Effect of Mooring Lines on the Responses of Spar Platforms

by

Nur Azimah Mohd Zin

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

JULY 2008

Universiti Teknologi PETRONAS
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CERTIFICATION OF APPROVAL

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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 acknowledgement, and that the original work contained herein have not been undertaken or done by unspecified sources or persons

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(NUR AZIMAH BINTI MOHD ZIN)

ABSTRACT

Spar platform, a competitive alternative structure for deepwater oil field development is modelled as a rigid body with six degree –of-freedom, connected to the sea floor by multi-component catenary mooring lines, which are attached to the spar platform at the fairleads. Since this spar platform is quite new in deepwater exploration, a lot of studies and researches still need to be done. Therefore in this project, the different type of spar platforms as well as the dynamic responses of spar platform such as surge, heave and pitch are being analyzed and compared by using comparison method based on its different mooring lines configurations. The mathematical results by using Linear Airy Wave Theory, Pierson-Moskowitz Spectrum, Morison Equation and Motion Response Spectrum have been conducted. The frequency domain analysis and time domain analysis have been performed by choosing frequency within 0.05 – 0.3Hz and time series within 0 – 100 seconds. For Neptune Spar Platform, the maximum profile obtained were 1.9 - 2m for surge, 0.78m for heave and 0.065radian for pitch. These values are within the permissible limits for offshore operations. Also, parametric studies have been made by using different number of mooring lines. It is shows that there is no significant effect on the surge and heave responses even though the stiffness increases as the number of mooring lines increases.

ACKNOWLEDGEMENT

In the name of ALLAH S.W.T. The Most Gracious and The Most Merciful for the blessings and strength to complete this project.

First and foremost, I would like to acknowledge my deepest gratitude to my inspired supervisor, Assoc. Prof. Dr. Kurian V. John for his extent guidance, constant attention, valuable suggestion and enthusiastic support as well as personal concern during one year of time completing this Final Year Project.

An enormous appreciation to Assoc. Prof. Ir Dr Hj Muhd Fadhil Nuruddin, the Programme Head of Civil Engineering Department for facilities and equipment provided in order to complete my project. Special thanks once again to Final Year Project Coordinators, Mr. Kalaikumar a/l Vallyutham and Ms. Niraku Rosmawati Ahmad for their excellent guidance to the Final Year students. Not to forget, an infinite gratitude to my internship supervisor, Ir. Abd Khalid Jaafar for his support and motivation that inspired me to complete this project.

Last but not least, special thanks to both of my beloved parents; Hj Mohd Zin Ismail and Hjh Samiah Hj Hasan and supportive brother, Khairul Anwar Hj Mohd Zin for being there all the time, giving continuous aspiration, encouragement and support for me to proceed with my Final Year Project.

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ABBREVIATIONS & NOMENCLATURES

CB	Center of Buoyancy
CG	Center of Gravity
FPS	Floating Production System
FPSO	Floating Production, Storage and Offloading
FYP1	Final Year Project 1
FYP2	Final Year Project 2
GoM	Gulf of Mexico
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HSA	Health Risk Assessment
HSE	Health, Safety and Environment
HSEM	Health, Safety and Environment Manual
PCSB	PETRONAS Carigali Sdn Bhd
PPE	Personal Protective Equipment
RAO	Response Amplitude Operations
SACS	Structural Analysis Computer System
TADU	Tender Assisted Drilling Unit
TLP	Tension Leg Platform

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND OF STUDY

Offshore exploration of oil and gas has started since nineteenth century back. Due to that many innovative structures or known as offshore structures have been constructed in order to support this activity that include exploration, drilling, production, storage and transportation of hydrocarbon. An offshore structure can be defined as one which has no fixed access to dry land and which is required to stay in position in all weather. This structure can be either fixed structure which is fixed to the seabed or free floating which need to be moored to the seabed by using mooring lines.

Rapid development of offshore industry has taken place since the last sixty years when the first fixed offshore platform was installed in Louisiana in 1947 to stand in 6.1m (20ft) water depth in the Gulf of Mexico (Chakrabarti, 2005). Since 1947, more than 10,000 offshore structures of various types and sizes have been constructed worldwide. Nowadays, due to the depletion of near shore resource, exploration and production of minerals are moving forward to the deeper water regions and more hostile environments. According to Chakrabarti (2005), 3% of the world's oil and gas supply came from deepwater (>350m) offshore production and this brings fixed structures become increasingly expensive and difficult to install as the water depths increase. Consequently, many oil and gas companies have taking initiatives to develop new alternatives in order overcome this challenge. Many innovative floating offshore structures are being proposed for cost savings such as spar platform, floating production systems (FPS), subsea system, floating, production, storage and offloading (FPSO), tension leg platform (TLP) and many more.

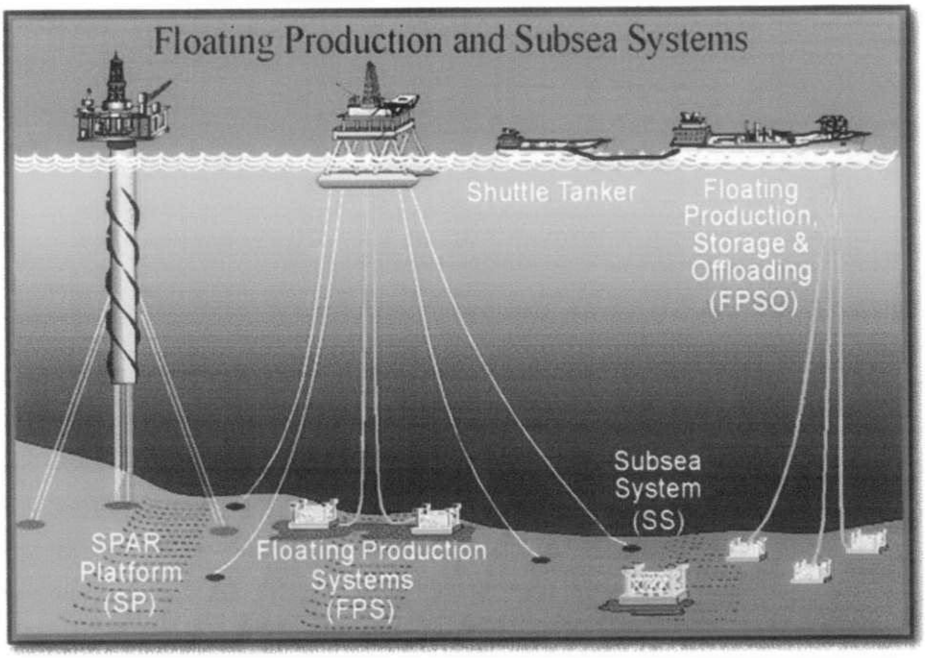
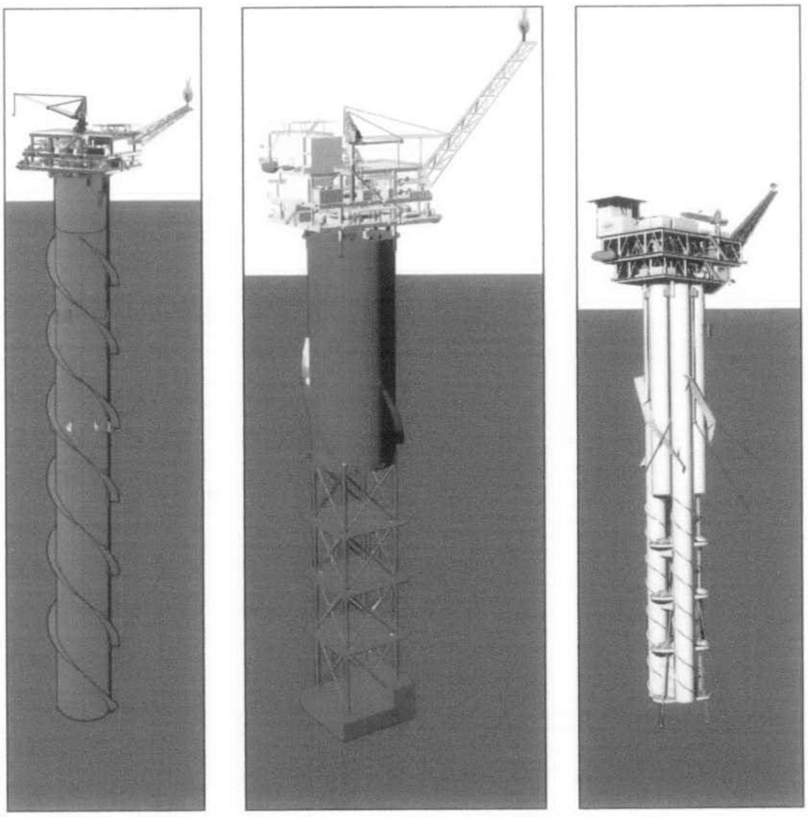


Figure 1.1 :- Floating Production and Subsea Systems (PETRONAS Carigali Sdn.Bhd, Presentation On Offshore Platform Design)

1.1.1 Spar Platform

One such type of floating structures that available is spar platform. It is one of such compliant offshore floating structure used for deep water applications such as drilling, production, processing, storage and offloading of ocean deposits. This spar platform is being considered as the next generation of deep water offshore structures by many oil companies. It is modelled as a rigid cylinder with six-degrees-of-freedom at its center gravity, connected to the sea floor by multi-component catenary mooring lines, which are attached to the Spar platform at the fairleads.

Historically, spars were used as marker buoys, for gathering oceanographic data, and for oil storage. But nowadays, spar with its concept as large deep draft and cylindrical floating Caisson is designed to support drilling, production, processing, storage and offloading operations of ocean's mineral. Its buoyancy is used to support facilities above the water surface. There are three types of production spars that have been built up to date : the "Classic" and "Truss" spars and recently the third generation cell spar (Finn and Maher, 2003).



(a) (b) (c)

Figure 1.2 :- (a) Classic Spar, (b) Truss Spar, (c) Cell Spar (Technip Offshore)

The shape of spar platforms is usually a long hollow cylinder with large diameter, which is normally moored by means of conventional spread chains. About 90 percent of the structure is submerged underwater.

The platform is designed as a rigid cylinder with six degrees-of-freedom. There are three displacement degrees-of-freedom consist of surge, sway and heave along X, Y and Z axis together with other three rotational degree-of-freedom which are roll, pitch and yaw about X, Y and Z also. Its stability and stiffness is depends on the number of mooring lines which attached near the spar's centre of gravity.

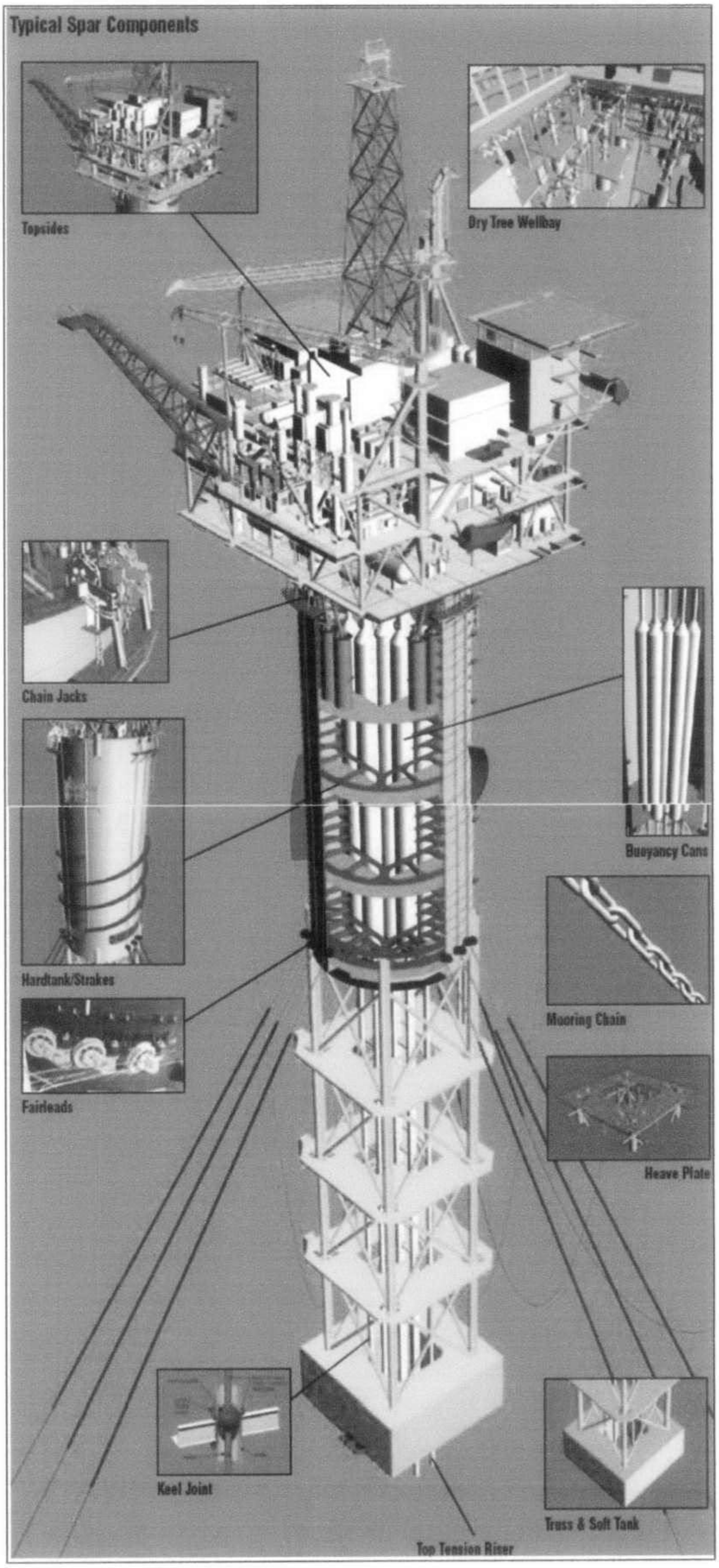


Figure 1.3 :- Typical Spar Components (Technip Offshore)

The first spar platform, Neptune was installed in 1996 by Oryx Energy (now a Kerr McGee subsidiary) and CNG (Vardeman et al, 1997). It is located in the Gulf of Mexico (GoM) at the water depths of 1930ft (588.25m). The world's deepest spar at the depth of 5610ft (1710m) is also located in the GoM which installed by Dominion Oil's Devil's Tower. Until today, there are 13 spar platforms that already installed in this world and another one is scheduled for delivery by this year. (Technip Offshore).

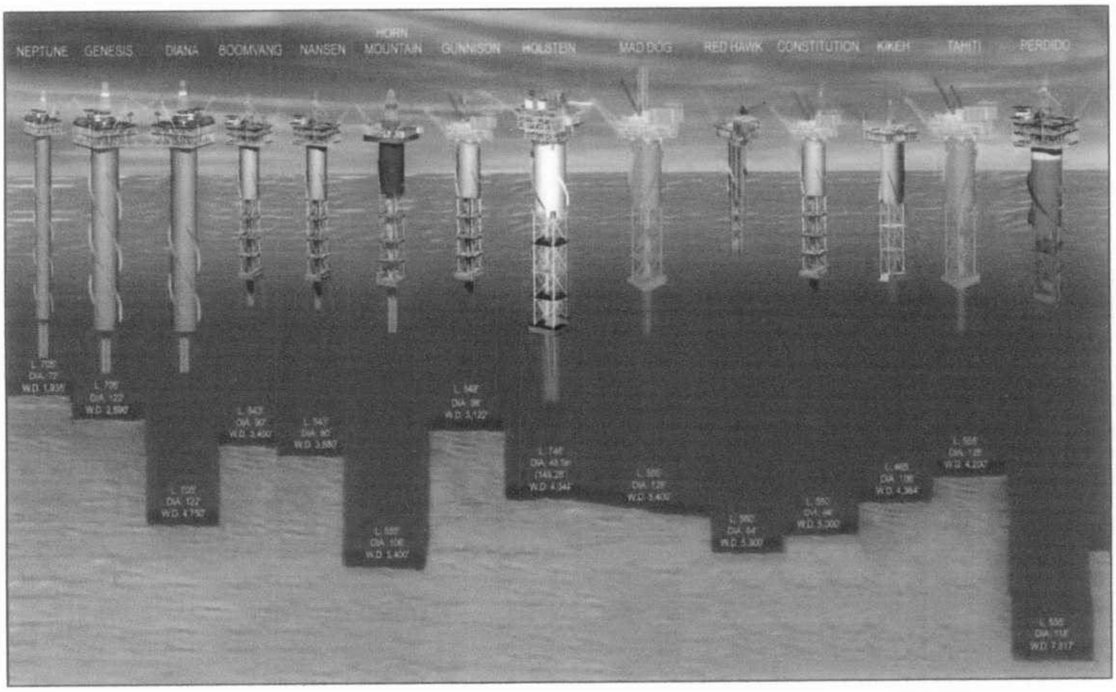


Figure 1.4 :- List of Spar Platform available in the world (Technip Offshore)

In Malaysia, the first spar platforms installed is in Kikeh field. Kikeh Spar Platform becomes the first Malaysia's spar platform as well as the first that ever installed outside the Gulf of Mexico. Located 120 km (75 miles) northwest of the island of Labuan, offshore Sabah, East Malaysia and lies in water depths of approximately 1,300 m (4,265 ft), this namely Block K is owned by Murphy Sabah Oil Company Ltd.(80% working interest) and its partner, Petronas Carigali Sdn Bhd (PCSB) which holds another 20% with Murphy as the operator. The Kikeh's truss spar platform which positioned in 4364ft of water is the premier application of a tender assist drilling unit (TADU) with a spar.

This Kikeh development – and its first deepwater discovery- has a recoverable reserve base in excess of 400 million barrels, consists of a Floating Production Storage and Offloading (FPSO) vessel which receives production from wells drilled from its truss spar dry tree unit (FMC Technologies). The specifications of Kikeh Spar Platform are as below;

- Hull – 142m long , 32m of diameter with weight – 13000MT
- Topsides with weight – 34000MT providing 25 slots wellbay for dry tree wellheads
- 10 legs of chainwire-chain in four groups, designed to handle 100-year conditions with a single mooring line failure
- Has riser / wellhead systems (Technip Offshore)

Figure 1.5 :- Kikeh Spar Platfrom (Technip Offshore)

1.2 PROBLEM STATEMENT

Recently, the depletion of near shore oil resources is quite a big issue and therefore, most of oil and gas companies starting doing research on other alternative, which is exploring the resources in deeper water depth or known as deepwater and ultra deepwater exploration and production. Deepwater and ultra deepwater oil operations are expected to increase by 200% ~ 300% over the next ten years.

Therefore many new researches are being done in order to enhance the deepwater and ultra deepwater technology for a better usage in the future. For offshore structures, spar platform becomes one of the alternatives that can be used in deepwater and ultra deepwater area. Due to that, some detail studies need to be done in order to understand more about this platform and its component's behaviour to the surroundings.

Since it is quite new technology especially in Malaysia, therefore, it is the main aim of this project to have studies on the responses of spar platforms subjected to random wave as well as the effect of variation of mooring lines configuration on its dynamic responses. The findings will help especially the author in better understanding of spar platforms and the technology applied.

1.3 OBJECTIVES

The objectives of this project are as below :

1) To prepare detailed literature survey about the spar technology and about the spar platforms that are already installed / being installed
2) To determine the dynamic response of the typical spar subjected to random wave loads by assuming the platform as a rigid body and by solving the dynamic equations in frequency domain and in time domain

3) To study the effect of variation of mooring lines configuration on the dynamic responses

1.4 SCOPE OF STUDY

For this project, the scope of study would be on deepwater and ultra deepwater technology in oil and gas business. The project will be more focusing on Spar platform which consist of :

1) Types of spar platform

   Analysis and comparison on different types of current availability spar platforms that are already installed or being installed.

2) Dynamic responses on Spar platform

   Analyze and determine dynamic responses of spar platform such as surge, heave and pitch subjected to wave loads and solving dynamic equations in frequency domain and in time domain.

3) Mooring lines configuration

   Study and analyze the effect of different mooring lines configuration such as number of lines, the arrangement and stiffness on the dynamic responses of Spar platforms.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 SPAR PLATFORM

Generally, there are many studies have been developed in order to enhance the knowledge on the deepwater exploration and spar technologies. According to Fisher and Spiess (1963), the concept of spar platform as an offshore structure is not new. In 1961, a floating platform known as FLIP was built for oceanographic research purposes. Brent spar platform built by Royal Dutch shell located in the North sea at intermediate water depth been used as a storage and offloading platform. (Bax and de Werk, 1974, Van Santen and de Werk, 1976; Glanville et al., 1997). Only recently, the usage of spar platform has been developed as production platform. This spar platform allows flexibility in the selection of well systems and drilling strategies, including early production or predrilling program (Glanville et al., 1997)

Mekha et al. (1995) has modelled the spar platform with three degrees-of-freedom (surge, heave and pitch). The analysis was performed in time domain. The inertia forces were calculated using a constant inertia coefficient, C_m, as in the standard Morison's equation or by using a frequency dependent C_m coefficient based on the diffraction theory. The drag forces were computed by using the nonlinear term of Morison's equation in both cases. As a result, it is showed that by using frequency dependent or constant inertia coefficient can produces similar results. This is due to most of the wave energy is concentrated over the range of frequencies where the value of C_m is equal to two for the spar platform size used in the literature.

Ran and Kim (1996) have studied the nonlinear response characteristics of a tethered/moored spar platform in regular and irregular waves. A time-domain coupled nonlinear motion analysis computer program was developed to solve both the static and dynamic behaviours of a moored compliant platform as an integrated system. In specific, an efficient global-coordinate based dynamic finite element program was developed to simulate the nonlinear tether/mooring responses. By using this program, the couple dynamic analysis results were obtained and compared with uncoupled dynamic analysis results in order to see the effects of tethers and mooring lines on hull motions and vice versa.

According to the studied done by Chitrapu et al. (1998), he concluded that Morison's equation combined with accurate prediction of wave particle kinematics and force calculations in the displaced position of the platform gave a reliable prediction of platform response both in wave-frequency and low frequency range.

Ran et al. (1999) investigated the nonlinear coupled response of a moored spar platform in random waves with and without co-linear current in both time and frequency domain. The first and second order wave forces, added mass, radiation damping and wave drift damping were calculated from a hydrodynamic software package called WINTCOL. The total wave force time series were then generated in the time and frequency domain based on a two-term volterra series method. The mooring lines were attached to the platform through linear and rotational springs and dampers. Various boundary conditions were modelled using proper spring and damping values. In time domain analysis, the nonlinear drag forces on the hull and mooring lines were applied at the instantaneous position. In frequency domain analysis, nonlinear drag forces were stochastically linearized and solutions were obtained by an iterative procedure.

Argawal et.al (2002) modelled spar platform as a rigid body with six degree-of-freedom, connected to the sea floor by multi-component catenary mooring lines, which are attached to the spar platform at the fairleads. The spar responses can be dependent on the stiffness matrix that consists of two parts (a) the hydrostatics provide restoring force in heave, roll and pitch, (b) the mooring lines that provide the restoring force which are represented by nonlinear horizontal springs. The wave model was used for computing the incident wave kinematics by Linear Airy wave theory and Morison's equation. The response analysis was performed in time domain in order to solve the dynamic behaviour of a moored spar platform using the iterative incremental Newmark's Beta approach. This numerical studies ware conducted for sea state conditions with and without coupling of degrees-of-freedom.

Argawal also listed the features of present generation of spar platform as per below :

a) It can be operated till 3000 Mts. depth of water from full drilling and production to production only,
b) It can have a large range of topside payloads,
c) Rigid steel production risers are supported in the center well by separate buoyancy cans,
d) It is always stable because center of buoyancy (CB) is above the center of gravity (CG),
e) It has favourable motions compared to other floating structures,
f) It can have a steel or concrete hull,
g) It has minimum hull /deck interface,
h) Oil can be stored at low marginal cost,
i) It has sea keeping characteristics superior to all other mobile drilling units,
j) It can be used as a mobile drilling rig,
k) The mooring system is easy to install, operate and relocate,
l) The risers, which normally take breathing in the wave zone from high waves on semi-submersible, drilling units would be protected inside the Spar platform. Sea motion inside the Spar platform center well would be minimal (Agarwal and Jain, 2002).

2.2 SPAR MOORING

The mooring lines are considered to stabilize the unstable motion. However, there is no study on the effect of the mooring lines on the stability of interacting motions. (Jun B Rho and Hang S.Choi, 2003). The performance of each floating structure is rely directly on the performance of its system of lines and anchors rather than the performance of its single line or anchor. Current used, there are three design of mooring lines based on water depth : 3000, 6000 and 10000 feet. There is a numerical code named COUPLE which was employed to compute motions and tensions in the mooring lines given met-ocean conditions. (Jun Zhang and Robert Gilbert, 2004).

The typical mooring system used in spar concept is a chain-wire-chain taut catenary system. A "taut" mooring can be defined as one in which the anchor loads have an uplift component for all load conditions i.e. the anchor chain or wire never lies on the seabed (Agarwal and Jain, 2002). It requires shorter mooring lines and smaller foot print of the anchoring location. Additionally the anchoring system is designed either as a pile or as a drag embedded anchors with high holding capacity. Due to that, even in the 100-years of hurricane, the spar motions are still small enough so that the taut system can be used without synthetic mooring lines. The system saves a considerable length of wire and chain needed for a conventional catenary mooring.

The platform chain is tensioned using chain jacks or windlasses, which are installed on the periphery of the upper deck of the hull (the "spar deck"). It runs from the chain jack to a fairlead, located from up to 350 feet below the mean waterline. Its length is determined by the amount chain, which needs to be pulled in or paid out to maneuver the spar. For midsection, the mooring system consists of a spiral strand wire rope or polyester line. The steel strand is usually coated with a urethane coating results to a long lasting chain. Its lower end is attached to a length of anchor chain that is connected to a piled anchor which can sustain uplift and lateral loads. Commonly, the pile padeye is about 50 feet below the mudline in order to minimize the bending moment from the mooring forces. The total scope of the taut moor from the fairlead to the anchor is typically about 1.5 times the water depth.

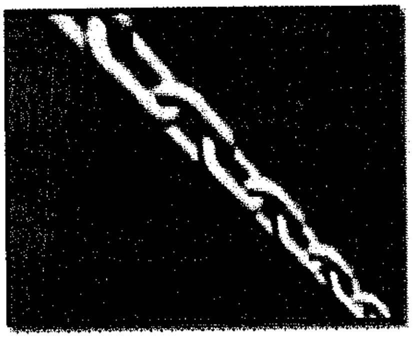


Figure 2.1 :- Sample of Mooring Lines used for Offshore Platform

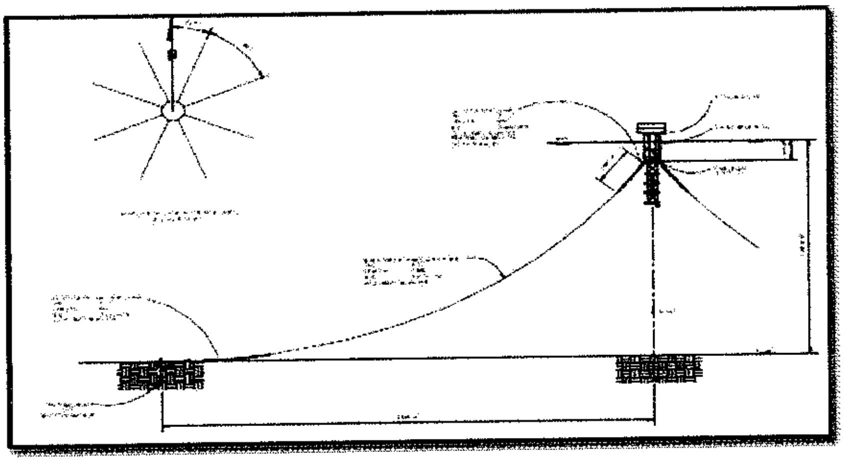


Figure 2.2 :- Sample of Taut Mooring configuration

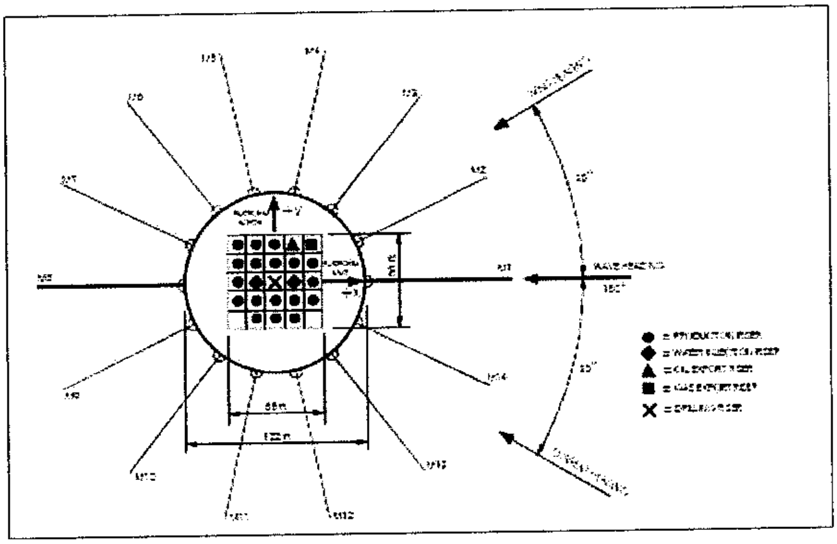


Figure 2.3 :- Sample of Layout of Mooring Lines and Risers and Environmental Orientation

2.3 THEORY

2.3.1 Linear Airy Wave Theory

Wave theories describe the kinematics of waves of water on the basis of potential theory. In particular, they serve to calculate the particle velocities and accelerations and the dynamic pressure as functions of the surface elevation of the waves. The waves are assumed to be long-crested, i.e. they can be described by a two-dimensional flow field, and are characterized by the parameters: wave height (H), period (T) and water depth (d) as shown in Figure 2.4 below :

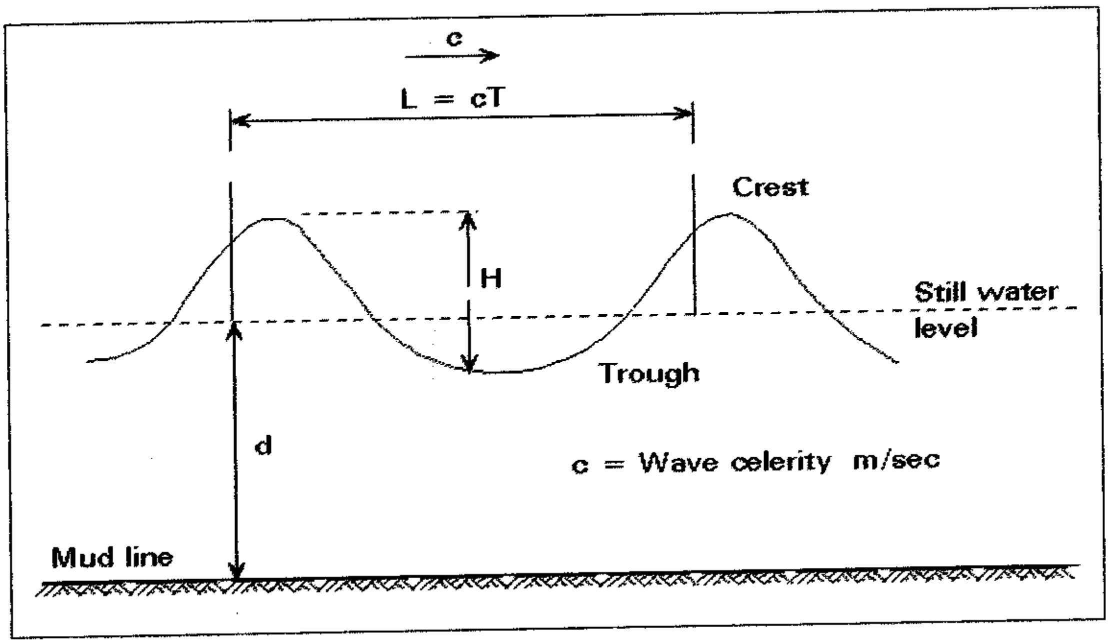


Figure 2.4:- Wave Theory (Design Of Offshore Structure, Lecture Notes, Chapter 2)

Different wave theories of varying complexity, developed on the basis of simplifying assumptions, are appropriate for different ranges of the wave parameters. Among the most common theories are: the Linear Airy theory, the Stokes fifth-order theory, the solitary wave theory, the cnoidal theory, Dean's stream function theory and the numerical theory by Chappelear.

Linear Airy Wave Theory is often applied in ocean engineering and coastal engineering for the modelling of random sea states — giving a description of the wave kinematics and dynamics of high-enough accuracy for many purposes. Further, several second-order nonlinear properties of surface gravity waves, and their propagation, can be estimated from its results. This linear theory is often used to get a quick and rough estimate of wave characteristics and their effects.

In order to use this theory, we will consider the small amplitude waves (small free surface slope). Underneath the surface, there is a fluid motion associated with the free surface motion. While the surface elevation shows a propagating wave, the fluid particles are in an orbital motion. Within the framework of Airy wave theory, the orbits are in deep water closed circles, and in finite depth closed ellipsoids — with the ellipsoids becoming flatter near the bottom of the fluid layer. So while the wave propagates, the fluid particles just orbit (oscillate) around their average position. With the propagating wave motion, the fluid particles transfer energy in the wave propagation direction, without having a mean velocity. The diameter of the orbits reduces with depth below the free surface. In deep water, the orbit's diameter is reduces to 4% of its free-surface value at a depth of half a wavelength.

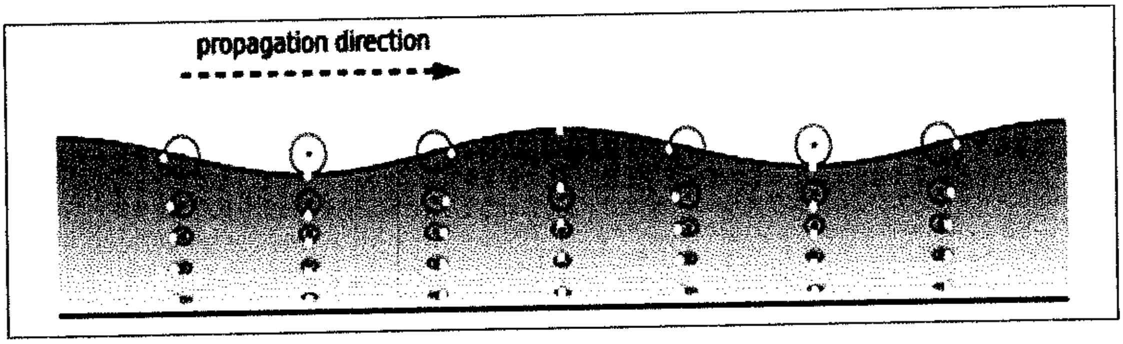


Figure 2.5 :- Orbital motion under linear waves. The yellow dots indicate the momentary position of fluid particles on their (orange) orbits. The black dots are the centres of the orbits (Wikipedia)

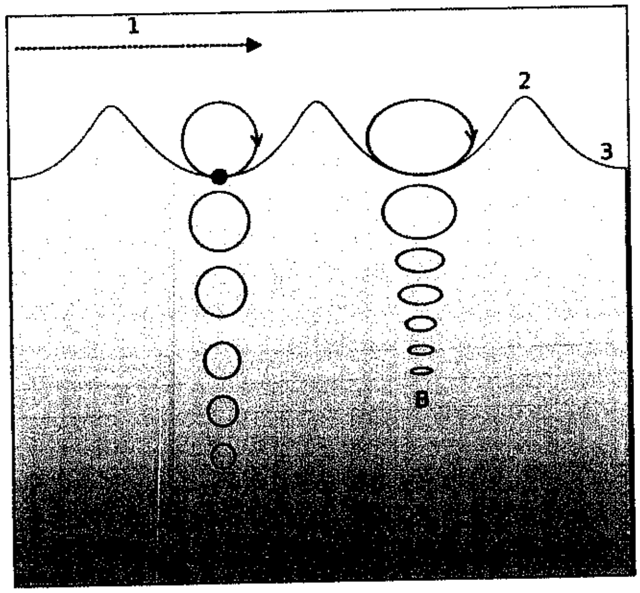


Figure 2.6 :- Motion of a particle in an ocean wave. [**A** = At deep water. **B** = At shallow water (ocean floor is now at B)] (Wikipedia)

2.3.2 Pierson-Moskowitz Spectrum

In 1964, Pierson and Moskowitz (1964) proposed a new formula for an energy spectrum distribution of a wind generated sea state based on the similiarity theory of Kitaigorodskii and more accurate recorded data. This spectrum known as PM Spectrum has since been extensively used by ocean engineers as one of the most representative for waters all over the world. It describes a fully-developed sea determined by one parameter – wind speed. This spectrum is very useful in representing a severe storm wave in offshore structure design

$$S(f) = \frac{\alpha g^2}{(2\pi)^4} f^{-5} \exp\left[-1.25\left(\frac{f}{f_0}\right)^{-4}\right]$$

where, $\alpha = 0.0081$ and peak frequency, $f_0 = \omega_0 / 2\pi$

From this above calculation, the wave height for each frequency can be obtained as follows

$$H(f_i) = 2\sqrt{2S(f_i)\Delta f}$$

And the wave profile can be computed from below equation

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

where, x was the location of evaluation of wave profile from the origin in the horizontal direction; t was the time at which the wave profile was evaluated; wave number, k(n) = 2π/L(n) corresponds to the wave length L(n) for the nth frequency, *f(n)*.

2.3.3 Morison Equation

The Morison equation was developed by Morison, O'Brien, Johnson and Shaaf (1950) in order to describe the horizontal wave forces acting on a vertical pile which extends from the bottom through the free surface Morison et al. (1950) proposed that the force exerted by unbroken surface waves on a vertical cylindrical pile which extends from the bottom through the free surface. It is composed of two components – inertia force and drag force.

$$f = C_m \rho \frac{\pi}{4} D^2 \frac{\partial u}{\partial t} + C_d \frac{1}{2} \rho D |u| u$$

where, C_m is the inertia coefficient, ρ is the water density, C_d is the drag coefficient, D is the platform diameter and u is the water particle velocity.

2.3.4 Motion-Response Spectrum

If a structure is free to move in waves its motion may be critical near the resonance of the structure. Therefore, it is important to study the overall response of the structure due to a design wave spectrum. In this case, the response-amplitude operators are written relating the dynamic motion of the structure to the wave-forcing function on the structure. If the relationship between the motion and force is linear, the conversion is relatively straightforward. The response amplitude operators (RAO) can be calculated as below

$$RAO = \frac{F_i/(H/2)}{[(K - m\omega^2)^2 + (C\omega)^2]^{1/2}}$$

where, F is total force for each frequency, H is the wave height for each frequency, K is the structure stiffness, m is the total mass and added mass of the structure and C is structural damping ratio.

This RAO value can generate the response spectrum and wave profile for every frequency.

$$H_{surge} = RAO^2_{surge} \times H_{wave\ height}$$

$$S(f)_{surge} = RAO^2_{surge} \times S(f)_{wave}$$

Note: *All of the theories are taken from S.K Chakrabati "Hydrodynamics of Offshore Structures"*

CHAPTER 3
METHODOLOGY

3.1 PROCEDURE

In order to run this project, there are some procedures that are required to be done. There are :

3.1.1 Familiarization on Offshore Structures

Early familiarizations on theories in offshore structures are important in order to make the flow of project become more efficiently. The theories that need to be familiarized are :

a) Wave Theory - Linear Airy Wave Theory
b) Mathematical Spectrum Models – Pierson-Moskowitz Spectrum
c) Morison Equation
d) Motion Response Spectrum for surge, heave and pitch

3.1.2 Research

A lot of research needs to be done in this project in order to enhance the familiarization on the topic. The scopes of research are about the current available spar platform that are already installed or being installed in entire world as well as its technology.

3.1.3 Data Gathering

During research, some data need to be gathered for calculating the dynamic responses of the typical spar platform subjected to random wave loads. This second procedure is to meet the second objective of this project. The required data are :

a) Platform Particulars
   i) Plan Dimension
   ii) Height
   iii) Draft
   iv) Draft Members
   v) CG Position – Centroid
   vi) Radii of Gyration
   vii) Mooring Lines Details
   viii) Mass / Weights

b) Environmental Loads
   i) Water Depth
   ii) Spectrum
   iii) Wind Speed
   iv) Wave Height

3.1.4 Conduct Analysis

From the data gained, some analysis will be conducted. The analysis is to determine the dynamic responses of the typical spar platform subjected to random wave loads by assuming the platform as a rigid body as well as by solving the dynamic equations in frequency domain and in time domain. This procedure will utilize the knowledge that the author gained from familiarization session.

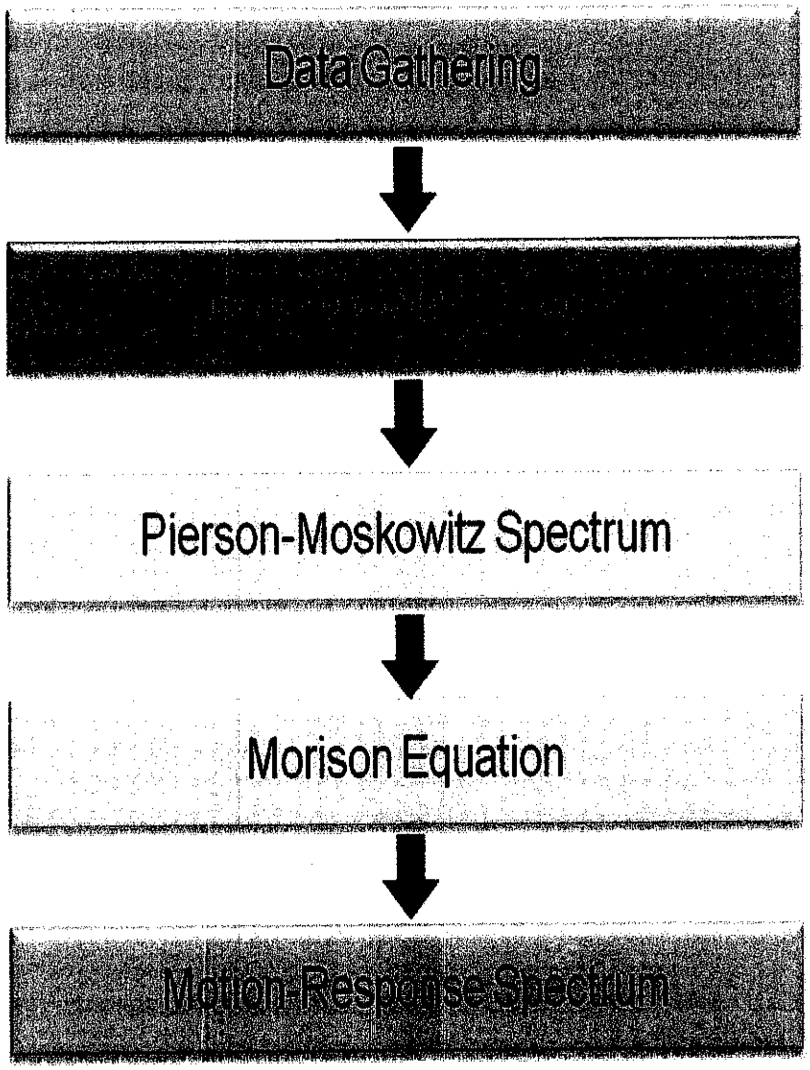


Figure 3.1 :- Steps of conducting analysis

After that, the project will be proceed with next phase which is study the effect of variation of mooring lines configuration on the dynamic responses.

Gantt Chart for this entire project can be viewed in Appendix 1

3.2 SOFTWARE REQUIRED

The software required in conducting this project are :

a) Microsoft Excel
b) MatLab (Optional)
c) SACS (Optional)

3.3 HEALTH, SAFETY & ENVIRONMENT (HSE) ANALYSIS

HSE is very important especially in oil and gas industry. It is because the damages deal with big amount of money as well as reputation. In order to execute this FYP, the author does not need to conduct any laboratory work. She just needs to do some calculation and researches through internet and journal. Therefore the main concern that she needs to be taken is her workspace. The workspace must be safe enough in order to provide a convenient space for her. The workspace must have good and safe electricity sources and far away from any danger such as sharp edge. The sitting arrangement and placement of the computer as well must be ergonomic enough in order to protect her eyes and sitting posture during conducting the simulation.

As additional, the author also is required to know the HSE application for individual who is going to offshore or oil platform. He or she needs to fulfil these below basic of requirements :

a) Personal Protective Equipment (PPE) – coverall, hard hat, safety boot, eye protection, hearing protection
b) Able to swimming
c) Not allowed to bring and use handphone on the platform
d) Not allowed to smoking on the platform
e) Has valid safety passport
f) Has valid work permit

For the company, they need to conduct certain analysis related to HSE such as Hazard Identification (HAZID), Hazard and Operability Study (HAZOP), Health Risk Assessment (HSA) and many more in order to decrease the possibility of any incident happen.

CHAPTER 4
RESULTS & DISCUSSION

4.1 RESEARCH AND DATA GATHERING

After learning some theories related to offshore structures, the author is required to do some literature review on available spar platform and then finalized the data required in order to calculate dynamic responses based on one spar platform. The author had chosen **Neptune Spar Platform** for her study since the platform is the first spar platform developed in the world. The details of Neptune Spar Platform are as below :

Table 4.1: Details of Neptune Spar Platform (Technip Offshore)

NEPTUNE SPAR PLATFORM (Classic Spar)

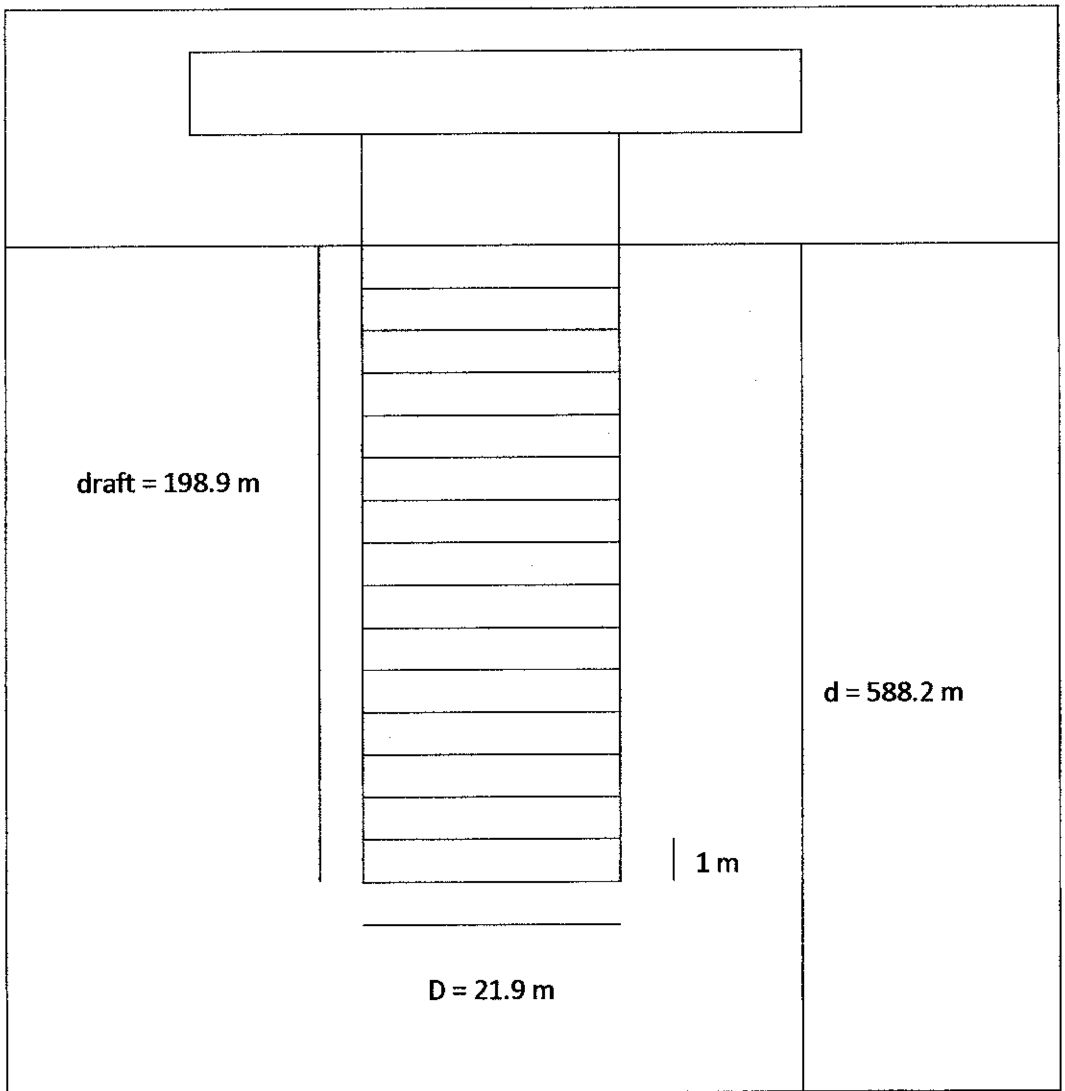
Platform Particulars	
Plan Dimension	- Deck elevations are 116ft, 93ft and 71ft - Hull 72ft-diameter cylinder
Height	- 705ft / 214.88m
Draft	- 650ft / 198.8m
Draft Members	- 32ftx32ft^2 centrewell inside the hull accommodates 16 buoyancy-supported risers, grouped in four rows of four.
Radii of Gyration	- Pitch = 62.33m

Mooring Lines details	- 6 semi taut-catenary point mooring - Securing each mooring leg to the seafloor is an 84in-diameter by 180ft-long pile. This is connected to 220ft of 4,3/4in chain, 2,400ft of 4,3/4in jacketed spiral-strand steel rope and 1,050ft of 4,3/4in chain, leading through a fairlead, to a chain jack at the spar's deck. Breaking strengths for the 4,3/4in wire and 4,3/4in chain are 2,750kips and 2,846kips, respectively.
Mass / weights	- 756660kN / 77.13 Mkg
Environmental Data	
Water Depth	- 1,935 ft / 589.8m
Wind Speed	- 7m/sec
Wave Height	- Assume 4.6m
Natural Period	- 300 – 350sec
X value	- 0

Table 4.2 : General Data for spar platform (OED Report No 9550, ABS Americas, Houston, June 1995)

Data		**Value**
Range of Natural Period, (T_N)	Surge	300 – 350 sec
	Heave	20 - 30 sec
	Pitch	60 – 70 sec
Pitch Radius of Gyration		≈ 65 m
Center of Gravity (COG)		≈ 104 m

This data are very important for the author to compare with her calculation results in order to make sure that the results that she got is within the permissible limits for offshore operations.



Given,

H_s = 4.6 m

d = 588.2 m

x = 0

t = 0

ρ = 1030 kg / m^3

C_d = 0.65

C_m = 1.6

Figure 4.1 :- Neptune Spar Platform Diagram

4.2 ANALYSIS

From the details of Neptune Spar Platform that the author gained, some analysis had been conducted based on the theories that the author learned before. The results of Neptune Spar Platform analysis are as below;

4.2.1 Wave Particle Velocity

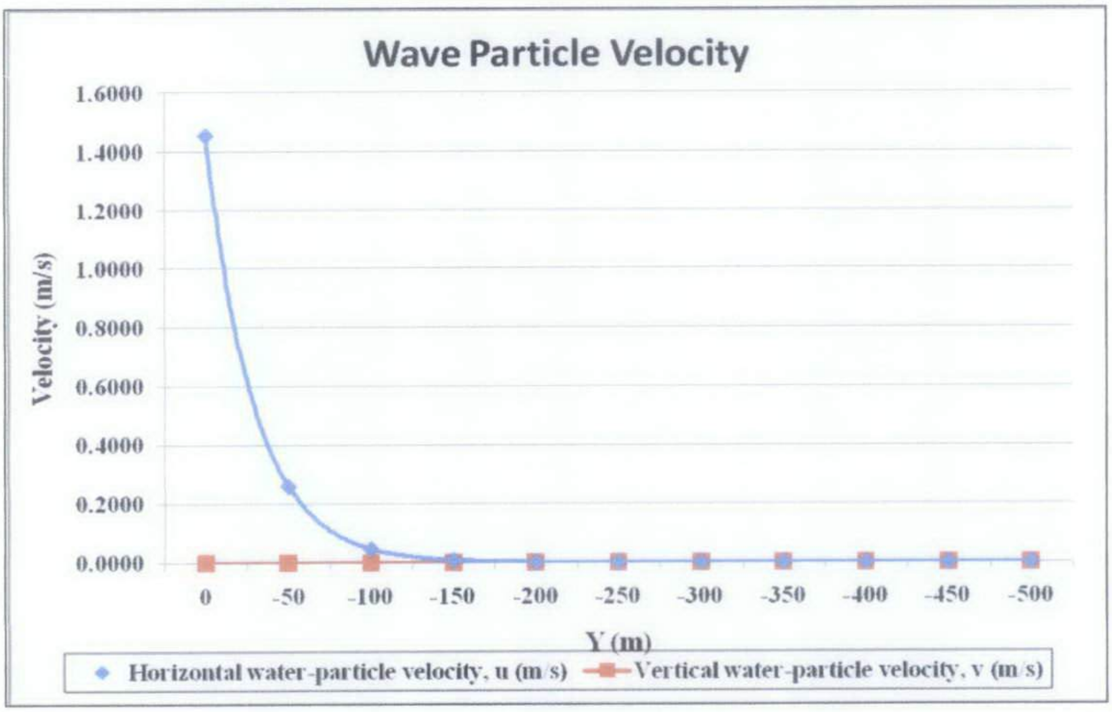


Figure 4.2 :- Wave-Particle Velocity

Wave particle velocity has been calculated by using Linear Airy Wave theory with assumption that it act at the origin, x = 0, t = 0s. Based on the graph above, it is approved that for deepwater, as the water depth increase (deeper), the value of Horizontal Wave-Particle Velocity, u (m/s) and Vertical Wave-Particle Velocity, v (m/s) will decrease and became zero.

Sample of calculation can be viewed in Appendix 2.

4.2.2 Wave Spectrum

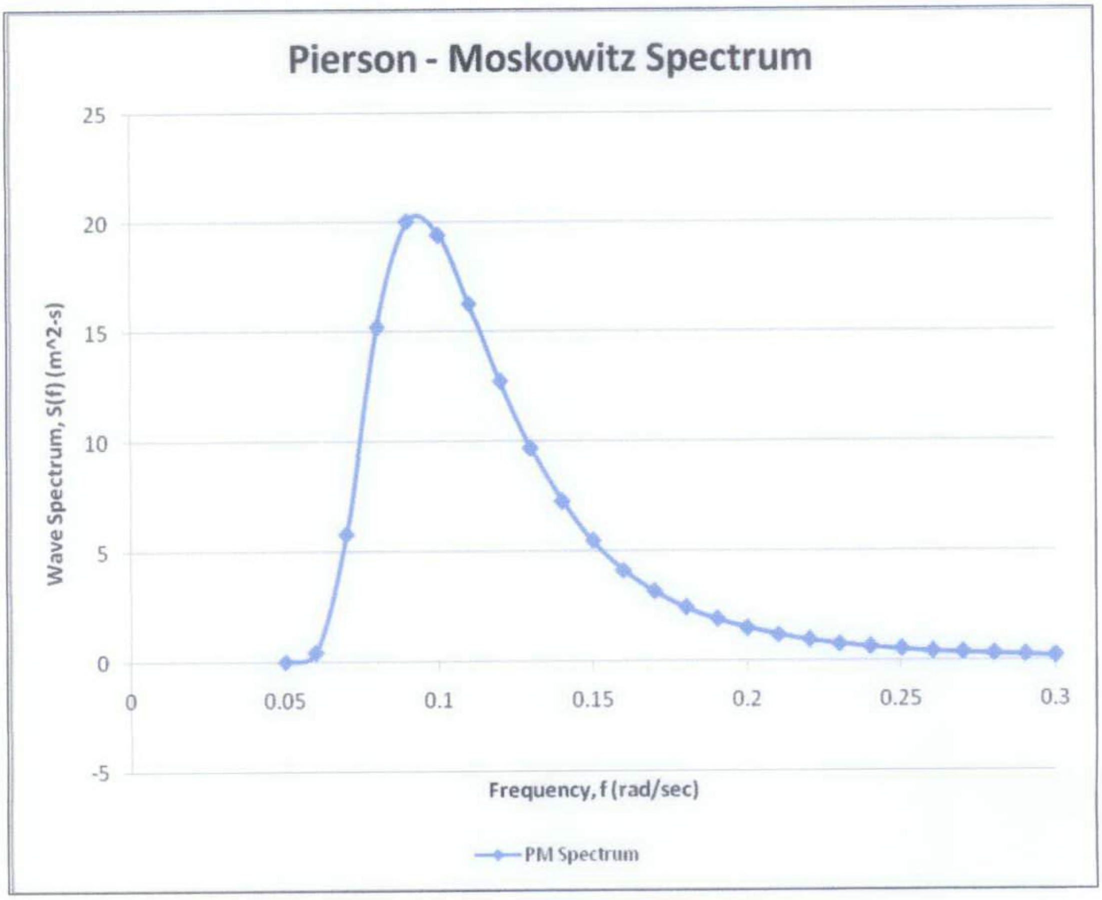


Figure 4.3 :- Wave Spectrum

Wave energy density spectrum, S(f) was determined based on the Pierson Moskowitz Spectrum theory. Based on the graph obtained above, it is shown that the wave spectrum behaviour as parabolic towards increasing of frequency. The highest wave spectrum is at f = 0.095rad/sec with the value is 20.05m2-s. and the total area under curve can be is 1.307079 m2. Apart from that, the significant height was obtained from this wave record which is 4.6m and wave height for each frequency as per Table 4.3 in the next page :

Table 4.3 : Wave Height (H(f)) for each frequency

f, Hz	H(f), m	f, Hz	H(f), m	f, Hz	H(f), m
0.015	4.7983E-127	0.115	1.077227185	0.215	0.289619408
0.025	1.35157E-24	0.125	0.946642175	0.225	0.259386713
0.035	1.35428E-07	0.135	0.823045329	0.235	0.233295036
0.045	0.004174755	0.145	0.713494828	0.245	0.210666293
0.055	0.132531574	0.155	0.619251956	0.255	0.190946943
0.065	0.500074815	0.165	0.539236312	0.265	0.173683792
0.075	0.916621638	0.175	0.471610063	0.275	0.158504373
0.085	1.187348832	0.185	0.414453303	0.285	0.145101233
0.095	1.256701689	0.195	0.366022358	0.295	0.13321941
0.105	1.195078556	0.205	0.324824918		

Sample of calculation for this Wave Spectrum can be viewed in Appendix 2.

From the calculated wave height, the time history of the wave profile (t = 0 – 100 seconds) around the platform was computed by using a random phase in range of 0 - 2π. The wave profile is shown below

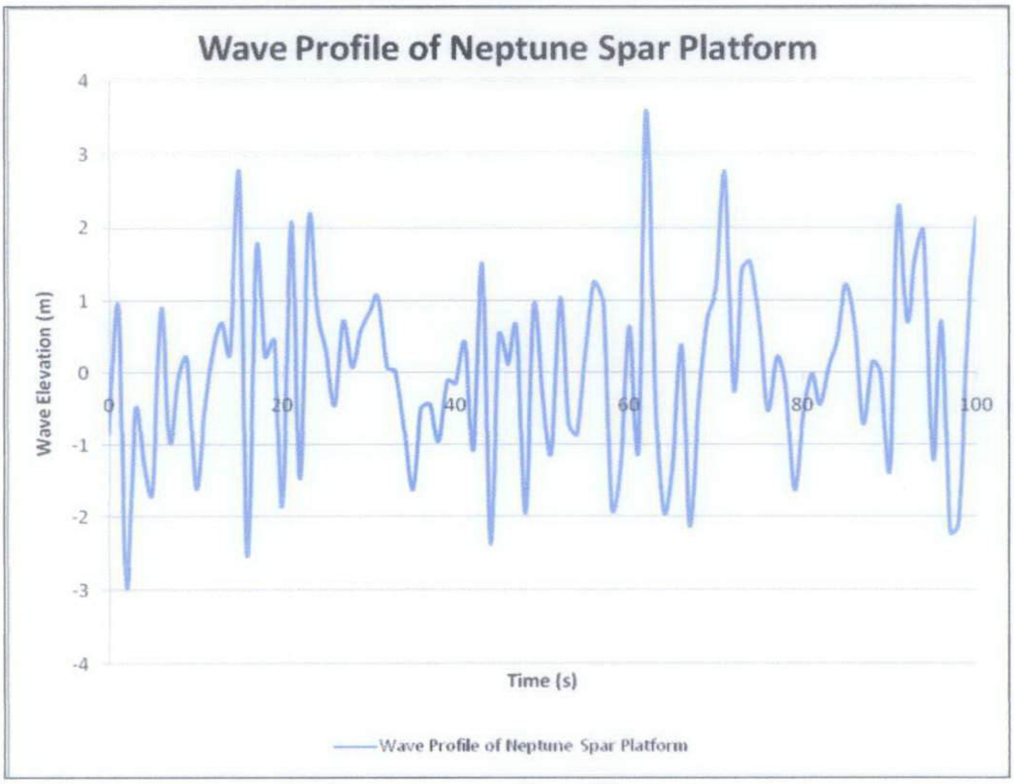


Figure 4.4 :- Wave Profile

Based on the graph above, it is shows that the highest wave elevation is 3.58m when the time is at range of 62-64 seconds.

Sample of calculation for wave profile can be viewed in Appendix 2.

4.2.3 Total Horizontal Forces Acting on the Neptune Spar Platform

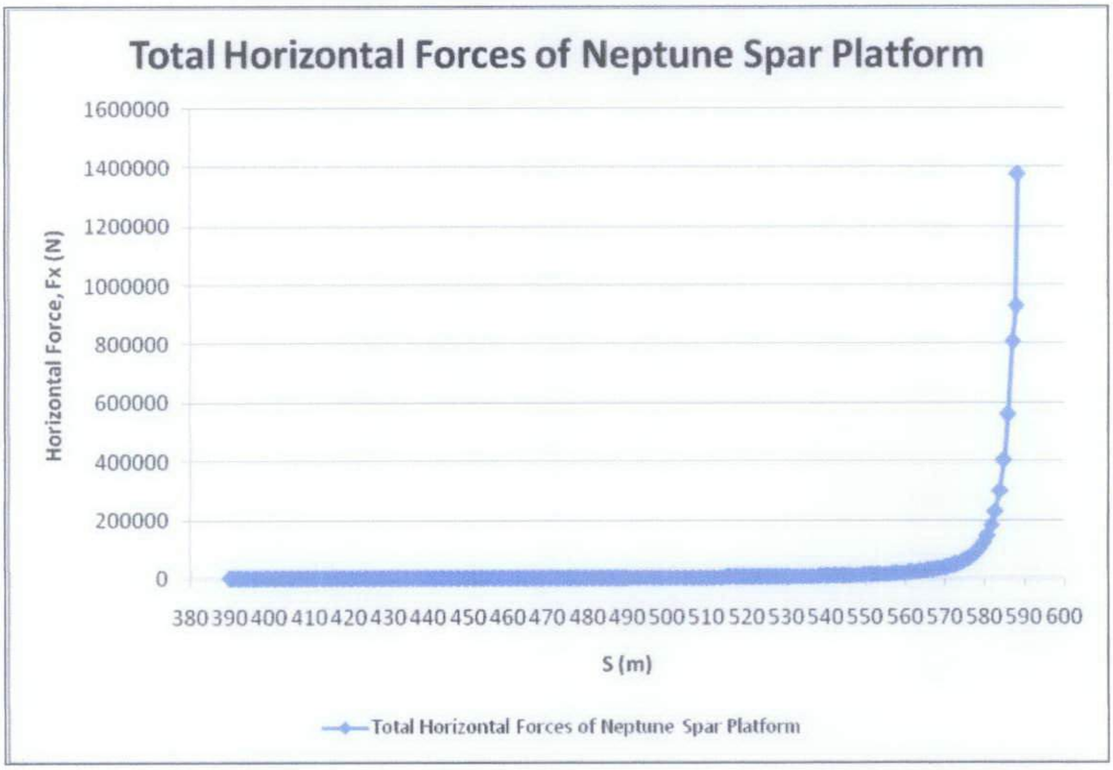


Figure 4.5 :- Wave Profile

Wave forces has been calculated using Morison's equation ($C_m = 1.6$ and $C_D = 0.65$) at different depth of Neptune Spar Platform. From the graph, it shows that as the depth of spar platform increase, the total horizontal forces will decrease towards zero value. The highest force value is 1378018.085 kN which is at the surface of water (when the depth of spar platform equals to zero).

Sample of calculation can be viewed in Appendix 2.

4.2.4 Motion Response Analysis

Neptune Spar Platform is a structure that is free to move in wave's motion and it is may be critical near the resonance of the structure. Therefore, it is important for the author to study the overall response of the structure due to a design-wave spectrum. This motion response spectrum of surge, heave and pitch were determined based on structure damping ratio 2% and the P-M model of $H_s = 4.6$ m.

a) Surge Response Analysis

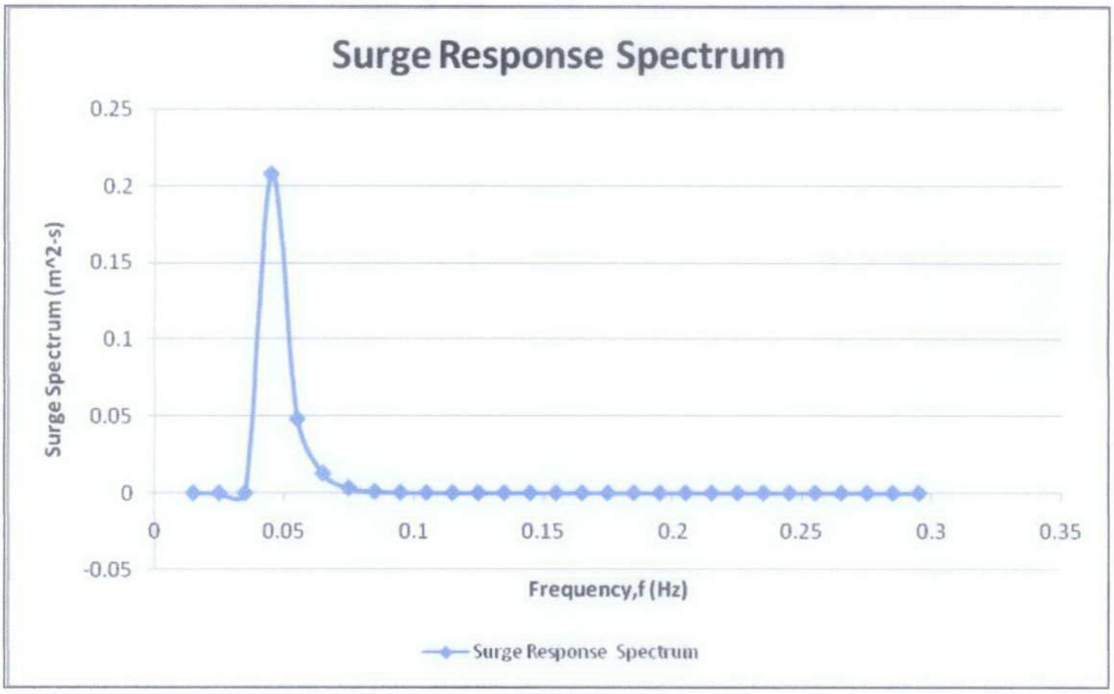


Figure 4.6 :- Surge Response Spectrum

From the graph obtained above, it is shown that the surge response spectrum behaviour as parabolic towards increasing of frequency. The highest surge response spectrum is at f = 0.05Hz with the value is $0.21 m^2$-s.

Sample of calculation can be viewed in Appendix 2.

From the calculated wave height, the time history of the surge profile (t = 0 – 100 seconds) around the platform was computed by using a random phase in range of 0 - 2π. The surge profile is shown below

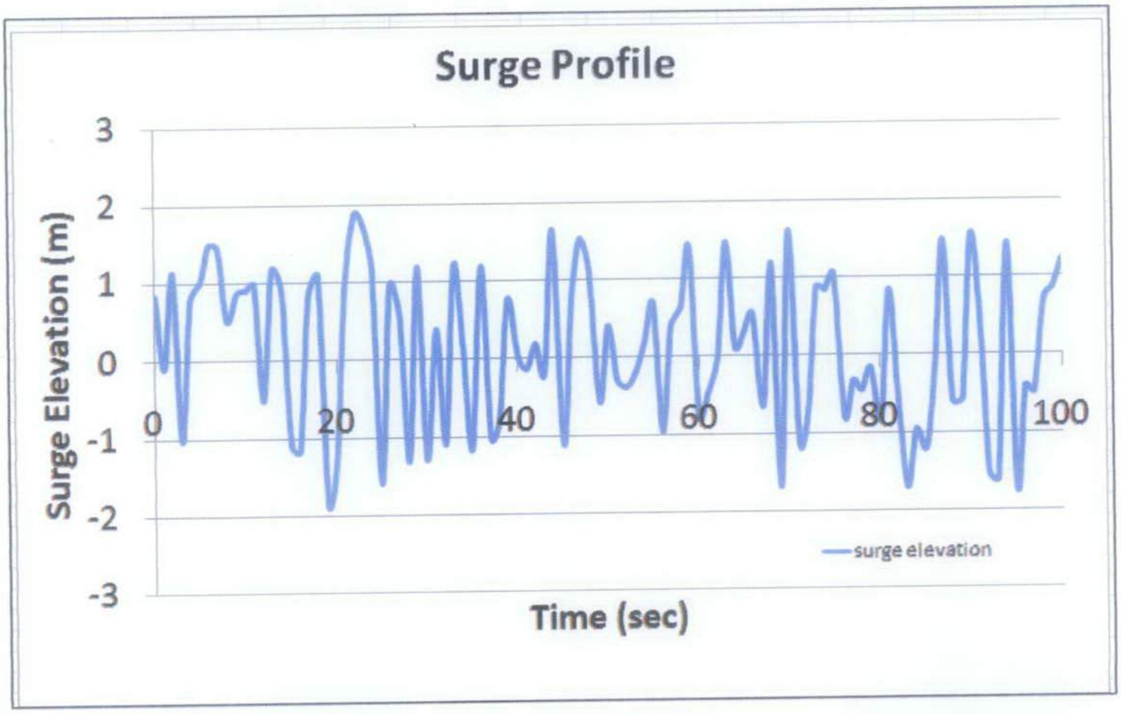


Figure 4.7 :- Surge Profile

Based on the graph, it is shows that the highest surge response elevation is around 1.9 - 2m when the time is at range of 20-25 seconds.

Sample of calculation can be viewed in Appendix 2.

b) Heave Response Analysis

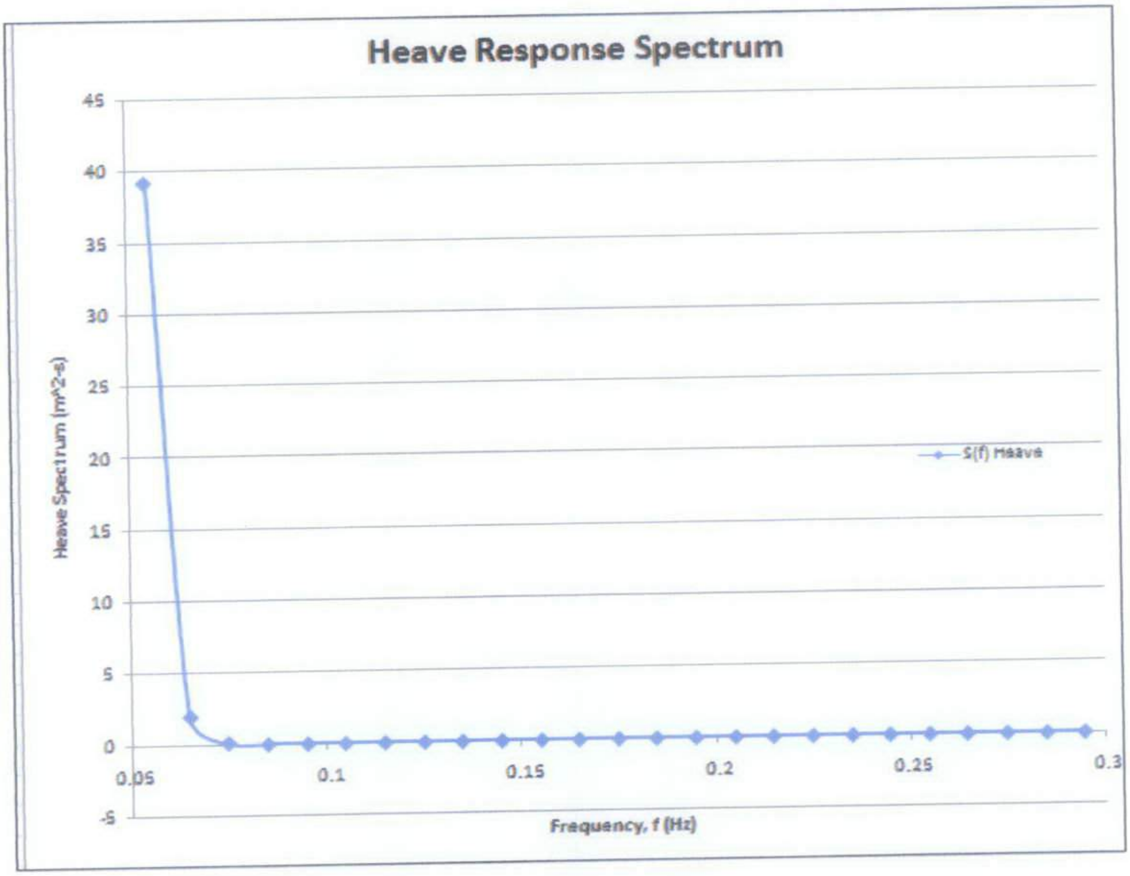


Figure 4.8 :- Heave Response Spectrum

From the graph obtained above, it is shown that the heave response spectrum decreasing towards increasing of frequency. The highest heave response spectrum is at f = 0.055Hz with the value is $39.14m^2$-s.

Sample of calculation can be viewed in Appendix 2.

From the calculated wave height, the time history of the heave profile (t = 0 – 100 seconds) around the platform was computed by using a random phase in range of 0 - 2π. The heave profile is shown below

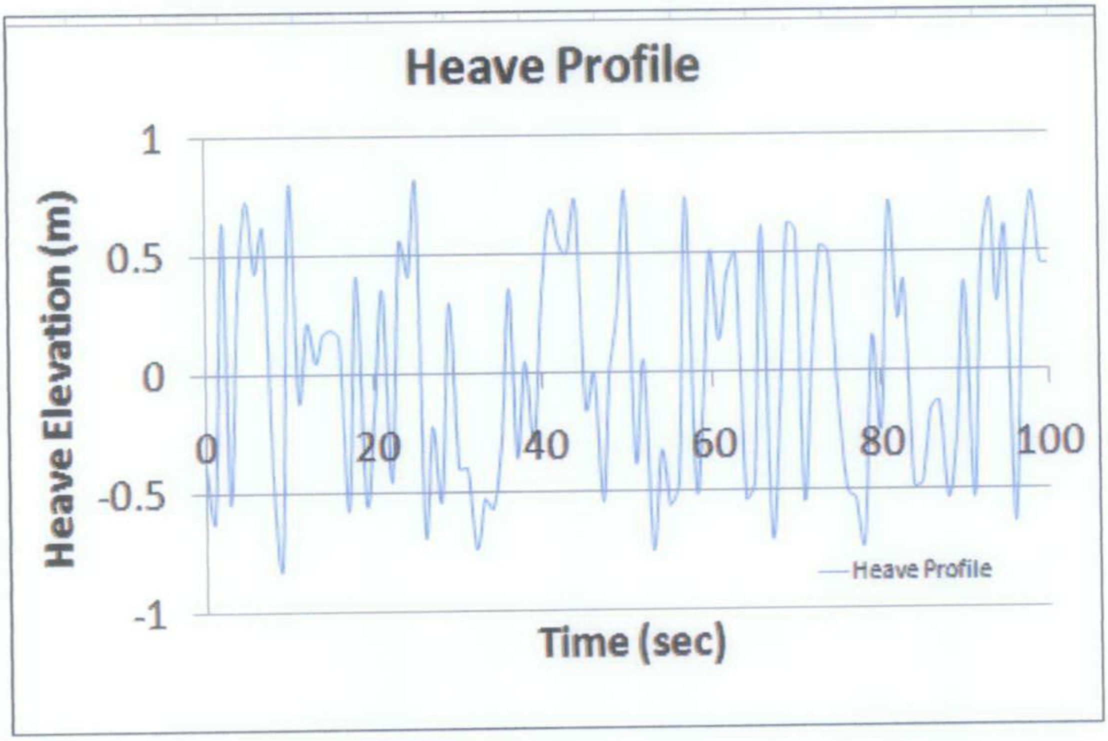


Figure 4.9 :- Heave Profile

Based on the graph, it is shows that the highest heave response elevation is around 0.78m when the time is at range of 10-12 seconds.

Sample of calculation can be viewed in Appendix 2.

c) Pitch Response Analysis

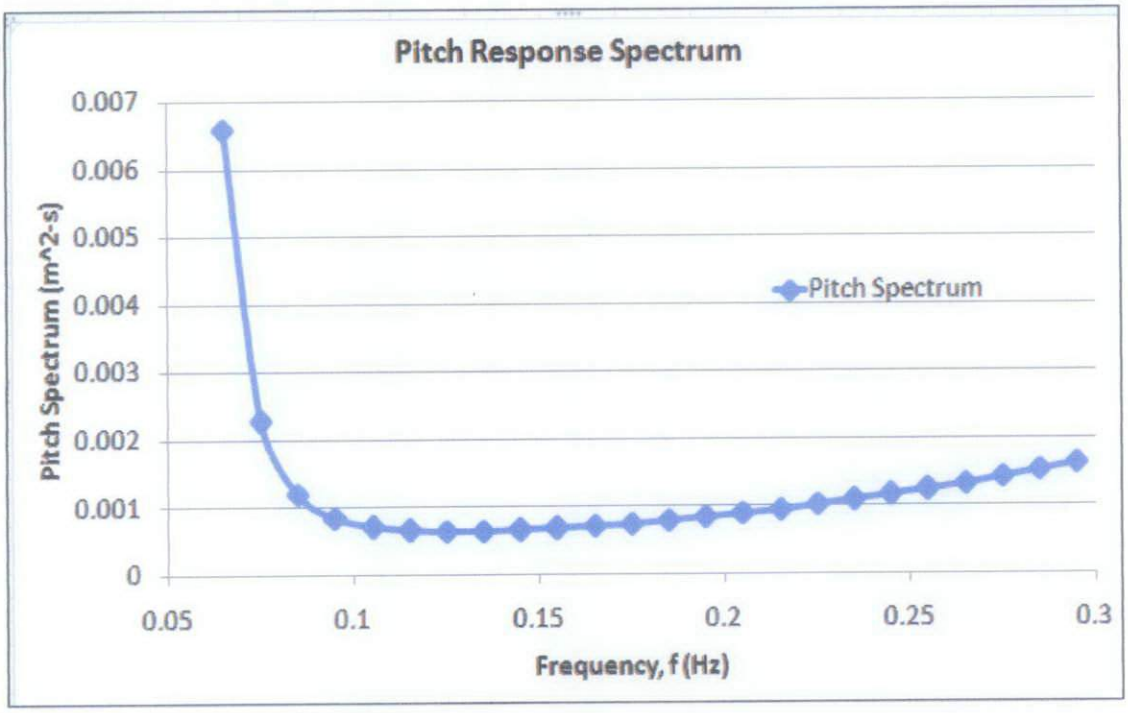


Figure 4.10 :- Pitch Response Spectrum

From the graph obtained above, it is shown that the pitch response spectrum decreasing at the early frequency and then increasing again towards increasing of frequency. The highest pitch response spectrum is at f = 0.065Hz with the value is 0.0065m^2-s.

Sample of calculation can be viewed in Appendix 2.

From the calculated wave height, the time history of the pitch profile (t = 0 – 100 seconds) around the platform was computed by using a random phase in range of 0 - 2π. The pitch profile is shown below

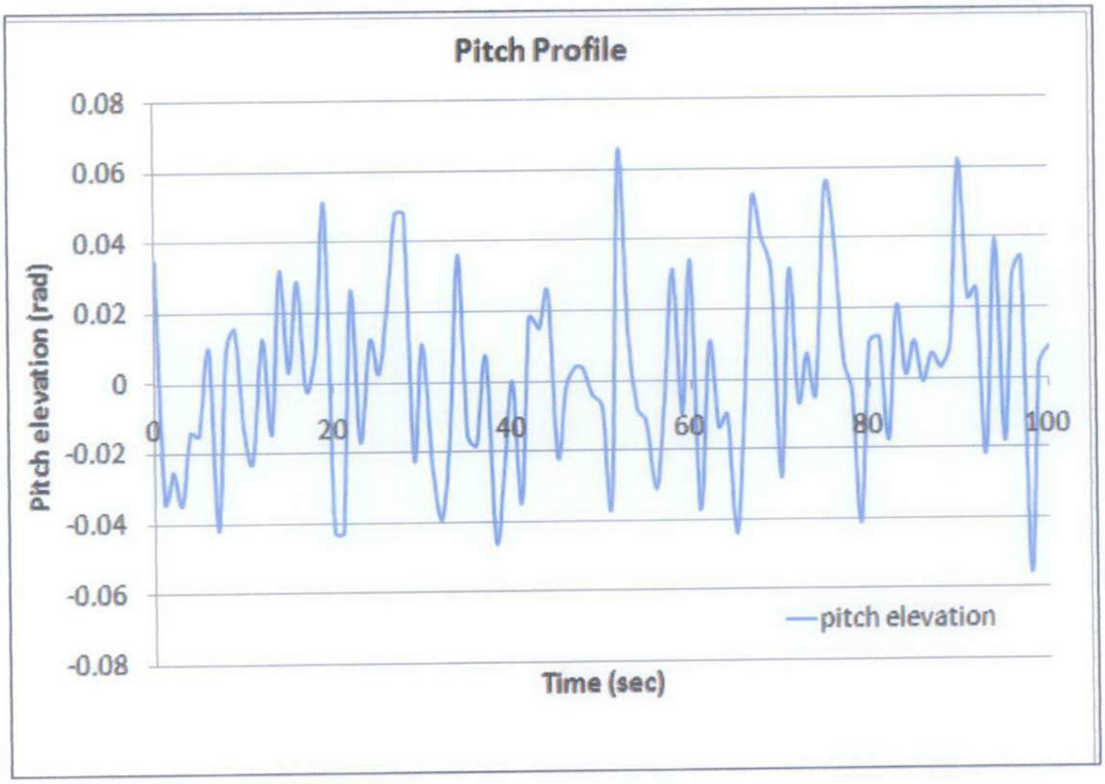


Figure 4.11 :- Pitch Profile

Based on the graph, it is shows that the highest pitch response elevation is around 0.065radian when the time is at range of 50-52 seconds.

Sample of calculation can be viewed in Appendix 2.

4.3 PARAMETRIC STUDY (MOORING LINES)

Different number of mooring lines was chosen to study the effect of this parameter on the response of spar platform. The changing parameters used in the study are 6, 8, 10, 12, 14, 16, 18 and 20 mooring lines. The stiffness of each mooring lines has been set to a constant value 28843.18 N/m. The comparison has been done between surges and heaves on all parameters through the response spectrum and time series curve (profile).

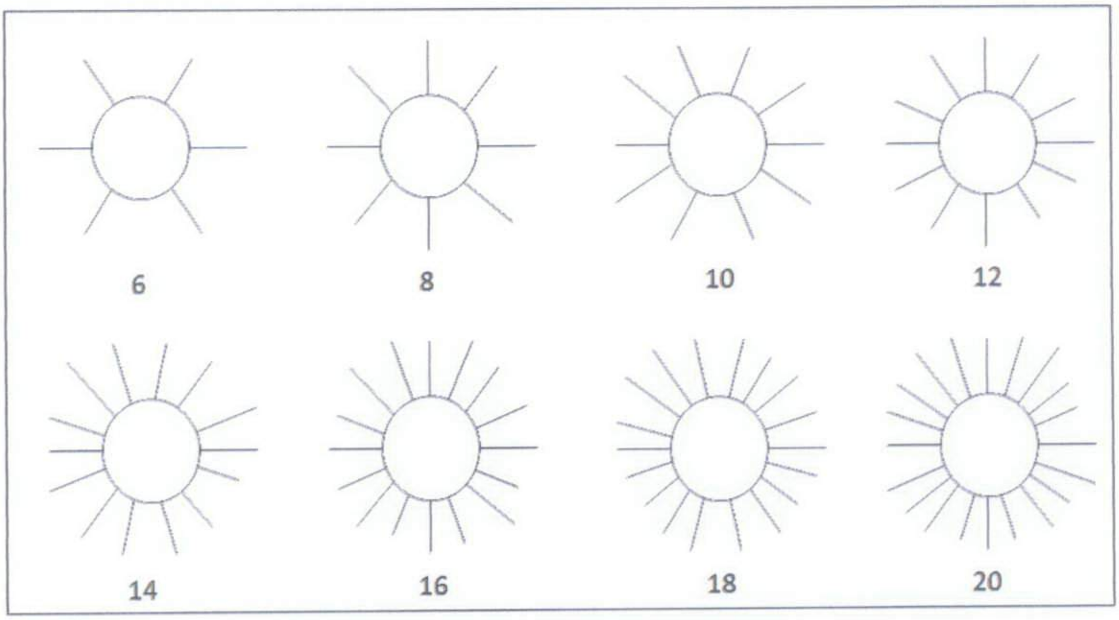


Figure 4.12 :- Mooring Lines Configuration

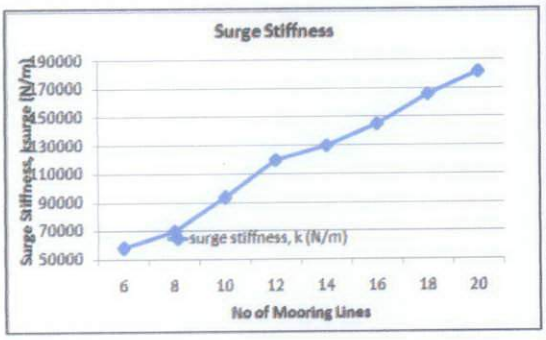


Figure 4.13 :- Surge Stiffness

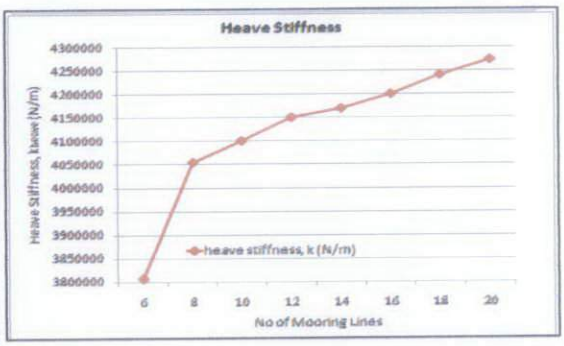


Figure 4.14 :- Heave Stiffness

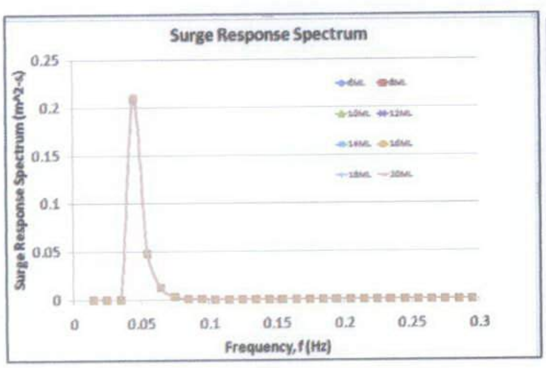


Figure 4.15 :- Surge Response Spectrum

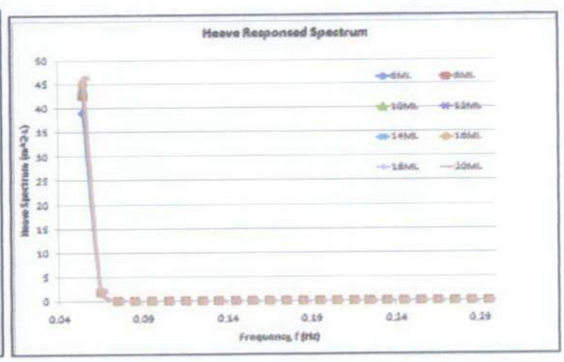


Figure 4.16 :- Heave Response Spectrum

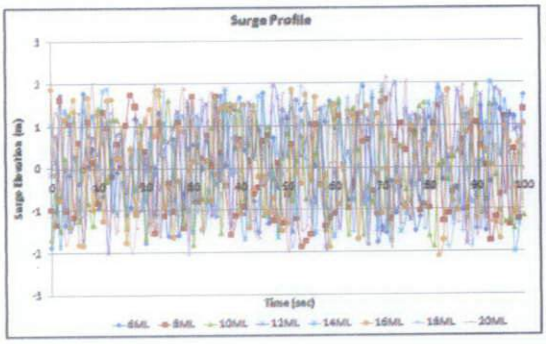


Figure 4.17 :- Surge Profile

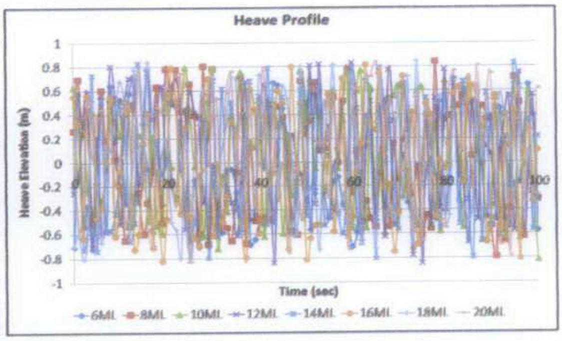


Figure 4.18 :- Heave Profile

Based on the graph above, it shows that as number of mooring lines increases, the surge stiffness and heave stiffness also will be increased. Although the stiffness increases, there is no significant effect in surge responses, surge profile and heave profile at all 8 different numbers of mooring lines. Only heave response spectrum increase as the number of mooring lines increases. Although there is no significant changes, the value for all surge and heave profiles is in the allowable range.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 CONCLUSIONS

This report has summarized what the author had done for the entire two semester of Final Year Project. From this report, it can be concluded that;

a) A detailed literature survey on Spar and its technology has been completed.

b) A frequency domain dynamic analysis of Neptune Spar Platform subjected to random waves has been completed and the surge, heave and pitch responses had been obtained.

c) For the environmental data assumed, the maximum responses that the author obtained for surge, heave and pitch is as in the table below

Table 5.1 : Maximum Responses for Surge, Heave and Pitch

	Maximum response
Surge	1.9 – 2.0m
Heave	0.78m
Pitch	0.065 rad

d) The responses that the author obtained for surge, heave and pitch responses are within the permissible limits for offshore operations.

e) As the number of mooring lines increases, the stiffness for surge and heave also increases. But there is no significant effect on the surge and heave responses.

It is a challenge for the author to find the correct data on the available spar platform since the different measurement from different references. Not only that, it is also a challenge for the author to familiarize new theories in order to complete her task in FYP. It is satisfied for the author since she managed to incorporate all the data that she have and did some analysis with help and support from the supervisor. Within these two semesters of running this project, the author managed to learn new things and enhance her knowledge towards offshore structures and their technologies.

5.2 RECOMMENDATIONS

Some recommendations can be done in order to improve this project. There are :

a) Conduct a model studies on classic spar platform that can be tested in a wave tank or wave flume and compare the results with the theoretical results.

b) Conduct analysis on other different types of configuration for mooring lines such as mooring tension, the arrangement and the stiffness values for each arrangement have to be worked out in detail for further study

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APPENDICES

APPENDIX 1 : Gantt Chart for FYP

(January - July 2008)

APPENDIX 2 : Analysis on Neptune Spar Platform

APPENDIX 1

Gantt Chart for FYP

(January - July 2008)

GANNT CHART FOR FINAL YEAR PROJECT (FYP) 1 - JANUARY 2008

No	Detail / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Selection Of Project																			
2	Preliminary Research Work																			
3	Submission of Preliminary Report				★															
4	Familiarization on Offshore Structures																			
5	Data Gathering & Analysis																			
6	Submission of Progress Report									★										
7	Submission of Interim Report															★				
8	Oral Presentation																			★

GANNT CHART FOR FINAL YEAR PROJECT (FYP) 2 - JULY 2008

No	Detail / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	PWC - Heave Calculation															
2	PWC - Pitch Calculation															
3	Submission of Progress Report 1 & 2						★									
4	PWC - Mooring Lines Configuration															
5	Finalization of project															
6	Poster Presentation										★					
7	Preparing Final Report															
8	Dissertation Report												★			
9	Oral Presentation															★

APPENDIX 2

(Analysis on Neptune Spar Platform)

WAVE PARTICLE VELOCITY

k = 0.0345 H = 7.5m T = 10.8s x = 1 θ = 0.0345

L = 182.04m d = 588.2m ρ = 1030 kg/m3 t = 0 ω = 0.5818 rad/sec

y(m)	d(m)	s(m)	kd	ks	sinh kd	tanh kd	cosh kd	cosh ks	sinh ks	u (m/s)	v(m/s)	u'(m/s2)	v'(m/s2)	ξ(m)	η(m)	P
0	588.2	588.2	20.2929	20.2929	325135578.9941	1.0000	325135578.9941	325135578.9941	325135578.9941	1.4544	0.0009	0.0005	-0.8462	-0.0015	2.5000	25250.45
-50	588.2	538.2	20.2929	18.5679	325135578.9941	1.0000	325135578.9941	57930398.3493	57930398.3493	0.2591	0.0002	0.0001	-0.1508	-0.0003	0.4454	4498.95
-100	588.2	488.2	20.2929	16.8429	325135578.9941	1.0000	325135578.9941	10321635.8643	10321635.8643	0.0462	0.0000	0.0000	-0.0269	0.0000	0.0794	801.59
-150	588.2	438.2	20.2929	15.1179	325135578.9941	1.0000	325135578.9941	1839037.3612	1839037.3612	0.0082	0.0000	0.0000	-0.0048	0.0000	0.0141	142.82
-200	588.2	388.2	20.2929	13.3929	325135578.9941	1.0000	325135578.9941	327666.8990	327666.8990	0.0015	0.0000	0.0000	-0.0009	0.0000	0.0025	25.45
-250	588.2	338.2	20.2929	11.6679	325135578.9941	1.0000	325135578.9941	58381.4114	58381.4114	0.0003	0.0000	0.0000	-0.0002	0.0000	0.0004	4.53
-300	588.2	288.2	20.2929	9.9429	325135578.9941	1.0000	325135578.9941	10401.9943	10401.9942	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.81
-350	588.2	238.2	20.2929	8.2179	325135578.9941	1.0000	325135578.9941	1853.3552	1853.3549	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.14
-400	588.2	188.2	20.2929	6.4929	325135578.9941	1.0000	325135578.9941	330.2187	330.2172	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.03
-450	588.2	138.2	20.2929	4.7679	325135578.9941	1.0000	325135578.9941	58.8402	58.8317	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
-500	588.2	88.2	20.2929	3.0429	325135578.9941	1.0000	325135578.9941	10.5068	10.4591	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
-550	588.2	38.2	20.2929	1.3179	325135578.9941	1.0000	325135578.9941	2.0016	1.7339	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00
-588.2	588.2	0	20.2929	0.0000	325135578.9941	1.0000	325135578.9941	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.00

WAVE SPECTRUM

Hs = 4.6m	Cd = 0.65
ρ = 1030 kg/m³	Cm = 1.6
d = 588.2m	Ø = 21.9m
draft = 198.8m	

ıonents	f	$\alpha g^2/(2\pi)^4$	f^{-5}	f/fo	$[-1.25\,(f/fo)^{-4}]$	$\exp[-1.25\,(f/fo)^{-4}]$	S(f)	Area	H(f)
	0.01	0.000499746	1E+10	0.10725064	-9447.358717	0	0		
	0.02	0.000499746	312500000	0.21450128	-590.4599198	3.6857E-257	5.8E-252	2.9E-254	4.8E-127
	0.03	0.000499746	41152263.4	0.32175193	-116.6340582	2.22061E-51	4.57E-47	2.28E-49	1.35E-24
	0.04	0.000499746	9765625	0.42900257	-36.90374499	9.39523E-17	4.59E-13	2.29E-15	1.35E-07
	0.05	0.000499746	3200000	0.53625321	-15.11577395	2.7246E-07	0.000436	2.18E-06	0.004175
1	0.06	0.000499746	1286008.23	0.64350385	-7.28962864	0.000682581	0.43868	0.002196	0.132532
2	0.07	0.000499746	594990.183	0.7507545	-3.934759982	0.019550391	5.813191	0.031259	0.500075
3	0.08	0.000499746	305175.781	0.85800514	-2.306484062	0.099610862	15.19169	0.105024	0.916622
4	0.09	0.000499746	169350.878	0.96525578	-1.439926645	0.236945139	20.05324	0.176225	1.187349
5	0.1	0.000499746	100000	1.07250642	-0.944735872	0.388782246	19.42924	0.197412	1.256702
6	0.11	0.000499746	62092.1323	1.17975707	-0.645267312	0.524522312	16.27608	0.178527	1.195079
7	0.12	0.000499746	40187.7572	1.28700771	-0.45560179	0.634066278	12.73438	0.145052	1.077227
8	0.13	0.000499746	26932.9074	1.39425835	-0.330778289	0.718364421	9.668907	0.112016	0.946642
9	0.14	0.000499746	18593.4432	1.50150899	-0.245922499	0.781982827	7.266183	0.084675	0.823045
10	0.15	0.000499746	13168.7243	1.60875963	-0.186614493	0.829763554	5.460688	0.063634	0.713495
11	0.16	0.000499746	9536.74316	1.71601028	-0.144155254	0.865753326	4.126136	0.047934	0.619252
12	0.17	0.000499746	7042.96278	1.82326092	-0.113113573	0.893049228	3.143259	0.036347	0.539236
13	0.18	0.000499746	5292.21494	1.93051156	-0.089995415	0.913935375	2.417143	0.027802	0.47161
14	0.19	0.000499746	4038.61073	2.0377622	-0.072492988	0.930072268	1.877146	0.021471	0.414453
15	0.2	0.000499746	3125	2.14501285	-0.059045992	0.942663413	1.472163	0.016747	0.366022
16	0.21	0.000499746	2448.51927	2.25226349	-0.048577284	0.952583717	1.165617	0.013189	0.324825
17	0.22	0.000499746	1940.37913	2.35951413	-0.040329207	0.960473193	0.931368	0.010485	0.289619
18	0.23	0.000499746	1553.6773	2.46676477	-0.033759738	0.966803763	0.750669	0.00841	0.259387
19	0.24	0.000499746	1255.86741	2.57401542	-0.028475112	0.971926483	0.609995	0.006803	0.233295
20	0.25	0.000499746	1024	2.68126606	-0.024185238	0.976104881	0.499512	0.005548	0.210666
21	0.26	0.000499746	841.653357	2.7885167	-0.020673643	0.979538592	0.412007	0.004558	0.190947
22	0.27	0.000499746	696.917194	2.89576734	-0.017776872	0.982380204	0.342145	0.003771	0.173684
23	0.28	0.000499746	581.0451	3.00301798	-0.015370156	0.984747362	0.285946	0.00314	0.158504
24	0.29	0.000499746	487.539728	3.11026863	-0.013357292	0.986731521	0.240413	0.002632	0.145101
25	0.3	0.000499746	411.522634	3.21751927	-0.011663406	0.988404348	0.203272	0.002218	0.133219

Total Area Under Curve = 1.307079

ulation

ω_o = 0.585841275

fo = 0.093239535

Mo = 1.30707868

Hs = 4 (Mo)

= 4.573101669 ≈ **4.6m (same as given in the question)**

WAVE PROFILE FOR NEPTUNE SPAR PLATFORM

Sample Calculation

f	R(n)	ε(f)	k(n)x	t(s)	2πft	cos (kx -2πft+ε(f))	H(f)	n(x,t)
0.015	0.015067	0.09467	0	0	0	0.995522095	4.7983E-127	2.3884E-127
0.025	0.984369	6.184971	0	0	0	0.995180895	1.35157E-24	6.72527E-25
0.035	0.55087	3.461216	0	0	0	-0.949353702	1.35428E-07	-6.42845E-08
0.045	0.57967	3.642171	0	0	0	-0.877305185	0.004174755	-0.001831267
0.055	0.900892	5.660472	0	0	0	0.812298859	0.132531574	0.053827623
0.065	0.710226	4.462479	0	0	0	-0.247316885	0.500074815	-0.061838473
0.075	0.289037	1.816075	0	0	0	-0.242826807	0.916621638	-0.111290153
0.085	0.449728	2.825725	0	0	0	-0.950527192	1.187348832	-0.564303676
0.095	0.575138	3.613697	0	0	0	-0.890613502	1.256701689	-0.559617746
0.105	0.548706	3.447621	0	0	0	-0.953537503	1.195078556	-0.569776111
0.115	0.404318	2.540407	0	0	0	-0.824665471	1.077227185	-0.444176032
0.125	0.610606	3.836549	0	0	0	-0.768081798	0.946642175	-0.363549312
0.135	0.895073	5.623912	0	0	0	0.790437327	0.823045329	0.325282875
0.145	0.014088	0.088521	0	0	0	0.996084609	0.713494828	0.355350608
0.155	0.920781	5.785437	0	0	0	0.878659733	0.619251956	0.272055879
0.165	0.799858	5.025659	0	0	0	0.308171201	0.539236312	0.083088551
0.175	0.984518	6.18591	0	0	0	0.995272458	0.471610063	0.234690253
0.185	0.828065	5.202883	0	0	0	0.471062098	0.414453303	0.097616621
0.195	0.142595	0.895949	0	0	0	0.624777848	0.366022358	0.11434133
0.205	0.452825	2.845185	0	0	0	-0.956391827	0.324824918	-0.155329948
0.215	0.838531	5.268647	0	0	0	0.528011703	0.289619408	0.076461218
0.225	0.085987	0.54027	0	0	0	0.857569996	0.259386713	0.111221131
0.235	0.160299	1.007188	0	0	0	0.534239642	0.233295036	0.062317728
0.245	0.266896	1.67696	0	0	0	-0.105964044	0.210666293	-0.011161526
0.255	0.726983	4.567768	0	0	0	-0.144117092	0.190946943	-0.013759359
0.265	0.271987	1.708943	0	0	0	-0.13770728	0.173683792	-0.011958761
0.275	0.028084	0.176456	0	0	0	0.984471974	0.158504373	0.078021556
0.285	0.460256	2.891875	0	0	0	-0.968982162	0.145101233	-0.070300253
0.295	0.423954	2.663779	0	0	0	-0.888002569	0.13321941	-0.059149589
							Total n(1,0)	-1.133766895

TOTAL HORIZONTAL FORCES OF NEPTUNE SPAR PLATFORM

y (m)	d (m)	s (m)	F_x
0	588.2	588.2	118643.9
-0.4	588.2	587.8	80429.03
-1.3	588.2	586.9	70790
-2.3	588.2	585.9	49681.01
-3.3	588.2	584.9	36169.76
-4.3	588.2	583.9	27257.5
-5.3	588.2	582.9	21195.84
-6.3	588.2	581.9	16946.14
-7.3	588.2	580.9	13878.74
-8.3	588.2	579.9	11603.51
-9.3	588.2	578.9	9873.164
-10.3	588.2	577.9	8527.247
-11.3	588.2	576.9	7459.15
-12.3	588.2	575.9	6596.37
-13.3	588.2	574.9	5888.476
-14.3	588.2	573.9	5299.625
-15.3	588.2	572.9	4803.825
-16.3	588.2	571.9	4381.868
-17.3	588.2	570.9	4019.316
-18.3	588.2	569.9	3705.143
-19.3	588.2	568.9	3430.805
-20.3	588.2	567.9	3189.597
-21.3	588.2	566.9	2976.19
-22.3	588.2	565.9	2786.307
-23.3	588.2	564.9	2616.478
-24.3	588.2	563.9	2463.863
-25.3	588.2	562.9	2326.117
-26.3	588.2	561.9	2201.29
-27.3	588.2	560.9	2087.748
-28.3	588.2	559.9	1984.114
-29.3	588.2	558.9	1889.219
-30.3	588.2	557.9	1802.064

y (m)	d (m)	s (m)	F_x
-31.3	588.2	556.9	1721.794
-32.3	588.2	555.9	1647.671
-33.3	588.2	554.9	1579.055
-34.3	588.2	553.9	1515.389
-35.3	588.2	552.9	1456.188
-36.3	588.2	551.9	1401.024
-37.3	588.2	550.9	1349.523
-38.3	588.2	549.9	1301.351
-39.3	588.2	548.9	1256.216
-40.3	588.2	547.9	1213.856
-41.3	588.2	546.9	1174.036
-42.3	588.2	545.9	1136.549
-43.3	588.2	544.9	1101.208
-44.3	588.2	543.9	1067.843
-45.3	588.2	542.9	1036.304
-46.3	588.2	541.9	1006.453
-47.3	588.2	540.9	978.1656
-48.3	588.2	539.9	951.3301
-49.3	588.2	538.9	925.8437
-50.3	588.2	537.9	901.613
-51.3	588.2	536.9	878.553
-52.3	588.2	535.9	856.5857
-53.3	588.2	534.9	835.6398
-54.3	588.2	533.9	815.6498
-55.3	588.2	532.9	796.5555
-56.3	588.2	531.9	778.3017
-57.3	588.2	530.9	760.8371
-58.3	588.2	529.9	744.1147
-59.3	588.2	528.9	728.0908
-60.3	588.2	527.9	712.7253
-61.3	588.2	526.9	697.9805
-62.3	588.2	525.9	683.8219

y (m)	d (m)	s (m)	F_x
-63.3	588.2	524.9	670.2172
-64.3	588.2	523.9	657.1364
-65.3	588.2	522.9	644.5516
-66.3	588.2	521.9	632.4366
-67.3	588.2	520.9	620.7672
-68.3	588.2	519.9	609.5206
-69.3	588.2	518.9	598.6756
-70.3	588.2	517.9	588.2123
-71.3	588.2	516.9	578.112
-72.3	588.2	515.9	568.3573
-73.3	588.2	514.9	558.9316
-74.3	588.2	513.9	549.8197
-75.3	588.2	512.9	541.0069
-76.3	588.2	511.9	532.4796
-77.3	588.2	510.9	524.2249
-78.3	588.2	509.9	516.2308
-79.3	588.2	508.9	508.4857
-80.3	588.2	507.9	500.9789
-81.3	588.2	506.9	493.7001
-82.3	588.2	505.9	486.6397
-83.3	588.2	504.9	479.7885
-84.3	588.2	503.9	473.1379
-85.3	588.2	502.9	466.6798
-86.3	588.2	501.9	460.4063
-87.3	588.2	500.9	454.3101
-88.3	588.2	499.9	448.3841
-89.3	588.2	498.9	442.6218
-90.3	588.2	497.9	437.0169
-91.3	588.2	496.9	431.5632
-92.3	588.2	495.9	426.2552
-93.3	588.2	494.9	421.0873
-94.3	588.2	493.9	416.0544

y (m)	d (m)	s (m)	F_x
-95.3	588.2	492.9	411.1516
-96.3	588.2	491.9	406.3742
-97.3	588.2	490.9	401.7176
-98.3	588.2	489.9	397.1777
-99.3	588.2	488.9	392.7502
-100.3	588.2	487.9	388.4314
-101.3	588.2	486.9	384.2174
-102.3	588.2	485.9	380.1047
-103.3	588.2	484.9	376.0899
-104.3	588.2	483.9	372.1697
-105.3	588.2	482.9	368.341
-106.3	588.2	481.9	364.6008
-107.3	588.2	480.9	360.9462
-108.3	588.2	479.9	357.3745
-109.3	588.2	478.9	353.883
-110.3	588.2	477.9	350.4693
-111.3	588.2	476.9	347.1308
-112.3	588.2	475.9	343.8653
-113.3	588.2	474.9	340.6704
-114.3	588.2	473.9	337.5442
-115.3	588.2	472.9	334.4844
-116.3	588.2	471.9	331.4891
-117.3	588.2	470.9	328.5564
-118.3	588.2	469.9	325.6844
-119.3	588.2	468.9	322.8714
-120.3	588.2	467.9	320.1157
-121.3	588.2	466.9	317.4156
-122.3	588.2	465.9	314.7696
-123.3	588.2	464.9	312.1761
-124.3	588.2	463.9	309.6337
-125.3	588.2	462.9	307.1409
-126.3	588.2	461.9	304.6963

y (m)	d (m)	s (m)	F_x
-127.3	588.2	460.9	302.2988
-128.3	588.2	459.9	299.9469
-129.3	588.2	458.9	297.6395
-130.3	588.2	457.9	295.3754
-131.3	588.2	456.9	293.1534
-132.3	588.2	455.9	290.9725
-133.3	588.2	454.9	288.8315
-134.3	588.2	453.9	286.7294
-135.3	588.2	452.9	284.6653
-136.3	588.2	451.9	282.6381
-137.3	588.2	450.9	280.647
-138.3	588.2	449.9	278.6909
-139.3	588.2	448.9	276.7692
-140.3	588.2	447.9	274.8808
-141.3	588.2	446.9	273.0251
-142.3	588.2	445.9	271.2011
-143.3	588.2	444.9	269.4082
-144.3	588.2	443.9	267.6455
-145.3	588.2	442.9	265.9124
-146.3	588.2	441.9	264.2082
-147.3	588.2	440.9	262.5322
-148.3	588.2	439.9	260.8836
-149.3	588.2	438.9	259.262
-150.3	588.2	437.9	257.6666
-151.3	588.2	436.9	256.0969
-152.3	588.2	435.9	254.5523
-153.3	588.2	434.9	253.0321
-154.3	588.2	433.9	251.536
-155.3	588.2	432.9	250.0633
-156.3	588.2	431.9	248.6135
-157.3	588.2	430.9	247.1861
-158.3	588.2	429.9	245.7806

y (m)	d (m)	s (m)	F_x
-159.3	588.2	428.9	244.3966
-160.3	588.2	427.9	243.0336
-161.3	588.2	426.9	241.6911
-162.3	588.2	425.9	240.3687
-163.3	588.2	424.9	239.066
-164.3	588.2	423.9	237.7826
-165.3	588.2	422.9	236.518
-166.3	588.2	421.9	235.2718
-167.3	588.2	420.9	234.0438
-168.3	588.2	419.9	232.8335
-169.3	588.2	418.9	231.6405
-170.3	588.2	417.9	230.4645
-171.3	588.2	416.9	229.3052
-172.3	588.2	415.9	228.1623
-173.3	588.2	414.9	227.0353
-174.3	588.2	413.9	225.924
-175.3	588.2	412.9	224.8282
-176.3	588.2	411.9	223.7473
-177.3	588.2	410.9	222.6813
-178.3	588.2	409.9	221.6298
-179.3	588.2	408.9	220.5925
-180.3	588.2	407.9	219.5692
-181.3	588.2	406.9	218.5595
-182.3	588.2	405.9	217.5633
-183.3	588.2	404.9	216.5803
-184.3	588.2	403.9	215.6102
-185.3	588.2	402.9	214.6528
-186.3	588.2	401.9	213.7078
-187.3	588.2	400.9	212.7751
-188.3	588.2	399.9	211.8544
-189.3	588.2	398.9	210.9455
-190.3	588.2	397.9	210.0482

y (m)	d (m)	s (m)	F_x
-191.3	588.2	396.9	209.1623
-192.3	588.2	395.9	208.2875
-193.3	588.2	394.9	207.4237
-194.3	588.2	393.9	206.5706
-195.3	588.2	392.9	205.7282
-196.3	588.2	391.9	204.8962
-197.3	588.2	390.9	204.0744
-198.3	588.2	389.9	203.2626
Total Force =		**616489.5844**	

SURGE RESPONSE SPECTRUM

Calculation for Surge Force

Calculation for Stiffness (k_{surge})

Total Mass =	77170287.63	kg
Added Mass for surge =	77170287.63	kg
Total Mass + Added Mass =	154340575.3	kg
Natural Period (T_N) =	325	sec
Natural Frequency (ω_n) =	0.019332878	rad/sec
Stiffness (k_{surge}) =	57686.35914	N/m

Given,

C = 119353.8997

RAO

f	Fx(f)	H(f)	H(f)/2	w	k	m	$(k-m\omega^2)^2$	c	$(c\omega)^2$	RAO
0.015	1378018.085	4.7983E-127	2.3991E-127	0.09424778	57686.35914	154340575.2501	1.72467E+12	119353.8997	126536402.1	4.3735E+126
0.025	929310.7735	1.35157E-24	6.75783E-25	0.157079633	57686.35914	154340575.2501	1.40664E+13	119353.8997	351490005.8	3.66655E+23
0.035	808270.2161	1.35428E-07	6.7714E-08	0.219911486	57686.35914	154340575.2501	5.48546E+13	119353.8997	688920411.4	1611644.046
0.045	559892.8214	0.004174755	0.002087378	0.282743339	57686.35914	154340575.2501	1.5082E+14	119353.8997	1138827619	21.84100156
0.055	402623.776	0.132531574	0.066265787	0.345575192	57686.35914	154340575.2501	3.37604E+14	119353.8997	1701211628	0.330677839
0.065	300040.9004	0.500074815	0.250037407	0.408407045	57686.35914	154340575.2501	6.59758E+14	119353.8997	2376072439	0.046717801
0.075	231044.8895	0.916621638	0.458310819	0.471238898	57686.35914	154340575.2501	1.17074E+15	119353.8997	3163410052	0.014733464
0.085	183191.4247	1.187348832	0.593674416	0.534070751	57686.35914	154340575.2501	1.93293E+15	119353.8997	4063224467	0.007018561
0.095	148995.3732	1.256701689	0.628350844	0.596902604	57686.35914	154340575.2501	3.01761E+15	119353.8997	5075515684	0.004316572
0.105	123858.3639	1.195078556	0.597539278	0.659734457	57686.35914	154340575.2501	4.50496E+15	119353.8997	6200283702	0.003088256
0.115	104891.6223	1.077227185	0.538613592	0.72256631	57686.35914	154340575.2501	6.48409E+15	119353.8997	7437528523	0.002418459
0.125	90237.80105	0.946642175	0.473321088	0.785398164	57686.35914	154340575.2501	9.05302E+15	119353.8997	8787250145	0.002003714
0.135	78674.21909	0.823045329	0.411522664	0.848230017	57686.35914	154340575.2501	1.23187E+16	119353.8997	10249448569	0.00172249
0.145	69376.85369	0.713494828	0.356747414	0.91106187	57686.35914	154340575.2501	1.63969E+16	119353.8997	11824123795	0.001518705
0.155	61777.45219	0.619251956	0.309625978	0.973893723	57686.35914	154340575.2501	2.14123E+16	119353.8997	13511275823	0.001363516
0.165	55475.40275	0.539236312	0.269618156	1.036725576	57686.35914	154340575.2501	2.74988E+16	119353.8997	15310904653	0.001240779
0.175	50182.32636	0.471610063	0.235805032	1.099557429	57686.35914	154340575.2501	3.47987E+16	119353.8997	17223010285	0.001140817
0.185	45686.55372	0.414453303	0.207226651	1.162389282	57686.35914	154340575.2501	4.34637E+16	119353.8997	19247592718	0.001057498
0.195	41829.90019	0.366022358	0.183011179	1.225221135	57686.35914	154340575.2501	5.3654E+16	119353.8997	21384651953	0.000986752
0.205	38492.18425	0.324824918	0.162412459	1.288052988	57686.35914	154340575.2501	6.55389E+16	119353.8997	23634187991	0.000925771
0.215	35580.71125	0.289619408	0.144809704	1.350884841	57686.35914	154340575.2501	7.92968E+16	119353.8997	25996200830	0.000872547
0.225	33022.99896	0.259386713	0.129693357	1.413716694	57686.35914	154340575.2501	9.51146E+16	119353.8997	28470690470	0.00082561
0.235	30761.65795	0.233295036	0.116647518	1.476548547	57686.35914	154340575.2501	1.13188E+17	119353.8997	31057656913	0.00078385
0.245	28750.72921	0.210666293	0.105333146	1.5393804	57686.35914	154340575.2501	1.33723E+17	119353.8997	33757100158	0.000746415
0.255	26953.02383	0.190946943	0.095473472	1.602212254	57686.35914	154340575.2501	1.56933E+17	119353.8997	36569020204	0.000712636
0.265	25338.16284	0.173683792	0.086841896	1.665044107	57686.35914	154340575.2501	1.8304E+17	119353.8997	39493417053	0.000681982
0.275	23881.11369	0.158504373	0.079252186	1.72787596	57686.35914	154340575.2501	2.12276E+17	119353.8997	42530290703	0.000654022
0.285	22561.084	0.145101233	0.072550616	1.790707813	57686.35914	154340575.2501	2.44883E+17	119353.8997	45679641155	0.000628405
0.295	21360.67583	0.13321941	0.066609705	1.853539666	57686.35914	154340575.2501	2.81108E+17	119353.8997	48941468409	0.00060484

$S(f)_{surge}$ & $H(f)_{surge}$

f	RAO^2	S(f)	$S(f)_{surge}$	$H(f)_{surge}$
0.015	1.9127E+253	5.7559E-252	110.0962578	2.967777052
0.025	1.34436E+47	4.56683E-47	6.13944834	0.700825133
0.035	2.5974E+12	4.58518E-13	1.19095352	0.308668563
0.045	477.0293489	0.000435715	0.207848639	0.128949181
0.055	0.109347833	0.43867974	0.047968679	0.061947513
0.065	0.002182553	5.813190767	0.012687597	0.031859186
0.075	0.000217075	15.19168992	0.003297736	0.016242501
0.085	4.92602E-05	20.0532413	0.000987827	0.008889665
0.095	1.86328E-05	19.42923705	0.000362021	0.005381605
0.105	9.53732E-06	16.27608181	0.00015523	0.003523978
0.115	5.84894E-06	12.73437836	7.44827E-05	0.002441027
0.125	4.01487E-06	9.668906839	3.88194E-05	0.001762258
0.135	2.96697E-06	7.266183485	2.15586E-05	0.001313273
0.145	2.30646E-06	5.460688246	1.25949E-05	0.001003788
0.155	1.85918E-06	4.12613638	7.67122E-06	0.000783388
0.165	1.53953E-06	3.143258623	4.83915E-06	0.000622199
0.175	1.30146E-06	2.417142671	3.14582E-06	0.000501663
0.185	1.1183E-06	1.877145832	2.09922E-06	0.000409801
0.195	9.7368E-07	1.472163332	1.43342E-06	0.000338634
0.205	8.57051E-07	1.16561735	9.98994E-07	0.0002827
0.215	7.61339E-07	0.931367688	7.09087E-07	0.000238174
0.225	6.81632E-07	0.750668989	5.1168E-07	0.000202323
0.235	6.14421E-07	0.609995359	3.74794E-07	0.000173158
0.245	5.57135E-07	0.499511814	2.78296E-07	0.00014921
0.255	5.0785E-07	0.412006563	2.09238E-07	0.000129379
0.265	4.65099E-07	0.342144927	1.59131E-07	0.00011283
0.275	4.27745E-07	0.285945978	1.22312E-07	9.89189E-05
0.285	3.94893E-07	0.240413215	9.49376E-08	8.71493E-05
0.295	3.65832E-07	0.203272064	7.43634E-08	7.71302E-05

SURGE PROFILE

le Calculation for Surge Profile when t = 0s

f	R(n)	ε(f)	k(n)x	t(s)	2πft	cos (kx -2πft+ε(f))	H(f)	n(x,t)
0.015	0.590346	3.709253	0	0	0	-0.843161399	2.967777052	-1.25115753
0.025	0.784883	4.931563	0	0	0	0.21742351	0.700825133	0.07618793
0.035	0.396685	2.492448	0	0	0	-0.796601293	0.308668563	-0.12294289
0.045	0.318689	2.002385	0	0	0	-0.41831428	0.128949181	-0.02697064
0.055	0.075109	0.471921	0	0	0	0.890696692	0.061947513	0.027588222
0.065	0.583771	3.667944	0	0	0	-0.864646024	0.031859186	-0.01377346
0.075	0.154257	0.969224	0	0	0	0.565939128	0.016242501	0.004596133
0.085	0.772666	4.854805	0	0	0	0.141935095	0.008889665	0.000630878
0.095	0.418184	2.627525	0	0	0	-0.870751641	0.005381605	-0.00234302
0.105	0.559345	3.514467	0	0	0	-0.931283972	0.003523978	-0.00164091
0.115	0.880431	5.531913	0	0	0	0.730821289	0.002441027	0.000891977
0.125	0.614405	3.860422	0	0	0	-0.752576833	0.001762258	-0.00066312
0.135	0.053284	0.334791	0	0	0	0.944478972	0.001313273	0.000620179
0.145	0.88508	5.561125	0	0	0	0.750445431	0.001003788	0.000376644
0.155	0.889892	5.591355	0	0	0	0.770079557	0.000783388	0.000301636
0.165	0.797716	5.012199	0	0	0	0.295339084	0.000622199	9.18799E-05
0.175	0.016021	0.100662	0	0	0	0.994937858	0.000501663	0.000249562
0.185	0.321388	2.01934	0	0	0	-0.433653697	0.000409801	-8.8856E-05
0.195	0.716178	4.499876	0	0	0	-0.210916665	0.000338634	-3.5712E-05
0.205	0.429471	2.698449	0	0	0	-0.903408153	0.0002827	-0.0001277
0.215	0.463805	2.914172	0	0	0	-0.974251082	0.000238174	-0.00011602
0.225	0.782458	4.916328	0	0	0	0.202528399	0.000202323	2.0488E-05
0.235	0.894312	5.619126	0	0	0	0.787496875	0.000173158	6.81805E-05
0.245	0.034642	0.217663	0	0	0	0.976404793	0.00014921	7.28447E-05
0.255	0.513576	3.226892	0	0	0	-0.99636418	0.000129379	-6.4454E-05
0.265	0.287361	1.805539	0	0	0	-0.232593098	0.00011283	-1.3122E-05
0.275	0.413784	2.599884	0	0	0	-0.856829075	9.89189E-05	-4.2378E-05
0.285	0.548957	3.449196	0	0	0	-0.953061887	8.71493E-05	-4.1529E-05
0.295	0.847911	5.327581	0	0	0	0.577115453	7.71302E-05	2.22565E-05
							Total n(1,0)	**-1.30830252**

HEAVE RESPONSE SPECTRUM

Calculation for Heave Force

Calculation for Stiffness (k_{heave})

Total Mass =	7.71E+07	kg
Added Mass for heave =	2832293.11	kg
Total Mass + Added Mass =	8.00E+07	kg
Natural Period (T_N) =	28.7991929	sec
Natural Frequency (ω_n) =	0.218172271	rad/sec
Stiffness (k_{heave}) =	3806136.358	N/m

Given,

C = 6.98E+05

RAO

f	Fheave(f)	H(f)	H(f)2	w	k	m	$(k-m\omega^2)^2$	c	$(c\omega)^2$	RAO
0.055	3598129.65	0.132531574	0.066265787	0.3456	3806136.358	79962293.1104	3.29836E+13	697822.2021	58153342479	9.446168879
0.065	1373039.541	0.500074815	0.250037407	0.4084	3806136.358	79962293.1104	9.08453E+13	697822.2021	81222437016	0.575881061
0.075	446722.5178	0.916621638	0.458310819	0.4712	3806136.358	79962293.1104	1.94624E+14	697822.2021	1.08136E+11	0.069848758
0.085	123448.0776	1.187348832	0.593674416	0.5341	3806136.358	79962293.1104	3.61062E+14	697822.2021	1.38895E+11	0.010941114
0.095	29382.28406	1.256701689	0.628350844	0.5969	3806136.358	79962293.1104	6.09292E+14	697822.2021	1.73499E+11	0.001894125
0.105	5820.236999	1.195078556	0.597539278	0.6597	3806136.358	79962293.1104	9.6084E+14	697822.2021	2.11947E+11	0.000314196
0.115	1010.10977	1.077227185	0.538613592	0.7226	3806136.358	79962293.1104	1.43962E+15	697822.2021	2.54241E+11	4.9423E-05
0.125	144.8418897	0.946642175	0.473321088	0.7854	3806136.358	79962293.1104	2.07195E+15	697822.2021	3.00379E+11	6.7223E-06
0.135	18.01827143	0.823045329	0.411522664	0.8482	3806136.358	79962293.1104	2.88651E+15	697822.2021	3.50362E+11	8.14904E-07
0.145	1.896543	0.713494828	0.356747414	0.9111	3806136.358	79962293.1104	3.91441E+15	697822.2021	4.0419E+11	8.49662E-08
0.155	0.163867049	0.619251956	0.309625978	0.9739	3806136.358	79962293.1104	5.18913E+15	697822.2021	4.61862E+11	7.34662E-09
0.165	0.012399299	0.539236312	0.269618156	1.0367	3806136.358	79962293.1104	6.74654E+15	697822.2021	5.2338E+11	5.59874E-10
0.175	0.0007655	0.471610063	0.235805032	1.0996	3806136.358	79962293.1104	8.62491E+15	697822.2021	5.88743E+11	3.49543E-11
0.185	4.50095E-05	0.414453303	0.207226651	1.1624	3806136.358	79962293.1104	1.08649E+16	697822.2021	6.5795E+11	2.08369E-12
0.195	2.00673E-06	0.366022358	0.183011179	1.2252	3806136.358	79962293.1104	1.35096E+16	697822.2021	7.31002E+11	9.43362E-14
0.205	7.80595E-08	0.324824918	0.162412459	1.2881	3806136.358	79962293.1104	1.66043E+16	697822.2021	8.07899E+11	3.7298E-15
0.215	2.43545E-09	0.289619408	0.144809704	1.3509	3806136.358	79962293.1104	2.0197E+16	697822.2021	8.88641E+11	1.18339E-16
0.225	6.29961E-11	0.259386713	0.129693357	1.4137	3806136.358	79962293.1104	2.43379E+16	697822.2021	9.73227E+11	3.11348E-18
0.235	1.75684E-12	0.233295036	0.116647518	1.4765	3806136.358	79962293.1104	2.90796E+16	697822.2021	1.06166E+12	8.83193E-20
0.245	2.99253E-14	0.210666293	0.105333146	1.5394	3806136.358	79962293.1104	3.4477E+16	697822.2021	1.15394E+12	1.53003E-21
0.255	4.9057E-16	0.190946943	0.095473472	1.6022	3806136.358	79962293.1104	4.05877E+16	697822.2021	1.25006E+12	2.55044E-23
0.265	6.33044E-18	0.173683792	0.086841896	1.6650	3806136.358	79962293.1104	4.74713E+16	697822.2021	1.35002E+12	3.34567E-25
0.275	9.25956E-20	0.158504373	0.079252186	1.7279	3806136.358	79962293.1104	5.51901E+16	697822.2021	1.45383E+12	4.97328E-27
0.285	8.27934E-22	0.145101233	0.072550616	1.7907	3806136.358	79962293.1104	6.38086E+16	697822.2021	1.56149E+12	4.51762E-29
0.295	6.41126E-24	0.13321941	0.066609705	1.8535	3806136.358	79962293.1104	7.33939E+16	697822.2021	1.67299E+12	3.5528E-31

$S(f)_{heave}$ & $H(f)_{heave}$

f	RAO^2	S(f)	$S(f)_{heave}$	$H(f)_{heave}$
0.055	89.23010649	0.43867974	39.14343995	0
0.065	0.331638997	5.813190767	1.927880754	1.281738206
0.075	0.004878849	15.19168992	0.07411796	0.282984008
0.085	0.000119708	20.0532413	0.002400533	0.055323952
0.095	3.58771E-06	19.42923705	6.97065E-05	0.0099403
0.105	9.87192E-08	16.27608181	1.60676E-06	0.001688943
0.115	2.44263E-09	12.73437836	3.11054E-08	0.000255958
0.125	4.51893E-11	9.668906839	4.36931E-10	3.55203E-05
0.135	6.64068E-13	7.266183485	4.82524E-12	4.2036E-06
0.145	7.21925E-15	5.460688246	3.94221E-14	4.4112E-07
0.155	5.39728E-17	4.12613638	2.22699E-16	3.9822E-08
0.165	3.13459E-19	3.143258623	9.85284E-19	2.99122E-09
0.175	1.2218E-21	2.417142671	2.95327E-21	1.9882E-10
0.185	4.34176E-24	1.877145832	8.15011E-24	1.08838E-11
0.195	8.89932E-27	1.472163332	1.31013E-26	5.71427E-13
0.205	1.39114E-29	1.16561735	1.62154E-29	2.29063E-14
0.215	1.40041E-32	0.931367688	1.3043E-32	8.0569E-16
0.225	9.69373E-36	0.750668989	7.27679E-36	2.28475E-17
0.235	7.80029E-39	0.609995359	4.75814E-39	5.39687E-19
0.245	2.341E-42	0.499511814	1.16936E-42	1.37976E-20
0.255	6.50473E-46	0.412006563	2.67999E-46	2.16298E-22
0.265	1.11935E-49	0.342144927	3.8298E-50	3.27437E-24
0.275	2.47335E-53	0.285945978	7.07245E-54	3.91434E-26
0.285	2.04089E-57	0.240413215	4.90656E-58	5.319E-28
0.295	1.26224E-61	0.203272064	2.56578E-62	4.43027E-30

HEAVE PROFILE

urge Profile when t = 0s

f	R(n)	ε(f)	k(n)x	t(s)	2πft	cos (kx -2πft+ε(f))	H(f)	n(x,t)
0.0550	0.6846	4.3013	0.0000	0.0000	0.0000	-0.3996	0.0000	0.0000
0.0650	0.1443	0.9069	0.0000	0.0000	0.0000	0.6162	1.2817	0.3949
0.0750	0.6345	3.9870	0.0000	0.0000	0.0000	-0.6634	0.2830	-0.0939
0.0850	0.6475	4.0686	0.0000	0.0000	0.0000	-0.6002	0.0553	-0.0166
0.0950	0.8397	5.2759	0.0000	0.0000	0.0000	0.5342	0.0099	0.0027
0.1050	0.2247	1.4119	0.0000	0.0000	0.0000	0.1582	0.0017	0.0001
0.1150	0.3552	2.2319	0.0000	0.0000	0.0000	-0.6140	0.0003	-0.0001
0.1250	0.2422	1.5216	0.0000	0.0000	0.0000	0.0492	0.0000	0.0000
0.1350	0.0059	0.0370	0.0000	0.0000	0.0000	0.9993	0.0000	0.0000
0.1450	0.2607	1.6382	0.0000	0.0000	0.0000	-0.0673	0.0000	0.0000
0.1550	0.9184	5.7706	0.0000	0.0000	0.0000	0.8715	0.0000	0.0000
0.1650	0.1626	1.0217	0.0000	0.0000	0.0000	0.5220	0.0000	0.0000
0.1750	0.7041	4.4242	0.0000	0.0000	0.0000	-0.2842	0.0000	0.0000
0.1850	0.5095	3.2014	0.0000	0.0000	0.0000	-0.9982	0.0000	0.0000
0.1950	0.5313	3.3380	0.0000	0.0000	0.0000	-0.9808	0.0000	0.0000
0.2050	0.7354	4.6208	0.0000	0.0000	0.0000	-0.0915	0.0000	0.0000
0.2150	0.0705	0.4430	0.0000	0.0000	0.0000	0.9035	0.0000	0.0000
0.2250	0.3631	2.2815	0.0000	0.0000	0.0000	-0.6523	0.0000	0.0000
0.2350	0.3100	1.9476	0.0000	0.0000	0.0000	-0.3679	0.0000	0.0000
0.2450	0.5923	3.7217	0.0000	0.0000	0.0000	-0.8364	0.0000	0.0000
0.2550	0.8467	5.3198	0.0000	0.0000	0.0000	0.5707	0.0000	0.0000
0.2650	0.5317	3.3408	0.0000	0.0000	0.0000	-0.9802	0.0000	0.0000
0.2750	0.2754	1.7301	0.0000	0.0000	0.0000	-0.1586	0.0000	0.0000
0.2850	0.4411	2.7717	0.0000	0.0000	0.0000	-0.9324	0.0000	0.0000
0.2950	0.2298	1.4438	0.0000	0.0000	0.0000	0.1266	0.0000	0.0000
							Total n(1,0)	0.2871

PITCH RESPONSE SPECTRUM

Assume,

Pitch of Gyration, R_x = 65 m

Mass + Added Mass = 154340575.3 kg

Total Moment of Inertia, I = 6.52089E+11 $kg.m^2$

Natural Period, T_N = 65 s

Natural Frequency, ω_N = 0.096664389

Stiffness of Pitch, k_{pitch} = 6093121685

C = 596769.4984

RAO

f	M(f)	H(f)	H(f)/2	w	k	m	$(k-m\omega^2)^2$	c	$(c\omega)^2$	RAO
0.015	-1433336.992	4.7983E-127	2.3991E-127	0.094248	6093121685	154325922.9	3.71094E+19	596769.498	3.16E+09	-9.807E+122
0.025	-3031351.897	1.35157E-24	6.75783E-25	0.15708	6093121685	154325922.9	3.70797E+19	596712.844	8.79E+09	-7.3665E+20
0.035	-6042119.148	1.35428E-07	6.7714E-08	0.219911	6093121685	154325922.9	3.70352E+19	596712.844	1.72E+10	-14662.3453
0.045	-9655205.276	0.004174755	0.002087378	0.282743	6093121685	154325922.9	3.69759E+19	596712.844	2.85E+10	-0.76067803
0.055	-12712668.08	0.132531574	0.066265787	0.345575	6093121685	154325922.9	3.69019E+19	596712.844	4.25E+10	-0.0315808
0.065	-14947054.04	0.500074815	0.250037407	0.408407	6093121685	154325922.9	3.68131E+19	596712.844	5.94E+10	-0.00985257
0.075	-16535315.18	0.916621638	0.458310819	0.471239	6093121685	154325922.9	3.67097E+19	596712.844	7.91E+10	-0.00595473
0.085	-17717820.83	1.187348832	0.593674416	0.534071	6093121685	154325922.9	3.65916E+19	596712.844	1.02E+11	-0.00493368
0.095	-18648959.43	1.256701689	0.628350844	0.596903	6093121685	154325922.9	3.64591E+19	596712.844	1.27E+11	-0.00491529
0.105	-19446741.73	1.195078556	0.597539278	0.659734	6093121685	154325922.9	3.63121E+19	596712.844	1.55E+11	-0.00540076
0.115	-20144507.7	1.077227185	0.538613592	0.722566	6093121685	154325922.9	3.61507E+19	596712.844	1.86E+11	-0.00622044
0.125	-20802236.98	0.946642175	0.473321088	0.785398	6093121685	154325922.9	3.59751E+19	596712.844	2.2E+11	-0.00732745
0.135	-21425517.46	0.823045329	0.411522664	0.84823	6093121685	154325922.9	3.57853E+19	596712.844	2.56E+11	-0.00870332
0.145	-22038023.49	0.713494828	0.356747414	0.911062	6093121685	154325922.9	3.55815E+19	596712.844	2.96E+11	-0.01035618
0.155	-22657277.5	0.619251956	0.309625978	0.973894	6093121685	154325922.9	3.53638E+19	596712.844	3.38E+11	-0.01230526
0.165	-23274224.78	0.539236312	0.269618156	1.036726	6093121685	154325922.9	3.51323E+19	596712.844	3.83E+11	-0.01456373
0.175	-23911050.1	0.471610063	0.235805032	1.099557	6093121685	154325922.9	3.48872E+19	596712.844	4.3E+11	-0.01716772
0.185	-24537000	0.414453303	0.207226651	1.162389	6093121685	154325922.9	3.46286E+19	596712.844	4.81E+11	-0.02012142
0.195	-25205196.76	0.366022358	0.183011179	1.225221	6093121685	154325922.9	3.43566E+19	596712.844	5.35E+11	-0.02349672
0.205	-25886726.53	0.324824918	0.162412459	1.288053	6093121685	154325922.9	3.40715E+19	596712.844	5.91E+11	-0.02730624
0.215	-26600606.12	0.289619408	0.144809704	1.350885	6093121685	154325922.9	3.37735E+19	596712.844	6.5E+11	-0.03160866
0.225	-27340718.96	0.259386713	0.129693357	1.413717	6093121685	154325922.9	3.34626E+19	596712.844	7.12E+11	-0.03644285
0.235	-28055568.42	0.233295036	0.116647518	1.476549	6093121685	154325922.9	3.31391E+19	596712.844	7.76E+11	-0.04178043
0.245	-28858827.5	0.210666293	0.105333146	1.53938	6093121685	154325922.9	3.28033E+19	596712.844	8.44E+11	-0.047836
0.255	-29660394.27	0.190946943	0.095473472	1.602212	6093121685	154325922.9	3.24553E+19	596712.844	9.14E+11	-0.05453201
0.265	-30499828.1	0.173683792	0.086841896	1.665044	6093121685	154325922.9	3.20953E+19	596712.844	9.87E+11	-0.06199366
0.275	-31307372.13	0.158504373	0.079252186	1.727876	6093121685	154325922.9	3.17236E+19	596712.844	1.06E+12	-0.07013648
0.285	-32200853.22	0.145101233	0.072550616	1.790708	6093121685	154325922.9	3.13405E+19	596712.844	1.14E+12	-0.07928182
0.295	-33113290.64	0.13321941	0.066609705	1.85354	6093121685	154325922.9	3.09461E+19	596712.844	1.22E+12	-0.08936391

$S(f)_{surge}$ & $H(f)_{surge}$

f	RAO2	S(f)	$S(f)_{surge}$	$H(f)_{surge}$
0.015	9.6183E+245	6.92595E-92	6.6616E+154	7.3E+76
0.025	5.42651E+41	1.90734E-15	1.03502E+27	9.1E+12
0.035	214984368.5	0.004638519	997209.1365	282.4477
0.045	0.57863106	5.460839709	3.159811467	0.502777
0.055	0.000997347	41.53826757	0.041428059	0.057569
0.065	9.70731E-05	67.79107575	0.006580688	0.022945
0.075	3.54588E-05	64.10914915	0.002273234	0.013486
0.085	2.43412E-05	49.26800592	0.001199242	0.009795
0.095	2.41601E-05	35.04163253	0.00084661	0.00823
0.105	2.91682E-05	24.34944873	0.000710229	0.007538
0.115	3.86938E-05	16.92374799	0.000654844	0.007238
0.125	5.36916E-05	11.88653059	0.000638207	0.007145
0.135	7.57478E-05	8.471859259	0.000641725	0.007165
0.145	0.00010725	6.135368943	0.000658021	0.007255
0.155	0.000151419	4.514666754	0.000683608	0.007395
0.165	0.000212102	3.373234124	0.000715471	0.007566
0.175	0.000294731	2.556825333	0.000753575	0.007764
0.185	0.000404871	1.964046125	0.000795186	0.007976
0.195	0.000552096	1.527439554	0.000843293	0.008214
0.205	0.000745631	1.201505752	0.00089588	0.008466
0.215	0.000999107	0.955113253	0.000954261	0.008737
0.225	0.001328081	0.766657029	0.001018183	0.009025
0.235	0.001745604	0.620935451	0.001083908	0.009312
0.245	0.002288283	0.507110562	0.001160412	0.009635
0.255	0.00297374	0.41735824	0.001241115	0.009964
0.265	0.003843214	0.345962969	0.00132961	0.010314
0.275	0.004919125	0.288702813	0.001420165	0.010659
0.285	0.006285607	0.242426253	0.001523796	0.011041
0.295	0.007985908	0.204757481	0.001635174	0.011437

PITCH PROFILE

Sample Calculation for Pitch Profile when t = 0s

f	R(n)	ε(f)	k(n)x	t(s)	2πft	cos (kx -2πft+ε(f))	H(f)	n(x,t)
0.055	0.311565	1.957622	0	0	0	-0.377250848	0.057569477	-0.010859067
0.065	0.291759	1.833178	0	0	0	-0.259381732	0.022944607	-0.002975706
0.075	0.539935	3.392512	0	0	0	-0.968684633	0.013485501	-0.006531599
0.085	0.048558	0.305097	0	0	0	0.953817783	0.009794865	0.004671258
0.095	0.747071	4.693985	0	0	0	-0.018402872	0.00822975	-7.57255E-05
0.105	0.071004	0.446133	0	0	0	0.902122352	0.007537795	0.003400007
0.115	0.088147	0.553845	0	0	0	0.850508322	0.007237925	0.003077958
0.125	0.563883	3.54298	0	0	0	-0.920519883	0.007145385	-0.003288735
0.135	0.842698	5.29483	0	0	0	0.550064382	0.007165052	0.00197062
0.145	0.661526	4.156493	0	0	0	-0.527704326	0.007255458	-0.001914368
0.155	0.157937	0.992348	0	0	0	0.54672515	0.007395178	0.002021565
0.165	0.335702	2.109279	0	0	0	-0.512833984	0.007565557	-0.001939937
0.175	0.074133	0.465788	0	0	0	0.89346778	0.007764404	0.003468622
0.185	0.374162	2.350927	0	0	0	-0.703372624	0.007975895	-0.002805013
0.195	0.764609	4.804182	0	0	0	0.091664504	0.008213613	0.000376448
0.205	0.723832	4.54797	0	0	0	-0.163679656	0.008465836	-0.000692843
0.215	0.385145	2.419936	0	0	0	-0.750712369	0.008737325	-0.003279609
0.225	0.361513	2.271456	0	0	0	-0.644721728	0.009025222	-0.002909378
0.235	0.987496	6.204621	0	0	0	0.99691545	0.009311961	0.004641619
0.245	0.434978	2.733045	0	0	0	-0.917698604	0.009634987	-0.004421007
0.255	0.627495	3.94267	0	0	0	-0.695933354	0.009964396	-0.003467278
0.265	0.488711	3.070659	0	0	0	-0.997485274	0.010313523	-0.005143794
0.275	0.301305	1.893153	0	0	0	-0.316802905	0.01065895	-0.001688393
0.285	0.899803	5.653629	0	0	0	0.808289042	0.011041	0.00446216
0.295	0.53222	3.344034	0	0	0	-0.979578567	0.011437393	-0.005601912
							Total n(1,0)	**-0.029504108**