response against the wave heights (higher RAOs indicate more critical conditions), are seen to be critical in the 0.1Hz region for surge & heave motions. This is concurrent with the JONSWAP spectrum which indicates peak densities at approximately the 0.1 – 0.2Hz region.

c) There is however no change in the RAO spectrums as the peak period, Tp increases in value based on theoretical analysis. This theoretical conclusion was proven by model tests which vary marginally between Tp=7s &Tp=8s. This marginal variation is suspected due to elements in the experiment that attributed to a certain degree of error, such as:

i. Due to the insufficient length of the wave tank (experimental setup limitations), waves that reach the wave attenuator at the end of the wave tank may be partially reflected back on to the barge.

ii. Due to limitation of time between experiments, a 10 minute window was allowed for the waves in the tank to "settle down" to an allowable wave height (perceived calmness of water). However this may be insufficient as the remaining waves in the tank may result in the next set of experiments having its waves interfered with the previous sets'.

iii. Although minor, due to the building in which the wave tank is located in is not entirely air tight, gust from outside the building can enter through doors & windows & thus causing small amplitude waves to occur on the water surface.

iv. This therefore could explain the anomalous results for the Heave RAO spectrum at Tp=8s for 2m barge draft

4.2.3 Varying Barge Drafts

a) The biggest deduction from the variation of barge drafts is that the increase in barge drafts from 2m to 4m will result in the reduction of RAO values. This is due to the added mass induced by the water body as the draft increases, thus providing additional stability by inertial means. This is seen across model results for both Tp=7s &Tp=8s thus further consolidating the consistency of the conclusion.

b) Model results show consistently that for varying barge drafts, the critical peak RAO frequency still falls within the 0.1Hz region.

c) There is however an observed anomaly in the theoretical results which indicated the increase of RAO as the barge depth increases. This could be attributed to the following possible reasons:

  i. The fact that the natural period & damping ratio of the barge in heave direction could not be accurately determined via decay tests. Thus as such, these values affected the theoretical calculation of the RAO which involved the damping ratio term, C.

ii. Heave motions at the peak period of Tp=7s &Tp=8s are very close to the barge's natural frequency & therefore it could result in resonance occuring.

Draft	Weight (M.kg)	Added Mass(M.kg)	Total mass (M.kg)	Stiffness,K
2.00	**9.8719824**	**9.8719824**	**19.7439648**	**48.4055381**
4.00	**19.7439648**	**19.7439648**	**39.4879296**	**48.4055381**

For 2m draft, barge natural frequency = $\sqrt{\frac{k}{m}} = \sqrt{\frac{48.4055381}{19.7439648}} = 1.57\ rad/s$

Therefore, barge period, $T_n = \frac{2\pi}{1.57} = 4.0s$(0.125Hz)

For 4m draft, barge natural frequency = $\sqrt{\frac{k}{m}} = \sqrt{\frac{48.4055381}{39.4879296}} = 1.11\ rad/s$

Therefore, barge period, $T_n = \frac{2\pi}{1.11} = 5.7s$(0.175Hz)

Basing on a Tp=7s (0.142Hz) &Tp=8s (0.125Hz), it can be said that the peak periods correspond very closely to the natural frequency of the structure at a 4m barge depth thus possibly causing resonance & a higher resultant RAO.

5.0 Conclusion

5.1 Introduction

In this report presented herein, both theoretical & model test results have been presented for the heave & surge motions in:

a) one direction (180deg),
b) Hs=2.0m,
c) Tp=7s &Tp=8s
d) draft of 2.0m& 4.0m

These theoretical results have been ascertained based on the Froude –Krylov Theory for force calculations & the corresponding RAOs calculated. The theoretical results have been compared against the experimental/modeling results to confirm the theories & assumptions. Based on the findings, several conclusions can be made with certainty due to consistency of the results obtained.

Based on the aforementioned report, we find that initial conclusions indicate that part of the objectives of this research has been achieved. Among the initial progress & conclusions obtained are:

a) Numerical analysis has been completed
b) Analysis of model test results have been conducted& analyzed

5.2 Conclusion from Results/Discussion

Findings based on analysis have yielded the following:

a) Significant wave heights do not play any role in inducing higher RAO values. This is due to the fact that increased wave heights will ultimately result in larger barge motions
b) Peak periods do not play any role in inducing higher RAO spectrum valuesThe change in peak period will result in the change of the resultant force upon the barge as well as peak frequencies, ω_0. These two values will offset each other in the RAO equation, resulting in no changes of the spectrum peaks& content

c) By far the dominant factor in causing changes in the barge's RAO is the barge draft. An increase of barge draft from 2m to 4m has seen the RAO drop significantly, thus concluding that draft control during mating motions are very critical to the floatover process. Optimization of barge drafts while avoiding water spillage on to the barge will allow the floatover vessel to mate with the jacket legs with minimum motions (can be predicted through the RAO)

d) Peak RAO frequencies for most factors are averaging around the frequencies of 0.1Hz – 0.15Hz. These values are concurrent with the current values obtained for the Caspian Seas. Waves that induce such frequencies should be avoided altogether as they induce large motions in the barge. Knowledge of peak RAOs will aid the forecasting of weather conditions using ARIMA modeling (not covered in this report)& therefore aid a safe floatover installation.

5.3 Recommendations for Future Research

It is also concluded that the current parameters of the model tests do not cover the entirety of this model setup's parameters. Due to time constraints of the research timeline, parameters are limited to the aforementioned parameters.

Based on the results of this report herein, there are several recommendations that are proposed for future reliability of results as well as correlation between the multiple variables present in the experiment

a) Varying the draft of the barge (to simulate different loading stages)
b) Varying the significant wave height & peak period
c) Varying the barge's directionality at 22.5°, 45°, 90°, 135°& 157.5°
d) Mooring line tension
e) Water depth
f) To improve the reliability, the experimental results should also be compared against theoretical forces calculated using the Pressure Area method on top of the existing Froude – Krylov method.

6.0 References

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7.0 Appendix

Theoretical Analysis (Tp=7.0s, 2m draft)

		2m draft			
		Surge		Heave	
f	**S(f), Hs=2m**	**Surge, RAO_{FK}**	**Surge, S_{surge}**	**Heave, RAO_{FK}**	**Heave, S_{heave}**
0.005	0.000000	0	0	0	0
0.015	0.000000	0	0	0	0
0.025	0.000000	0	0	0.090442554	0
0.035	0.000000	9.703319114	4.2771E-145	0.154503617	1.0844E-148
0.045	0.000000	3.883040106	6.65628E-51	0.242946127	2.6056E-53
0.055	0.000000	1.213551534	6.41071E-22	0.302471034	3.98251E-23
0.065	0.000000	0.112353847	2.63024E-12	0.311869533	2.02659E-11
0.075	0.000034	0.629908001	1.34041E-05	0.24521163	2.03125E-06
0.085	0.011792831	0.562853113	0.003736012	0.115883868	0.000158367
0.095	0.243064771	0.1555392	0.005880331	0.007785952	1.47348E-05
0.105	1.21428308	0.187703162	0.042782201	0.026895637	0.000878382
0.115	2.846306809	0.181448109	0.093710144	0.135696324	0.052410449
0.125	4.364400154	0.005478505	0.000130993	0.164854948	0.118611975
0.135	5.226832533	0.04832701	0.012207267	0.102941925	0.055388953
0.145	5.39898569	0.027522103	0.004089549	0.063107829	0.02150199
0.155	5.0958617	0.003401482	5.89595E-05	0.021830916	0.002428631
0.165	4.550275971	0.060006712	0.016384659	0.059141587	0.015915625
0.175	3.927310121	0.010116553	0.000401939	0.146365346	0.084134036
0.185	3.321058243	0.032655787	0.003541578	0.020484534	0.00139357
0.195	2.775635976	0.033228007	0.003064581	0.016166695	0.000725446
0.205	2.305751561	0.007190472	0.000119214	0.071687709	0.011849551
0.215	1.910904272	0.003784184	2.73642E-05	0.010022625	0.000191956
0.225	1.583805817	0.008991513	0.000128046	0.008871747	0.000124658
0.235	1.314910346	0.011169284	0.000164039	0.029636035	0.001154879
0.245	1.094639853	0.008315159	7.56854E-05	0.018541188	0.000376311
0.255	0.914347476	0.00236041	5.09432E-06	0.063672125	0.003706892
0.265	0.766632621	0.001841323	2.59925E-06	0.054453429	0.002273201
0.275	0.645346869	7.07051E-05	3.22623E-09	0.005777911	2.15444E-05
0.285	0.545468911	0.002107915	2.42369E-06	0.026541763	0.000384264
0.295	0.462937729	0.001539558	1.09727E-06	0.008134869	3.06354E-05
0.305	0.394485811	0.002875944	3.26281E-06	0.001988982	1.56061E-06
0.315	0.337489758	0.001777958	1.06685E-06	0.00736557	1.83094E-05
0.325	0.289843664	0.000705054	1.44081E-07	0.006019102	1.05009E-05
0.335	0.249855024	0.000401573	4.02919E-08	0.004469177	4.99049E-06
0.345	0.216160723	0.000194946	8.21496E-09	0.005660381	6.92577E-06
0.355	0.18765993	3.75517E-05	2.64625E-10	0.001392413	3.63838E-07
0.365	0.163460833	0.000358391	2.09956E-08	0.004285422	3.00193E-06

0.375	0.142838481	0.000553966	4.3834E-08	3.34895E-05	1.602E-10
0.385	0.125201446	0.000739748	6.85136E-08	0.000607673	4.62327E-08
0.395	0.110065459	0.000290842	9.31033E-09	0.001715669	3.2398E-07
0.405	0.097032518	0.000234044	5.31513E-09		
0.415	0.085774305	0.000242172	5.03041E-09		
0.425	0.076018992	0.000467645	1.66247E-08		
0.435	0.067540703	8.54669E-05	4.93357E-10		
0.445	0.060151077	0.00052717	1.67165E-08		
0.455	0.053692492	0.000266498	3.8133E-09		
0.465	0.0480326	0.000108143	5.61733E-10		
0.475	0.043059907	0.000113575	5.55445E-10		
0.485	0.038680185	0.000193602	1.44979E-09		
0.495	0.03481355	1.11443E-05	4.32368E-12		

Theoretical Analysis (Tp=7.0s, 4m draft)

4m draft			
Surge		Heave	
Surge, RAO_{FK}	**Surge, S_{surge}**	**Heave, RAO_{FK}**	**Heave, S_{heave}**
0	0	0.002602895	0
0	0	0.065460147	0
0	0	0.176321355	0
9.589452658	4.177E-145	0.30378697	4.1922E-148
3.824600353	6.4574E-51	0.483062505	1.03014E-52
1.190569684	6.1702E-22	0.610259067	1.62113E-22
0.109700945	2.5075E-12	0.640722922	8.55382E-11
0.611640144	1.2638E-05	0.515063401	8.96197E-06
0.543100913	0.0034784	0.250065487	0.000737438
0.14902296	0.00539794	0.017366698	7.33089E-05
0.178446272	0.0386665	0.062547434	0.004750496
0.171045134	0.0832728	0.333156369	0.315920606
0.005118188	0.00011433	0.435417109	0.827438153
0.044718756	0.01045245	0.300862839	0.47312477
0.02521679	0.00343314	0.21347699	0.246044873
0.003084492	4.8482E-05	0.092058676	0.043186408
0.053710056	0.0131265	0.349238593	0.554986215
0.008946083	0.00031431	0.2232	0.195651678
0.028515659	0.00270049	0.097484494	0.031560769
0.02863804	0.0022764	0.038045042	0.004017526
0.006113926	8.6189E-05	0.092955547	0.019923385
0.003173094	1.924E-05	0.007529318	0.00010833
0.007432444	8.7491E-05	0.003853162	2.35145E-05
0.009098501	0.00010885	0.007169987	6.75979E-05
0.006673222	4.8746E-05	0.002591243	7.35E-06

0.001865803	3.183E-06	0.007964516	5.80003E-05
0.001433285	1.5749E-06	0.008539838	5.59096E-05
5.41885E-05	1.895E-09	0.001112367	7.98527E-07
0.001590416	1.3797E-06	0.005884514	1.88882E-05
0.001143462	6.0529E-07	0.001981756	1.81812E-06
0.002102614	1.744E-06	0.000515597	1.0487E-07
0.001279552	5.5256E-07	0.001986586	1.33191E-06
0.000499503	7.2317E-08	0.001661807	8.00433E-07
0.000280092	1.9601E-08	0.001247746	3.88992E-07
0.000133883	3.8746E-09	0.001583115	5.41754E-07
2.53976E-05	1.2105E-10	0.000387243	2.81409E-08
0.000238761	9.3184E-09	0.001178053	2.26852E-07
0.000363613	1.8885E-08	9.0555E-06	1.17131E-11
0.000478532	2.867E-08	0.000160969	3.24408E-09
0.000185477	3.7864E-09	0.000443697	2.16682E-08
0.000147192	2.1023E-09		
0.000150253	1.9364E-09		
0.000286352	6.2334E-09		
5.16709E-05	1.8033E-10		
0.000314811	5.9613E-09		
0.000157268	1.328E-09		
6.30942E-05	1.9121E-10		
6.55432E-05	1.8498E-10		
0.000110563	4.7284E-10		
6.3012E-06	1.3823E-12		

Model Tests Analysis (Tp=7.0s, 2m draft)

		2m draft			
		Surge		Heave	
f	**S(f)**	**Surge, RAO**	**Surge, S_{surge}**	**Heave, RAO**	**Heave, S_{heave}**
0.004882813	0.012065	1.615346427	0.031482154	2.025260681	0.049487435
0.009765625	0.012065	1.615346427	0.031482154	2.025260681	0.049487435
0.014648438	0.012065	1.615346427	0.031482154	2.025260681	0.049487435
0.01953125	0.012065	1.493948549	0.026928016	2.025260681	0.049487435
0.024414063	0.012065	1.215301871	0.017819742	2.025260681	0.049487435
0.029296875	0.013246	1.129407978	0.016895546	2.125733395	0.059853303
0.034179688	0.015606	1.244102878	0.024155428	2.272354756	0.080585039
0.0390625	0.017352	1.265429094	0.027785369	3.996640782	0.277160141
0.043945313	0.018481	1.226143306	0.027785369	5.928557044	0.649578611
0.048828125	0.019046	1.191124313	0.027022321	6.624357895	0.835787846
0.053710938	0.019046	1.157000928	0.025496225	6.361253435	0.770715107
0.05859375	0.017226	1.102229633	0.020928591	5.54956532	0.530534652
0.063476563	0.013587	0.990106138	0.013319417	4.024641506	0.220077745

0.068359375	0.011767	0.853624268	0.008574448	2.227530907	0.058387536
0.073242188	0.012066	0.744807188	0.006693683	1.510292247	0.027523231
0.078125	0.012665	0.673999152	0.0057533	1.170105226	0.017339964
0.083007813	0.012964	0.666175927	0.0057533	0.848101435	0.009324698
0.087890625	0.013055	0.663860437	0.0057533	0.719792701	0.006763607
0.092773438	0.013236	0.642339794	0.005461089	0.703137139	0.006543795
0.09765625	0.013326	0.604930562	0.004876667	0.695598596	0.006448065
0.102539063	0.013273	0.562823058	0.004204349	0.674466836	0.006037765
0.107421875	0.013165	0.511482086	0.003444137	0.632014991	0.005258651
0.112304688	0.013111	0.48342163	0.003064031	0.592608194	0.004604434
0.1171875	0.013111	0.48342163	0.003064031	0.572437557	0.004296326
0.122070313	0.013111	0.48342163	0.003064031	0.558350284	0.004087469
0.126953125	0.013111	0.48342163	0.003064031	0.539637247	0.003818078
0.131835938	0.013288	0.475742315	0.003007543	0.4851169	0.003127239
0.13671875	0.013642	0.460622455	0.002894567	0.405247826	0.002240448
0.141601563	0.01382	0.45317365	0.002838079	0.368788508	0.001879533
0.146484375	0.016071	0.412486557	0.00273446	0.33955951	0.001853035
0.151367188	0.020575	0.350472185	0.00252722	0.295782908	0.00180004
0.15625	0.022827	0.325844428	0.0024236	0.26876303	0.001648844
0.161132813	0.022827	0.311516647	0.002215149	0.247604199	0.001399447
0.166015625	0.022827	0.280675401	0.001798246	0.236315416	0.001274749
0.170898438	0.022827	0.263906633	0.001589795	0.232377462	0.001232618
0.17578125	0.022278	0.265458206	0.001569919	0.227036598	0.001148356
0.180664063	0.021182	0.268771788	0.001530167	0.228526232	0.001106225
0.185546875	0.020634	0.266718215	0.001467882	0.231541552	0.001106225
0.190429688	0.020409	0.260318722	0.001383063	0.229924305	0.001078949
0.1953125	0.01996	0.252128866	0.001268843	0.226543979	0.001024396
0.200195313	0.019735	0.238778856	0.001125223	0.224776156	0.000997119
0.205078125	0.018744	0.237067029	0.001053412	0.232628446	0.001014336
0.209960938	0.01676	0.250702094	0.001053412	0.250148856	0.001048768
0.21484375	0.015769	0.258465338	0.001053412	0.260003112	0.001065984
0.219726563	0.019131	0.234654174	0.001053412	0.23605028	0.001065984
0.224609375	0.025856	0.205617146	0.001093163	0.192169683	0.000954852
0.229492188	0.029013	0.201043191	0.001172665	0.157986718	0.000724163
0.234375	0.028602	0.205887038	0.001212416	0.144375207	0.000596182
0.239257813	0.026583	0.213563437	0.001212416	0.148696313	0.000587758
0.244140625	0.022956	0.228307953	0.00119655	0.160012867	0.000587758
0.249023438	0.021142	0.234722522	0.001164816	0.165678513	0.000580337
0.25390625	0.022132	0.22491564	0.001119585	0.159847309	0.000565495
0.258789063	0.025424	0.20427286	0.001060858	0.14815892	0.000558074
0.263671875	0.030922	0.182641136	0.001031494	0.132496719	0.00054285
0.268554688	0.036003	0.169262734	0.001031494	0.117513345	0.000497185
0.2734375	0.037888	0.163190888	0.001009006	0.109166902	0.000451527
0.278320313	0.038115	0.159037315	0.000964031	0.106991976	0.00043631
0.283203125	0.038933	0.155511298	0.000941543	0.105861853	0.00043631
0.288085938	0.039889	0.153046077	0.000934325	0.104585355	0.00043631

0.29296875	0.040254	0.146114871	0.0008594	0.104110451	0.00043631
0.297851563	0.040254	0.134777177	0.000731205	0.102197641	0.000420425
0.302734375	0.05412	0.111324958	0.000670717	0.084743158	0.000388654
0.307617188	0.081851	0.090522672	0.000670717	0.067340361	0.000371172
0.3125	0.095717	0.082060112	0.000644544	0.062003605	0.000367978
0.317382813	0.132558	0.066839224	0.000592199	0.050426342	0.00033707
0.322265625	0.206239	0.052388104	0.000566026	0.036743862	0.000278446
0.327148438	0.24308	0.048255153	0.000566026	0.031969569	0.000248441
0.33203125	0.35862	0.03972842	0.000566026	0.026246963	0.000247054
0.336914063	0.589699	0.029625557	0.000517563	0.020439522	0.000246361
0.341796875	0.705238	0.024422246	0.000420637	0.018690369	0.000246361
0.346679688	0.711315	0.022873979	0.000372173	0.018653184	0.000247496
0.3515625	0.909386	0.020230121	0.000372173	0.016572666	0.000249766
0.356445313	1.287299	0.01757255	0.000397511	0.014065423	0.000254674
0.361328125	1.514258	0.017203983	0.000448186	0.013253076	0.00026597
0.366210938	1.59634	0.017222958	0.000473523	0.013178545	0.000277243
0.37109375	1.678067	0.016798321	0.000473523	0.012940254	0.000280993
0.375976563	1.759437	0.016349684	0.000470319	0.012694825	0.000283548
0.380859375	1.909484	0.015586884	0.000463911	0.01229519	0.00028866
0.385742188	2.128207	0.014713141	0.000460707	0.011697698	0.000291216
0.390625	2.237569	0.014556799	0.000474142	0.01150537	0.000296195
0.395507813	2.237569	0.014963585	0.000501012	0.011697185	0.000306153
0.400390625	2.237569	0.015162885	0.000514446	0.011542298	0.000298099
0.405273438	2.237569	0.015093663	0.00050976	0.01102611	0.000272033
0.41015625	2.284274	0.014800589	0.000500387	0.010197515	0.00023754
0.415039063	3.013283	0.012112021	0.000442052	0.008036658	0.000194621
0.419921875	4.331186	0.008791425	0.000334754	0.006322999	0.000173162
0.424804688	4.966785	0.007523092	0.000281105	0.005872532	0.000171288
0.4296875	5.6347	0.007125014	0.00028605	0.005452832	0.000167539
0.434570313	6.970529	0.00651583	0.000295941	0.004875076	0.000165664
0.439453125	8.018816	0.006125567	0.000300887	0.004630304	0.000171921
0.444335938	8.779559	0.005854166	0.000300887	0.004583375	0.000184435
0.44921875	9.159931	0.005731328	0.000300887	0.004562681	0.000190692
0.454101563	9.099044	0.005735202	0.000299291	0.004681038	0.000199379
0.458984375	8.97727	0.005743098	0.000296099	0.004913732	0.000216754
0.463867188	8.916383	0.005747123	0.000294503	0.005057794	0.000228093
0.46875	8.916383	0.005747123	0.000294503	0.005116243	0.000233395
0.473632813	11.85952	0.004974733	0.000293499	0.004461333	0.000236046
0.478515625	17.74579	0.00405289	0.000291491	0.003619299	0.000232458
0.483398438	20.73214	0.003743185	0.000290487	0.003221076	0.000215103
0.48828125	20.81856	0.003735407	0.000290487	0.003030187	0.000191157
0.493164063	20.93201	0.003730775	0.000291346	0.002940405	0.000180978
0.498046875	21.07249	0.003729266	0.000293064	0.002930587	0.000180978
0.502929688	21.14273	0.003728519	0.000293923	0.002925716	0.000180978

Model Tests Analysis (Tp=7.0s, 4m draft)

	4m draft			
	Surge		Heave	
S(f)	**Surge, RAO**	**Surge, S_{surge}**	**Heave, RAO**	**Heave, S_{heave}**
0.014002	1.19368181	0.01995121	1.858435464	0.048360084
0.013796	1.202577894	0.01995121	1.872285718	0.048360084
0.013383	1.220983544	0.01995121	1.900941356	0.048360084
0.013176	1.181192663	0.018384046	1.915771546	0.048360084
0.013176	1.075798914	0.015249718	2.086896202	0.057385386
0.013193	1.163296405	0.017853557	2.391207712	0.07543599
0.013226	1.407338343	0.026195563	4.569891284	0.276211935
0.014132	1.465874097	0.030366567	6.832449328	0.659713222
0.015911	1.381507859	0.030366567	7.315409226	0.851463865
0.0168	1.206339003	0.024448341	6.707893177	0.755932362
0.0168	0.86643258	0.012611891	5.798540255	0.564869357
0.01673	0.585918907	0.005743386	4.674344985	0.365539681
0.01659	0.481291362	0.003842827	3.029156873	0.152222284
0.016519	0.404582044	0.002704003	1.393421352	0.032074423
0.014901	0.392672032	0.002297672	1.037510128	0.016040314
0.011666	0.419269119	0.002050645	0.875980006	0.008951446
0.010048	0.448534269	0.002021404	0.759572979	0.005796968
0.011356	0.405465482	0.001866991	0.578961007	0.003806563
0.013974	0.330893629	0.00152997	0.465337224	0.00302581
0.015282	0.293803878	0.001319168	0.412257932	0.002597306
0.014468	0.293328222	0.001244816	0.39566102	0.002264874
0.012839	0.299614223	0.0011525	0.394348198	0.00199653
0.012024	0.297232422	0.001062287	0.379491676	0.001731626
0.012024	0.27601761	0.000916058	0.351043018	0.001481734
0.012024	0.25070844	0.000755766	0.339150057	0.001383036
0.011712	0.244065299	0.000697648	0.33164747	0.001288183
0.011087	0.247443815	0.000678865	0.316215704	0.001108656
0.011194	0.239350733	0.000641298	0.295336323	0.000976392
0.012032	0.22746056	0.000622515	0.275396658	0.000912546
0.014306	0.201019304	0.000578086	0.243151518	0.000845806
0.018118	0.164324823	0.000489228	0.205940254	0.0007684
0.020176	0.148477583	0.000444799	0.187318564	0.000707952
0.020278	0.148104581	0.000444799	0.179015023	0.000649839
0.020278	0.148803901	0.000449009	0.170109635	0.000586793
0.019899	0.152354106	0.000461892	0.166160493	0.000549399
0.019141	0.15753489	0.000475027	0.16612237	0.000528228
0.018762	0.159863751	0.000479489	0.163167512	0.000499513
0.019175	0.158133316	0.000479489	0.157436301	0.000475272
0.020283	0.153751978	0.000479489	0.149456673	0.000453073
0.021261	0.150173489	0.000479489	0.141009167	0.000422754

0.021544	0.143617577	0.000444369	0.136917546	0.000403874
0.021544	0.131778721	0.000374127	0.135650798	0.000396436
0.021544	0.125440992	0.000339006	0.130268099	0.000365598
0.021544	0.125440992	0.000339006	0.120217843	0.000311362
0.023672	0.120027539	0.00034104	0.109249526	0.000282541
0.027929	0.111159932	0.000345107	0.099643094	0.000277301
0.030057	0.10746738	0.000347141	0.09511562	0.00027193
0.027274	0.112818069	0.000347141	0.098902696	0.000266787
0.021707	0.126459994	0.000347141	0.108983898	0.000257825
0.019352	0.133935214	0.000347141	0.112276113	0.000243945
0.020208	0.128116424	0.000331686	0.10664845	0.000229841
0.020839	0.120139257	0.000300777	0.103669131	0.000223962
0.021245	0.115888248	0.000285322	0.102098548	0.00022146
0.021448	0.115338371	0.000285322	0.098689988	0.000208898
0.022424	0.112800118	0.000285322	0.092210301	0.000190667
0.024376	0.108188951	0.000285322	0.086381362	0.00018189
0.026742	0.103293744	0.000285322	0.081154479	0.000176122
0.02952	0.098313078	0.000285322	0.074943445	0.000165798
0.034637	0.088608699	0.000271952	0.067896017	0.000159671
0.042093	0.076324614	0.00024521	0.061216361	0.000157741
0.045821	0.071131437	0.00023184	0.058002	0.000154152
0.055402	0.064689007	0.00023184	0.051843316	0.000148906
0.074564	0.056239996	0.000235843	0.044282609	0.000146217
0.084718	0.053650355	0.000243849	0.041525635	0.000146086
0.085863	0.05372714	0.000247852	0.040865408	0.000143389
0.160318	0.039214119	0.000246529	0.029352757	0.000138128
0.308084	0.028135528	0.000243881	0.020736805	0.000132481
0.40972	0.024331216	0.000242558	0.017567632	0.000126449
0.493237	0.022175829	0.000242558	0.015800796	0.000123144
0.652904	0.019551675	0.000249584	0.013701304	0.000122567
0.901061	0.017105128	0.000263637	0.01158597	0.000120954
1.113669	0.015589675	0.000270664	0.010230996	0.000116571
1.255901	0.014680381	0.000270664	0.009434215	0.000111781
1.640797	0.01290376	0.000273204	0.008089165	0.000107365
2.188959	0.011275255	0.000278285	0.006826207	0.000101999
2.426101	0.010758807	0.000280826	0.006398169	9.93163E-05
2.426101	0.010758807	0.000280826	0.006360009	9.81351E-05
2.426101	0.010758807	0.000280826	0.006282993	9.57728E-05
2.42694	0.010756948	0.000280826	0.006240402	9.45114E-05
2.428616	0.010406437	0.000263004	0.006232949	9.43509E-05
2.429454	0.009673954	0.000227361	0.006229223	9.42706E-05
2.615949	0.008949912	0.00020954	0.005922253	9.17494E-05
2.988938	0.008372881	0.00020954	0.005386023	8.67069E-05
3.197049	0.008095781	0.00020954	0.005131499	8.41856E-05
3.356339	0.007838053	0.000206197	0.00500825	8.41856E-05
3.610072	0.007434049	0.000199511	0.004829042	8.41856E-05

4.566755	0.006554056	0.000196168	0.00426675	8.31385E-05
6.453859	0.005513206	0.000196168	0.003543655	8.10443E-05
7.706196	0.005039874	0.00019574	0.003221939	7.99972E-05
7.912052	0.00496299	0.000194884	0.003114279	7.67369E-05
7.912052	0.004957537	0.000194456	0.002979028	7.02163E-05
7.978181	0.004936949	0.000194456	0.002878776	6.6118E-05
8.11044	0.005131502	0.000213567	0.002818783	6.44418E-05
8.17657	0.005549222	0.000251788	0.002788083	6.35598E-05
10.41972	0.005098891	0.000270899	0.002468102	6.3472E-05
14.90601	0.004263075	0.000270899	0.002062814	6.34281E-05
18.59595	0.003796953	0.000268095	0.00185337	6.38767E-05
21.48954	0.003438711	0.000254108	0.00173615	6.47741E-05
23.54478	0.003156214	0.000234546	0.001664379	6.52228E-05
24.76169	0.002978491	0.000219671	0.001604945	6.37824E-05
25.37014	0.002854224	0.00020668	0.001549362	6.09016E-05
25.47024	0.002788781	0.00019809	0.001522038	5.90044E-05
25.67044	0.002748349	0.0001939	0.001504307	5.80907E-05