CERTIFICATION OF APPROVAL

ANALYSIS OF KIKEH TRUSS SPAR SUBJECTED TO REGULAR WAVES

by

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

NORHIDAYAH BINTI NGADNI

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ABSTRACT

This report describes an analysis of Kikeh Truss Spar subjected a regular wave loading. Many innovative floating offshore structures have been constructed over the world nowadays. This is because shallow water hydrocarbon reserves continue to reduce while global demand increases. One such type of floating offshore structures is the Spar platform. Recently, the first Malaysia deepwater platform was installed which is Kikeh Truss Spar. A Study on this Kikeh Spar Platform was conducted to analyze its dynamic behavior when subjected to regular waves. Generally, the spar platform is described as a rigid body with six degree of freedom at the Center of Gravity (COG). A unidirectional regular wave is used for computing the incident wave kinematics by Airy's wave theory and excitation forces by Morison equation. Severe storm wave was predicted using the P-M model. The response analysis was conducted in frequency domain approach without any iteration by using Response-Amplitude Operator as transfer function. It is important to analyze the motion response of spar in order to ensure its stability even during extreme wave condition. Parametric study was also conducted to observe the response behavior with changing parameters. The results obtained from the analysis are presented using graphs and tables.

Key words: Regular wave, Kikeh Truss Spar, dynamic analysis, frequency domain, parametric study

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CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Spar Technology

As oil and gas exploration are pushed into deeper water, many innovative floating offshore structures are being constructed and installed worldwide. This is due to increasing global demand for oil while in contrast shallow water oil reserves continue to reduce. Those floating structures such as Tension Leg Platform, Spar and FPSO are therefore become main interest for water depth region of 1000 to 3000 m.

Spar platform is one of the compliant floating offshore structures used for deep and very deep water application which are more than 600 m water depth. This type of platform is among the largest offshore platforms in use and designed to support drilling, production, processing, storage and offloading operation. It consists of large cylinder which floats vertically in the water and tethered to the seafloor with multiple taut mooring lines. This cylinder serves to stabilize the platform in the water and allows for movement to absorb the force of potential hurricanes [Luis, 2001]. The main function of the mooring lines is to provide restoring force to the cylinder and reduce its degree of freedom. Other than that, the floating spar platform is designed so that its center of gravity is lower than its center of buoyancy for stability. Its buoyancy is used to support facilities above the water surface. The concept of spar platform was widely recognized due to its adaptation of wide range of water depth and benign motion characteristics [Zhang *et al.*, 2006]. This type of platform is commonly used in the Gulf of Mexico for oil production. For example, the world's first production spar was the Neptune Spar installed in 1996 by Kerr-McGee. Figure 1.1 shows the progression of spars technology built by Technip Offshore, Inc.

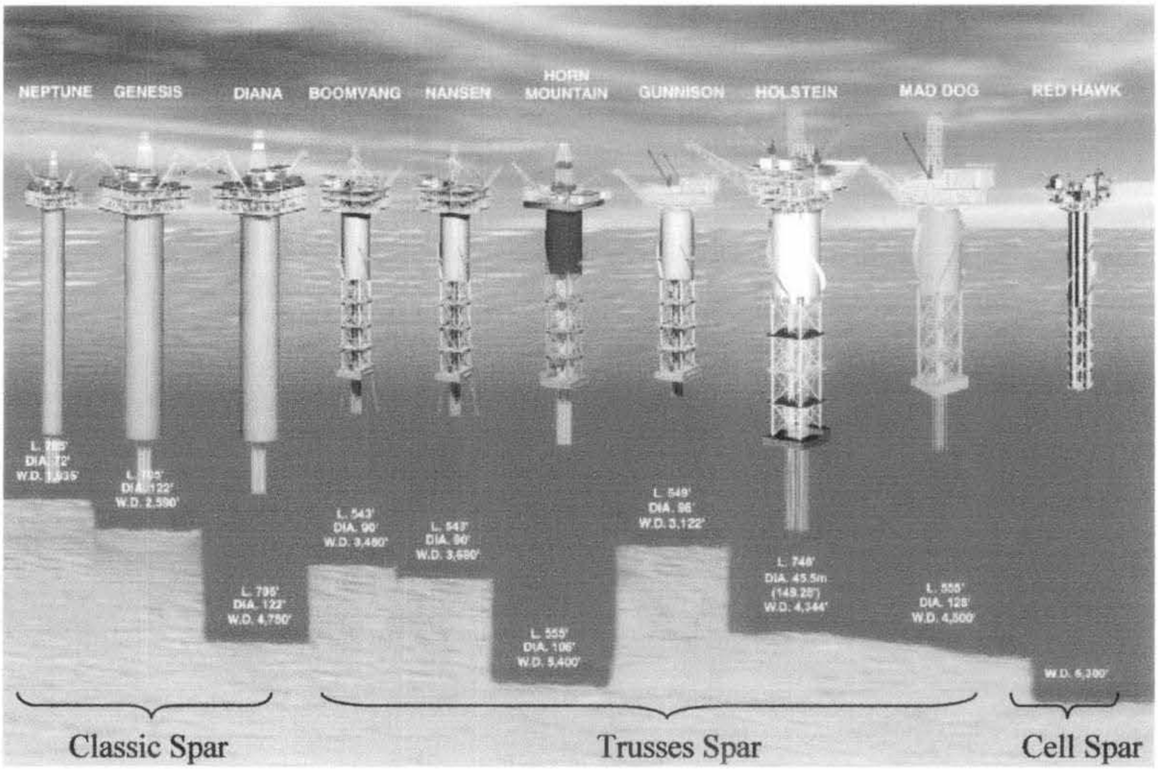


Figure 1.1: Progression of Spars (Technip Offshore)

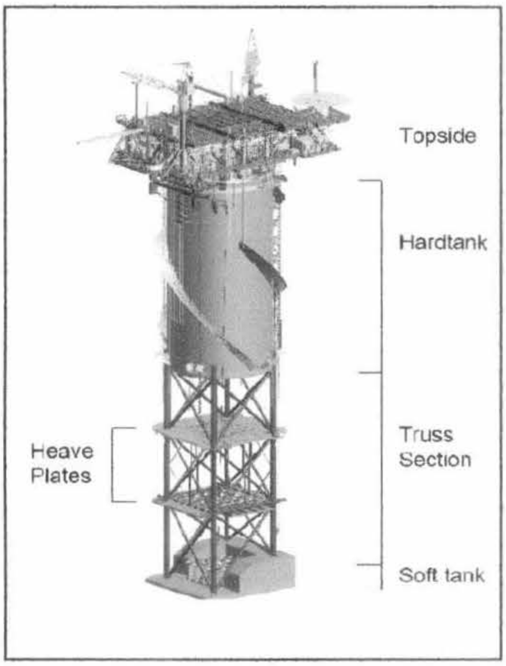
Generally, spar platform can be divided into three types which are classic, truss and cell spar. The first generation classic spar basically has large vertical cylinder that may used as a production, storage and off-loading platform. Converse and Bridges (1996) noted that the hull of the classic spar may has diameter and total length of up to 40 m and 250 m deep respectively depending on its application and the environments of its location. Ma and Patel (2001) mentioned several advantages of classic spar compared with other floating platforms which including structural simplicity, insensitivity to water depth, good protection of riser connections to the sea bed and also low overall cost. Besides, the main feature of the classic spar is its excellent motion characteristics even in severe sea states due to its deep-draft vertical cylinder hull. However, in some sea area, where the ambient deep current becomes a major factor, the drag on the large cylindrical shape can be significant [Zhang *et al.,* 2006]. Other than that, it was discovered [Adee, 1970] that a long circular cylinder has a large heave motion near its natural period due to small damping.

In such cases, a truss spar is an attractive alternative since the lower cylindrical part of typical classic spar is replaced with an open truss structure to reduce the draft portion. The truss spar configuration consists of a top hard tank and a bottom soft tank separated by the truss section. Horizontal plates were included between the truss bays to minimize heave motion by increasing both added mass and damping in the vertical direction. Downie *et al.* (2000) mentioned some advantages of truss spar over the classic spar such as lower cost, lower drag area and therefore reduced current and mooring loads, and less sensitivity to vortex-induced vibrations. In addition, the truss spar is also more structurally efficient when there is no oil storage required. All these advantages have made the spar platform generally and the truss spar in particular, attractive for the offshore industry.

A third generation of spar which is cell spar was introduced in 2004 which has similar function with the other spar but different in physical characteristics. Instead of single hull, it consist a cluster of smaller cylinders which are connected by horizontal and vertical plates. The upper portion of the multiple hulls is composed of six outer cells surrounding a center cell to provide the buoyancy. Otherwise, the lower portion is formed by extending three of the outer cells down to the keel. Zhang *et al.* (2006) noted that the cell spar concept is efficient and can be considered to reduce the fabrication and installation difficulty as well as the cost since the standard rolling technique could be utilised. Furthermore this method of construction is cheaper than the traditional plate and frame methods.

1.1.2 Kikeh Truss Spar

In this project, a truss spar platform which is Kikeh Spar was selected to be analyzed upon its responses due to regular waves. Kikeh Truss Spar is the first Malaysian deepwater development located in Blok K, 125 km offshore Sabah and lies at a water depth of 1330 m. It is the first spar application outside the Gulf of Mexico and the topside was first ever installed by float over technique onto a spar on the November 2006. This structure which also called as Kikeh Dry Tree Unit (DTU) consists of a Truss Spar floating structure with the topsides located above the Spar Deck (Deck 7) and has 10 legs mooring system. The truss spar consists of a cylindrical upper hull (Hard tank) with a square center well, a jacket-type middle-section truss with heave plates, and a soft tank (keel tank) at the keel (refer to Figure 1.2). The soft tank is provided on the east side of the spar so as to provide buoyancy during horizontal wet tow. In order to conduct the analysis, the principle dimensions and some particulars regarding the Kikeh Spar is needed and is given as follows:



Total hull Spar Length	=	141.732 m
Total draft	=	131.064 m
Hard Tank diameter	=	32.300 m
Hard Tank freeboard	=	10.668 m
Hard tank length	=	67.054 m
No. of heave plates	=	2.0
Truss leg spacing	=	22.86 m
Topside weight	=	4.323×10^6 kg
Hull weight	=	13.535×10^6 kg
Well system	=	3.839×10^6 kg
Total weight	=	33.562×10^6 kg

Figure 1.2: Kikeh DTU spar (PETRONAS Carigali)

1.2 Problem Statement

With the depletion of onshore and offshore shallow water oil reserves, the exploration and production of oil in deep water oil fields present challenge to the offshore industry. It is because deep water floating structures basically involve high development cost and technological uncertainty. In this regard, an innovative, reliable and cost-effective platform concept need to be explored to justify such investment and risk involved in ultra-deepwater development [Ran *et al.*, 1996]. Therefore, a study on the update technology especially the spar platform concept becomes important nowadays in order to produce oil in regions, which are inaccessible to exploit with the existing technologies.

Furthermore the first deepwater development has been installed in our country recently which is Kikeh Truss Spar (as mentioned previously). Like others offshore structures, it also has been designed against extreme weather and wave condition. Since all components in spar are subjected to environmental forces, dynamic response is therefore a key consideration in the design of such system. Furthermore, various aspects of the physics of deepwater system make dynamic analysis a particularly challenging computational task [Low, 2006].

The floating spar platform also permits motions in six degrees of freedom. If structure is free to move in waves, its motion may be critical near the resonance of the structure. An analysis was conducted based on this platform to observe the dynamic behavior of this platform when subjected to regular wave. It is important to study the overall response of the structure in order to determine its stability with respect to the motion in six degree of freedom. The motion response of the spar platform, the heave mode of which is of special interest, should be adequately low to satisfy the installation of rigid riser with dry heads [Tao, 2001].

1.3 Objectives

- To prepare a detailed literature survey about the spar technology, existing spars, truss spars, and dynamic analysis.
- To analyse the hydrodynamic responses of the spar such as surge, heave and pitch by conducting rigid body analysis in frequency domain and compare with analysis done by using any software such as the SACS Software.
- To determine the effect of various parameters on the above responses like wave period, wave height, hard tank diameter and also heave plate effect.

1.4 Scope of Study

This project analyses the motion responses of spar for its dominant degrees of freedom which is surge, heave and pitch. A one directional regular wave is used for computing the incident wave kinematics by using Linear Airy Wave Theory and hydrodynamic forces by Morison's equation. This project is only concerned about the wave loading since its effect on the offshore structure is more severe compare to other environmental loading. The analysis is conducted in frequency domain to solve the dynamic behavior of the moored spar platform using simpler approach which is without any iteration. All sea states are generated using the Pierson-Moskowitz Spectrum. In this analysis also, the wave directions are assumed heading toward positive x-axis and the analysis was done for both operating and storm condition. Apart from the frequency domain analysis, the dynamic response analysis of Kikeh Truss Spar was also conducted by using SACS Software for comparison purposes.

CHAPTER 2

LITERATURE REVIEW

2.1 Global Axis Coordinate System

The wave analysis of a Kikeh spar platform comprising hull and mooring system is perform by considering the wave propagate in one direction which is positive x direction. The platform global axis system used for Center of Gravity (COG) is shown in Figure 2.1. All locations are specified based on this coordinate system. The origin of the reference coordinate axes is taken at the centerline of the hull at the Sea Water Level (SWL) as shown in Figure 2.2.

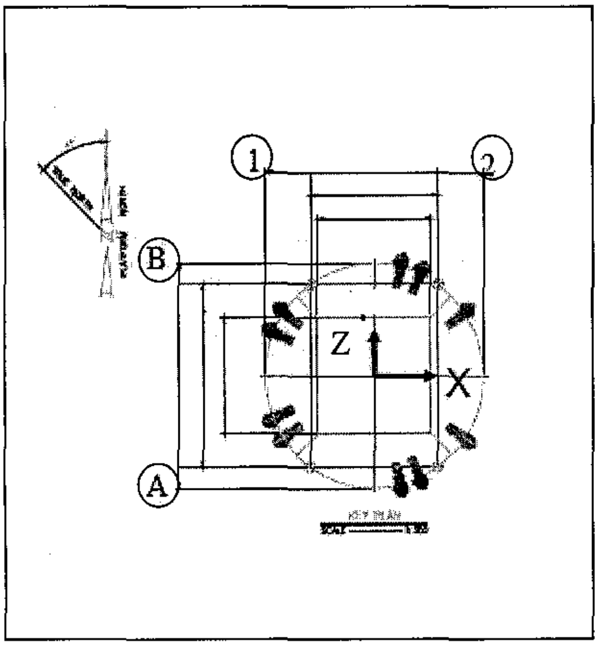


Figure 2.1: Global co-ordinate system (Kikeh Global Weight Report)

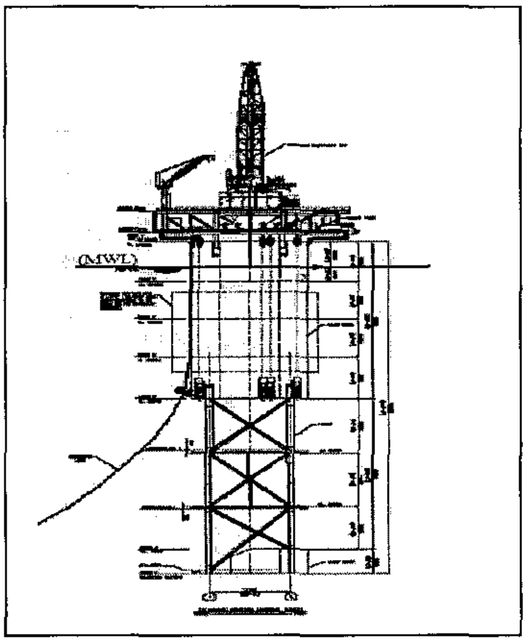


Figure 2.2: Side view co-ordinate system (Kikeh Global Weight Report)

2.2 Design Wave

Generally, there are two basic approaches applicable for choosing the design wave environment of an offshore structure. It can use either single wave method or wave spectrum. Wave spectrum is used to represent the random sea state on a short term basis. In reality, waves are normally in the form of random waves instead of ideal form. However, throughout this project, a single wave method or regular wave is selected which represented by a wave period and a wave height. Chakrabarti (1987) states the prediction of response of an offshore structure is generally made in regular wave because of the simplicity of the design analysis.

Regular wave basically is the ocean wave in its simplest form of sinusoidal where the wave amplitude does not vary throughout the time. This kind of wave oscillates about the still water level (SWL) and has simpler characteristics compare to random wave. Figure 2.3 below shows the parameters that define a simple, progressive wave as it passes a fixed point in the ocean.

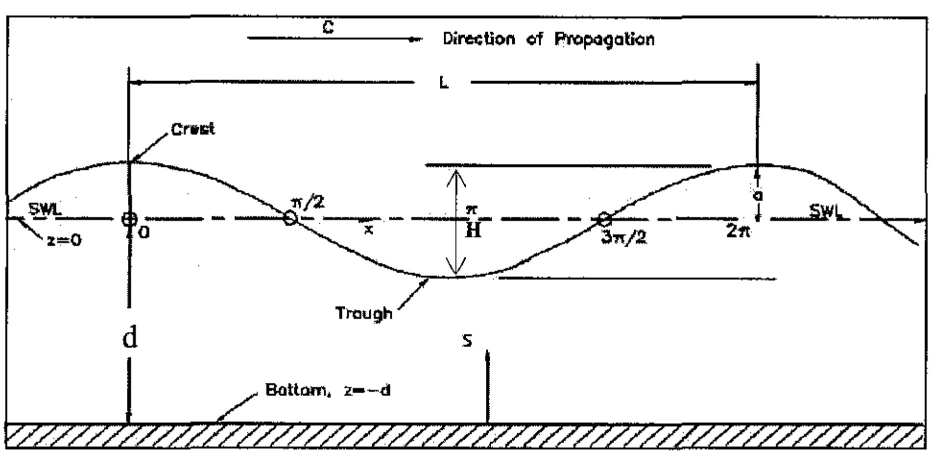


Figure 2.3: Single wave design parameters [Chakrarbarti, 1987]

This simple, periodic wave propagating along the bottom may be characterized by wave height, H wave length, L and water depth, d. As shown in Figure 2.3, the highest point of the wave is crest and the lowest point is the trough. For linear or small amplitude wave, the wave height, H is the vertical distance from crest to trough. The wavelength, L is the horizontal distance between two identical points on two successive wave crests or two successive wave troughs. The time interval between two successive wave crests or troughs at a given point is the wave period, T. All these parameters are the key consideration in Linear Airy wave theory. Normally, for the analysis of offshore platforms, the environmental parameter such as wave heights is considered as much as 21 m depending on the water depth [Luis, 2001].

2.3 Dynamic Analysis

In general, spar platforms show excellent motion behavior even in extreme sea states. Thus it is regarded as an attractive design solution for regions of ultra deepwater where the water conditions are relatively harsh [Hang, 2005]. This is because spar has long natural period of motion due to the deep draft of the hull and relatively small water plane area.

However, the prediction of wave loads on offshore structures is an important component of offshore design. It is because once this structure is taken into production, it mostly stays at the field for 15 or 20 years, without the possibility of sailing away when a storm is approaching. Therefore, they must be designed against all weather and wave conditions. Furthermore, harsh environment require that the motions of structure be small to allow the use of dry trees and SCRs [Luis, 2001].

Low and Langley (2007) state:

'Although spar structure is connected to the sea floor by mooring lines to promote restoring forces to the vessel, the action of the mooring system cannot be approximated by simple nonlinear quasi-static springs. It is because the inertia and damping forces arising from the moorings may be comparable to those acting directly on the floating vessel'.

In other word, floating structure such as spar is free to move within certain range although it is restrained with the mooring lines. Thus, a simple dynamic analysis and numerical simulation method is developed to predict the extreme spar motion due to the wave forces on it. The dynamic analysis of Kikeh Truss Spar is performed by considering motion of structure in six degrees of freedom at the COG which are surge, sway, heave, roll, yaw and pitch. However the most dominant are surge, heave and pitch while effect of the other motions are relatively small [Agarwal, 2001]. Figure 2.4 shows the six degrees of freedom.

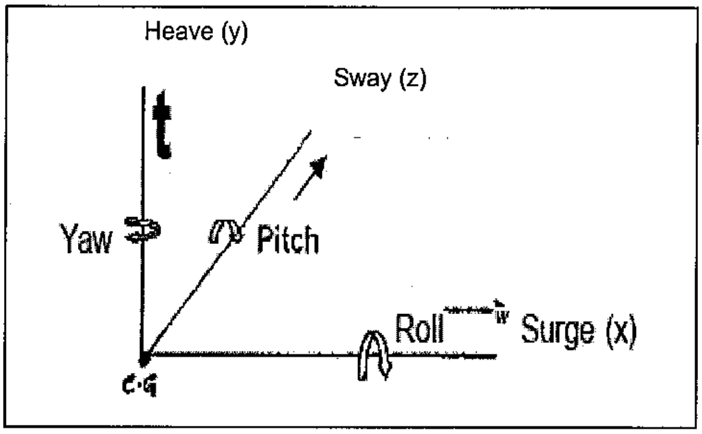


Figure 2.4: Six Degrees of Freedom [Agarwal, 2001]

Based on above figure, floating structure undergoes three translational and rotational motions. Surge response is basically the longitudinal motion along x while heave is the vertical motion along y. The transverse motion along z is sway. Pitch otherwise is the angular or rotational motion about z, about x is roll and about the vertical axis, y is yaw.

2.4 Frequency Domain

In numerical simulations there are two basic approaches involving frequency-domain or time-domain analyses. Gunther *et al.* (2002) states that in order to detect local extreme motion or extreme loads due to splitting forces and bending moments, it is necessary to analyze the hydrodynamic behavior in time-domain. However, due to time constraints, for this particular project the analysis only been done for frequency domain.

Chakrabarti [1987, pp.329-30] states:
'Frequency domain analysis is performed for the simplified method solution. It is widely used in problems related to floating structure dynamics and is particularly useful for long term response prediction. Other than that, the frequency domain computation is simpler than the time domain and the results are easier to interpret and apply for further analyses'.

The frequency-domain technique basically has advantage of computational cost and faster than the time domain approach since requires fewer computing resources. It also can be solved without any iteration or sometimes by simple iterative technique. However, the frequency-domain technique has been applicable only for linearized equations of motion, where large error or an overestimation of viscous effects may occur [Keyvan *et al.*, 2004]. In the frequency-domain analysis, an extreme storm is described as a spectrum. The key approximation used in a frequency-domain approach is the technique for linearising any non-linear features in the process.

2.5 Numerical Computation

2.5.1 Linear Airy wave theory

Small Amplitude or Linear Airy wave theory is the most useful and simplest among other wave theories. It can be used for determining the incident wave kinematics by using a one directional regular wave model. It is based on the assumption that the wave height is small compared to the wave length or water depth. This theory is easy to apply and give a reasonable approximation of wave characteristics for a wide range of wave parameters. Although there are limitations to its applicability, linear theory can still be useful provided the assumption made in developing this theory are not grossly violated [Zhang *et al.*, 2006]. In this project, Linear Airy wave theory is mainly used for computation of the wave parameters such as following:

1. Wave length, L
2. Wave Celerity, c
3. Wave number, k
4. Wave frequency, ω
5. Horizontal and vertical water particle velocity, u and v
6. Horizontal and vertical water particle acceleration, u' and v'

Formulation regarding those parameters can be found in Chapter 3 (Methodology). All these parameters are required during wave force computation.

2.5.2 Morison Equation

When dealing with the design of an offshore structure, it is very important to compute the wave forces exerted on the structure. Since the process involves the complexity of the interaction of waves with the structure, the process is one of the most difficult tasks. 7Basically, there are different ways applicable to calculate the wave forces base on the type and size of the members in an offshore structure. One of the methods is by Morison equation.

Chakrabarti [2005, pp.168-75] states:
'The Morison equation is developed for describing the horizontal wave forces acting on a vertical pile which extend from the bottom through the free surface. This equation basically composes of inertia and drag forces which are linearly added together. It is applicable when the drag force is significant such as when the structure is small compared to the water wave length. The principle behind the inertia force is that a water particle moving in a wave carries a momentum with it. The principle cause of the drag force term is the presence of a wake region on the "downstream" side of the cylinder'.

Basically, there are three cases related to Morrison's Equation which are:
- Vertical cylindrical structure
- Moving body and fluid
- Inclined cylindrical structure

However, this project only considers the wave loads on a vertical cylindrical structure since the wave analysis will be done to the spar hull in its upright position. Suppose the vertical cylinder is subjected to a wave with horizontal velocity changing both in time and vertically in the y-direction: $u(y, t)$ (refer to Figure 2.5).

In this case, the force acting on a small cylinder at each depth, d is done by integrating the Morrison's Equation to get the total force.

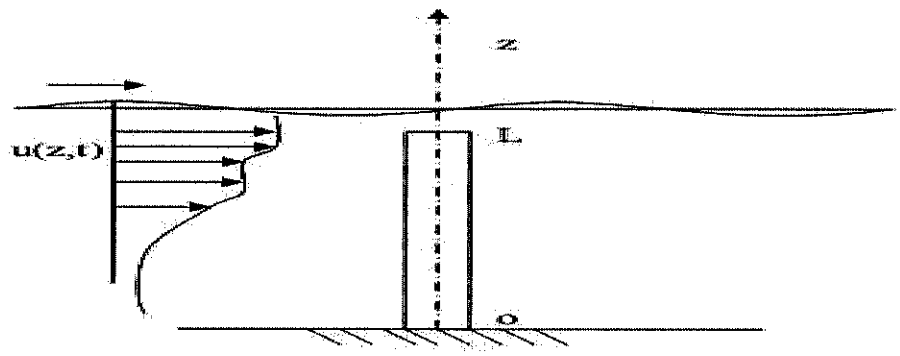


Figure 2.5: Waves Forces Acting on a Vertical Cylinder [Chakrabarti, 1987]

2.5.3 Pierson-Moskowitz Spectrum

As mentioned previously, waves are normally in the form of random waves instead of ideal form. However, since a single sinusoidal wave or regular wave is taken into consideration. The maximum wave height is being used instead of the significant wave height. This is to make the energy distribution of the single wave approach compatible with the energy exerted by the random wave approach.

In order to generate the maximum wave height, a mathematical spectrum model is required. This spectrum models are generally based on one or more parameters such as significant wave height, wave period, shape factor, etc. For this project, a single-parameter spectrum which is Pierson-Moskowitz spectrum is being used. The Pierson-Moskowitz Spectrum was developed by offshore industry for fully developed seas in the North Sea.

According to Chakrabarti [1987, pp.102-106]:
'Pierson-Moskowitz model is the most common spectrum used and based on significant wave height or wind speed. This spectrum which is commonly known as P-M model represents the energy density distribution of the single wave. It has been extensively used as one of the most representative spectrum for water all over the world. Furthermore, this P-M model is very useful in representing a severe storm wave in offshore structure design'.

Therefore, the prediction for extreme seastate can be generated by using this P-M model.

2.5.4 Response-Amplitude Operator (RAO)

In designing an offshore structure, the extreme response of the structure due to ocean waves must be known. This can be obtained by using the Response-Amplitude Operator (RAO). This RAO generally translate the regular wave responses to responses in the presence of random ocean wave.

According to Chakrabarti (1987, pp.391-93):
'Response Amplitude Operator (RAO) also called as Transfer Function since it allows the transfer of the exciting waves into the responses of the structure. It is often found in practice that an RAO is defined as amplitude of response per unit wave amplitude'.

Therefore, the amplitude of structure's response is generally normalized with respect to the amplitude of wave. In the computation of RAO, the waves are considered regular and a sufficient number of frequencies are chosen to cover the entire range of frequencies covered by the wave spectrum. The RAO could be theoretical or measured. The theoretical RAO's are obtained from simplified mathematical formulas as described in Chapter 3. Based on the formula, the spar response due to surge, heave and pitch can be obtained.

2.6 Analysis using SACS Software

Since the Kikeh Truss Spar does not have experimental result yet regarding its dynamic response. Thus the response analysis can also be done by using SACS Software for comparison. The dynamic analysis using SACS Software is done by using the Wave Response program module. This program generally used to generate loading for fatigue or extreme wave analysis or to determine dynamic amplification factors. It is also designed to compute the dynamic responses of a structure subjected to wave action including forces due to water particle velocities and accelerations. This program uses the dynamic characteristics calculated by Dynpac and hydrodynamic properties along with wave kinematics calculated by Seastate program module.

This Wave Response program requires a SACS model file, Seastate input, and dynamic mode shape and mass file in addition to the Wave Response input file. It can be run in two basic modes which is deterministic wave mode (regular wave) or the random wave mode. In either procedure, the structural compliance effects can be determined by an iterative procedure and all Seastate override capabilities are supported. However, for this project, the analysis only focuses on the deterministic wave mode only.

CHAPTER 3

METHODOLOGY

The overall methodology used in the numerical computation is summarized in Figure 3.1 below.

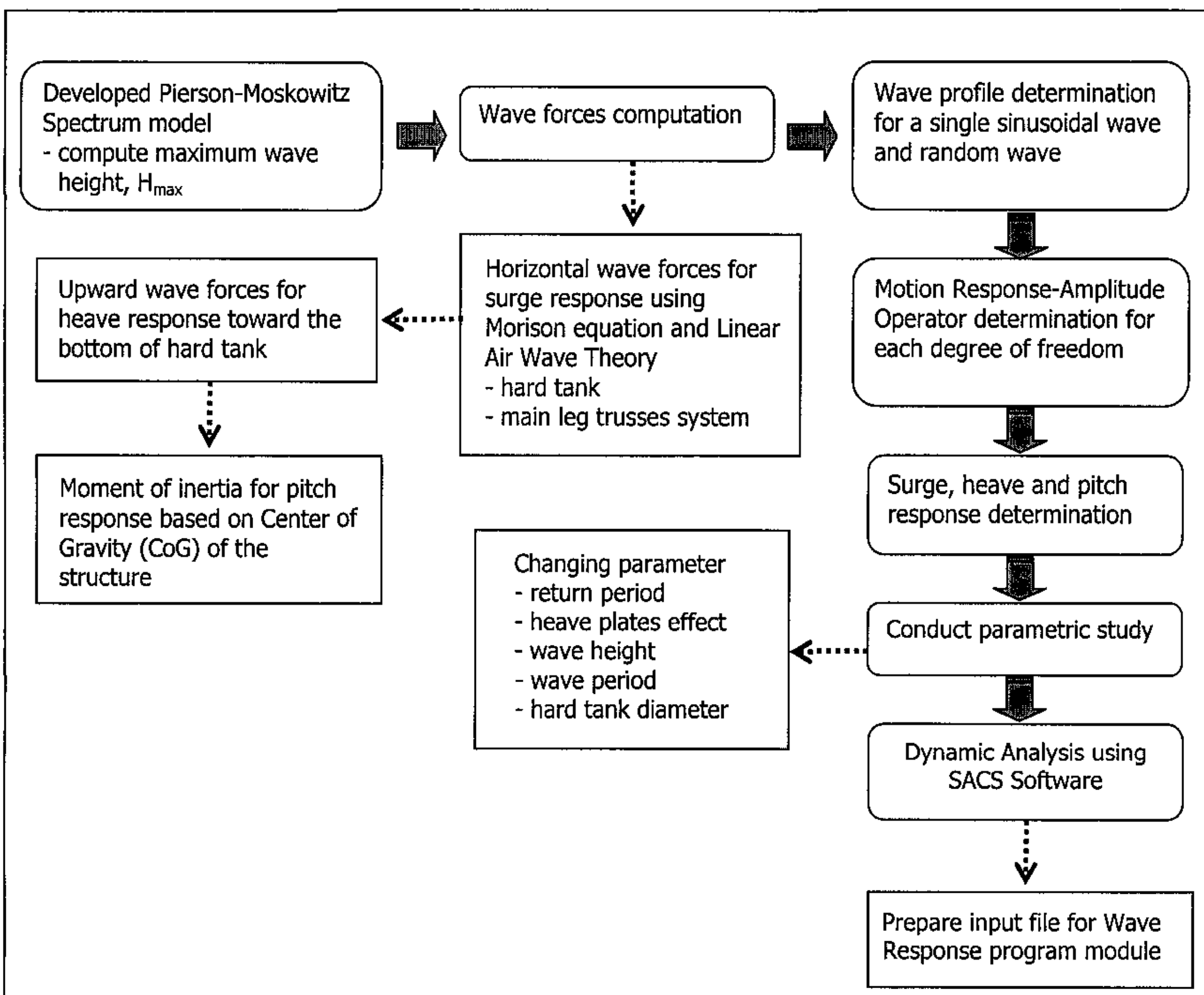


Figure 3.1: Summary of Numerical Computation

3.1 P-M Spectrum Model

To initiate frequency domain analysis, a P-M spectral model is developed to get the energy spectrum distribution of wave. Then it is used to determine the maximum wave height, H_{max}. The P-M spectrum model is given in term of single-parameter which is the significant wave height, H_s at the location of Kikeh Truss Spar (Table 3.1).

Table 3.1: Extreme Wave Return Period

Return Period	Hs	Tp
	(m)	(sec)
1-year	3.5	12.2
10-years	4.9	12.7
50-years	5.9	13.0
100-years	6.3	13.1

From the above table, a significant wave height is selected with respect to its return period. For this project, the overall analysis is done based on storm condition happening once in 100 years. However, for parametric study later on, the analysis also done for 1 year normal operating condition, 10 years and 50 years return period.

The P.M spectrum model is written as

$$S(f) = \frac{0.0081 g^2}{(2\pi)^4} f^{-5} \exp\left[-1.25\left(\frac{f}{f_0}\right)^{-4}\right] \tag{3.1}$$

Where f is the range of frequencies between 0.005 to 0.205 Hz and f_o equal to $\omega_0 / 2\pi$. The peak frequency, ω_0 is related to the significant wave height, H_s by

$$\omega_0 = \frac{0.161g}{H_s} \tag{3.2}$$

Then, from the P-M model the root-mean-square wave height, H_{rms} is related to the total area under the wave energy density spectrum, m_0 and the formula is given by:

$$H_{rms} = 2\sqrt{2m_0} \tag{3.3}$$

Next, the maximum wave height at a particular frequency can be calculated as following:

$$H_{max} = \left[\sqrt{\ln N} + \frac{0.2886}{\sqrt{\ln N}}\right] H_{rms} \tag{3.4}$$

And the corresponding number of waves, N is calculated based on design life of Kikeh Truss Spar which is 20 years. The average period, T is the taken from table 3.1 for its corresponding significant wave height, H_s for 100 years storm condition.

$$N = \frac{\text{Design period}}{\text{Average Period}} \tag{3.5}$$

Please refer to **Appendix A** for calculation regarding the P-M spectrum model and the maximum wave height, H_{max}.

3.2 Wave Forces Computation

3.2.1 Horizontal Wave Forces

As mentioned in Chapter 2, horizontal wave forces on the element of the structure are estimated using Morison equation, ignoring the diffraction effects. The application of the Morison equation in regular wave is straightforward in principle and requires that the wave particle kinematics be obtained by the appropriate wave theory (Linear Airy wave theory). The Morison Equation is given as:

$$f = \frac{1}{4} C_m \rho \pi D^2 u + \frac{1}{2} C_d \rho D |u| u \qquad (3.6)$$

Where;

C_m - inertia coefficient

C_d - drag coefficient

ρ - seawater density

D - diameter of cylinder

u - velocity

u'- acceleration

To initiate the computation, all the parameters in the equation 3.6 such as velocity and acceleration should be determined by the Linear Airy wave theory as following:

Horizontal water particle velocity,

$$u = \pi \frac{H}{T} \frac{\cosh ks}{\sinh kd} \cos \Theta \tag{3.7}$$

Vertical water particle velocity,

$$v = \pi \frac{H}{T} \frac{\sinh ks}{\sinh kd} \sin \Theta \tag{3.8}$$

Horizontal water acceleration velocity,

$$u' = 2\pi^2 \frac{H}{T} \frac{\cosh ks}{\sinh kd} \sin \Theta \tag{3.9}$$

Vertical water acceleration velocity,

$$v' = 2\pi^2 \frac{H}{T} \frac{\cosh ks}{\sinh kd} \cos \Theta \tag{3.10}$$

Where:

Wave length, $L_o = g T^2 / 2\pi$ (for $d/L > 0.5$, $L_o = L$)

Gravity, $g = 9.806$ kgm/s^2

Number of wave, $k = 2\pi / L$

Wave frequency, $\omega = 2\pi / T$

Vertical distance from seabed, $s = y + d$

Phase angle, $\Theta = kx - \omega t$

All data related to the calculation such as the dimensions of the spar and wave information can be obtained from the drawing (see **Appendix B**) and table 3.1. Below is the information needed in the wave forces calculation;

Water depth, d = 1330 m

Wave period, T = 13.10 m
Wave height, H = 6.30 m
} Refer to Table 3.1 for target environmental condition of 100 years wave

Seawater density, ρ = 1030 kg/m

Hard Tank diameter, D = 32.30 m

Truss leg diameter, D = 1.80 m

Freeboard = 10.67 m

Total hard tank length = 67.05 m

Hard tank draft = 56.39 m

Truss leg draft = 64.0 m

The computation of wave forces is done on cylindrical members of the spar hull which comprises a hard tank and four main leg of trusses system. The diagonal bracing member of trusses is ignored since the dimension is small and insignificant. The wave forces are calculated at mid depth of each 1 m length of the cylindrical member. The design spreadsheets in **Appendix C** shows the wave forces computation on hard tank and trusses leg.

Basically, the wave forces obtained from the Morison equation is used for determining the surge response. For computation of heave and pitch response, upward forces and moment of inertia is required.

3.2.2 Upward Wave Forces

The upward forces basically are the total forces on y-direction which is related to the heave motion. The computation is done by multiplying the upward pressure exerted toward the bottom of hard tank with the cross sectional area of the hard tank (see equation 3.11)

$$F_y = p \times A \tag{3.11}$$

The dynamic pressure, p is given as

$$p = \rho g(\frac{H}{2}\frac{\cosh ks}{\cosh kd}\cos\Theta) \tag{3.12}$$

3.3 Moment of Inertia Computation

Moment of inertia is computed by multiplying the calculated wave forces for each m length (see **Appendix C**) with its vertical distance to the Center of Gravity (COG) of whole system. For Kikeh Truss spar, the COG is x = 0.71, y = -46.27 and z = 0. All values is measured from the origin of global axis which located at centerline of hull at the Sea Water Level (SWL). The moment is basically used for determining the pitch response.

3.4 Wave Profile

Wave profile for a single sinusoidal wave of frequency, ω, is given as

$$\eta = \frac{H}{2}\cos\,(kx - \omega t) \tag{3.13}$$

Choosing the origin at x = 0,

$$\eta = \frac{H}{2}\cos\,\omega t \tag{3.14}$$

Where H is the significant wave height, H_s for 100 years storm condition and time, t is taken from 0 till 100 sec. For comparison, random wave profile also been done by using wave combination with multiples of the fundamental frequency. The random wave profile may be given as

$$\eta\ (x,t) = \sum_{n=1}^{N} \frac{H(n)}{2} \cos\left[k(n)x - 2\pi f(n)t + \varepsilon(n)\right] \tag{3.15}$$

Where ε represent the random number. The wave height, H wave number, k and range of wave frequencies, f is obtained from the P-M spectrum model as computed in **Appendix A.**

3.5 Responses-Amplitude Operator (RAO) Computation

Response-Amplitude Operator is used to transfer the exciting waves into the responses of the structure in surge, heave and pitch. The mathematical formula which describing the RAO function is given as following:

$$RAO = \left[\frac{\frac{F_I}{0.5H}}{\left[\left(K - m\omega^2\right)^2 + \left(C\omega\right)^2\right]^{1/2}} \right] \tag{3.16}$$

Where,

F_I – Total wave forces

H – Maximum wave height

K – Stiffness of the structure

m – Total mass of the system

3.5.1 Total Forces, F_I

For surge, the total wave forces, F_I are based on the previous value obtained by the Morison equation. For heave response, the wave forces are based on computation in Part 3.2.2. While for pitch response the wave forces is replaced with the moment of inertia as mentioned in Part 3.3.

3.5.2 Stiffness, K

The stiffness, K is based on following equation;

$$Surge, K_{11} = \left(\frac{EA}{L} \sin\theta \times \text{numbers of mooring lines in one direction} \right) \quad (3.17)$$

$$Heave, K_{22} = \left(\frac{EA}{L} \cos\theta \times \text{total number of mooring lines} \right) + \frac{\pi}{4} \rho g D^2 \quad (3.18)$$

$$Pitch, K_{33} = K_3 + K_x {h_2}^2 \quad (3.19)$$

$$K_2 = \pi \rho g R^2 \quad (3.20)$$

$$K_3 = k_2 H_d h_1 - \frac{\pi}{4} \rho g R^4 \quad (3.21)$$

$$h_1 = S_{cb} - S_{cg}$$

$$h_2 = S_{sp} - S_{cg}$$

Where,

E, Elastic modulus of the mooring line

A, Cross section of the mooring line

L, Total length of the mooring line

θ, The angle in between the hull and mooring line at fairlead

R, Radius of the Hard Tank

k_x, The initial stiffness of the horizontal spring

S_{cg}, S_{cb} and S_{sp} are the distances from the keel of the spar to the center of gravity, to the center of buoyancy and to the fairleads, respectively

3.5.3 Total mass, m

The total mass, m for surge, heave and pitch which used in equation 3.16 are given as following

$$Surge, m_{11} = (m + m_{a11}) \tag{3.22}$$

$$Heave, m_{22} = (m + m_{a22}) \tag{3.23}$$

$$Pitch, m_{33} = (MI + MI_a) \tag{3.24}$$

$$m_{a11} = (A \times Draft \times \rho) \tag{3.25}$$

$$m_{a22} = \frac{\rho \pi D^3}{12} \tag{3.26}$$

$$MI = \pi D^2 L \rho_{spar} \left(\frac{D^2}{4} + \frac{L^2}{12} + d_1^{\ 2} \right) \tag{3.27}$$

$$MI_a = \pi D^2 L \rho \left(\frac{D^2}{4} + \frac{l^2}{12} + d_2^{\ 2} \right) \tag{3.28}$$

Where,

m, Mass of the structure

m_{a11}, Added mass of the structure in surge motion

m_{a22}, Added mass of the structure in heave motion

A, Cross section area of the Hard Tank

D, Diameter of the Hard Tank

L, Total length of the Kikeh Truss Spar

l, Total length of the Draft section

3.6 Responses of Structure

After the RAO has been computed for surge, heave and pitch then the response of spar with respect to the three degree of freedom motion can be obtained. For a linear system, the response function at a wave frequency can be written as:

$$\text{Response (t)} = (\text{RAO})\ \eta\ (\text{t}) \tag{3.28}$$

Below are the equations use for determining the surge, heave and pitch responses respectively.

$$Surge\ response, \eta_{surge} = (RAO_{surge})\ \frac{H_{\max}}{2}\cos(kx - \omega t) \tag{3.29}$$

$$Heave\ response, \eta_{heave} = (RAO_{heave})\ \frac{H_{\max}}{2}\cos(kx - \omega t) \tag{3.30}$$

$$Pitch\ response, \eta_{pitch} = (RAO_{pitch})\ \frac{H_{\max}}{2}\cos(kx - \omega t) \tag{3.31}$$

After the surge, heave and pitch response has been determined, graph of each response versus time is plotted. The time, t is taken from 0 till 33 seconds. Please refer to **Appendix D** for the RAO and response computation for all three degree of freedom motion.

3.7 Parametric Study

Parametric study is done to observe the structure responses with respect to some parameter changing such as heave plates, wave height, wave period and hard tank diameter.

3.7.1 Effect of Heave Plates

The heave response computed previously is done by considering the volume of heave plates in the vertical added mass. As mentioned in earlier chapter, the main function of heave plates is to reduce the heave motion by trapping mass in vertical direction. Furthermore, it also increases the damping of the structure. Thus, to observe the effectiveness of this heave plate, an analysis regarding heave motion is conducted without considering the heave plates. The graph then is plotted and the result is compared with the previous result.

3.7.2 One Year, 10 Years and 50 Years Return Period

This parametric study is conducted to sea the response of the spar for different environmental condition. This study in conducted by changing two parameters simultaneously which is the wave period, T and the significant wave height, H_S. For each different return period, the procedures basically similar with the analysis conducted for the 100 years return period. All the input data required is taken from table 3.1 and graph for all three degree of freedom with different environmental condition is plotted for comparison.

3.7.3 Change in Wave Height, Wave Period and Hard Tank Diameter

This analysis basically similar with those conducted in part 3.7.2. However, only one parameter is changed at one time instead of two parameters. Other parameters are remaining same throughout the analysis. This is to observe the dynamic response pattern with respect to single parameter change which is significant wave height, H_s, wave period, T or hard tank diameter, D.

For significant wave height, H_s the value is varies from 1.9 m to 7.9 m while wave period, T the values is varies from 3.2 sec till 15.2 sec. For hard tank diameter, D the values is varies from 23.3 m to 27.3 m. Once completed, the maximum response for each different parameter values is tabulated. Then, graph of maximum dynamic response versus wave height, H, wave period, T and hard tank diameter are plotted separately. From the graphs, the relationship between each parameters and the maximum dynamic response is determined.

3.8 Wave Response Program

The analysis using Wave Response program is done based on deterministic wave mode. In the deterministic procedure, the steady state response of the structure is calculated due to the passage of infinite wave train composed of a single repeatable wave. The wave theory available in the Seastate program such as Airy wave theory can be used.

Before initiate the Wave Response program, the SACS model file, Seastate input and Wave Response input file has to be prepared (Please refer to **Appendix E**). In the SACS model file, only a hard tank and mooring lines is modeled to represent the Kikeh Truss

Spar. Total mass and buoyancy of the structure is put as point load at joint of hard tank. Member and joint fixities is set at appropriate location which is at the connection of mooring lines with seabed and fairleads. In the Seastate input file, the water depth, wave height and wave period is specified while in the Wave Response input file, the type of spectrum being used and other wave information is specified. The details procedures used while preparing the input files is obtained form manual provided in the SACS Software.

Then, once the input files is prepared, the Wave Response program can be run and the output file such as the plot of joint deflection with respect to surge, heave and pitch is generated.

3.9 Hazard Analysis

3.9.1 Potential Hazards

While perform the analysis of Kikeh Truss Spar, the main activities involve is computer use. Other activities involve are filing, printing and photocopying and also stationary use. While performing those activities, potential hazards has to be identified since it may cause unsafe working condition. For this kind of office work, many potential hazards are fall under the category of ergonomics.

Ergonomic hazards refer to workplace conditions that pose the risk of injury to the musculoskeletal system of the worker. Examples of musculoskeletal injuries include tennis elbow (an inflammation of a tendon in the elbow) and carpal tunnel syndrome (a condition affecting the hand and wrist). This kind of hazard should not be ignored since it has adverse effect on health such as blood circulation, fatigue to the muscles, bones, tendons and ligaments, and also reduced heart and lung efficiency, and digestive problems. Below are examples of potential hazards that may arise at the workplace.

- Repetitive motion injuries caused by repeatedly performing the same motion over significant periods of time such as while using the computer keyboard or mouse, sitting in the same position without changing or taking break
- Awkward postures due to non-adjustable chair that are too high or low for a user's body size and shape
- The physical arrangement of work space elements such as work surfaces, tools and equipment may not correspond with the reaches and clearances of seated user.
- Strikes and bumps which common accidents happen when striking doors, desks, file cabinets, and open drawers
- Strains and overexertion which due to lifting incorrectly, although the job may not involve lifting large or heavy objects, still can cause discomfort and injuries to back, neck and shoulders
- Electrical equipment which can cause serious shock and burn injuries if improperly used or maintained

3.9.2 Precautions

After identify and analyze potential hazard that may cause harm, some rules and procedures have to be adopt to minimize the hazard or even get rid them completely. Here are some controls that can be considered especially when dealing with computer usage:

- When working, maintain good posture. Sit all the way back in the chair against the backrest. Keep the knees equal to, or lower, than the hips with feet supported.
- Keep elbows in a slightly open angle (100° to 110°) with wrists in a straight position.
- Avoid overreaching. Keep the mouse and keyboard within close reach. Center the most frequently used section of the keyboard directly in front of user.

- Place source documents on a document folder positioned between monitor and keyboard. If there is not enough space, place documents on an elevated surface close to screen.
- Use good typing technique. Float arms above the keyboard and keep wrist straight when keying. If use a wristrest, use it to support palms when pausing, not while keying.
- Hit the keyboard keys with light force. The average user keys four times harder than necessary.
- Use adjustable chair to set height and angle for comfortable position
- Reduce glare. Place monitor away from bright lights and windows. Use an optical glass glare filter when necessary.
- Take eye breaks and intermittently refocus on distant objects once every 10 minutes. Try palming your eyes in your hands to reduce eye fatigue.
- Work at a reasonable pace and take frequent stretch breaks. Take 1 or 2 minute breaks every 20-30 minutes, and 5 minute breaks every hour. Every few hours, try to get up and move around.
- Handle electrical component properly. Make sure all electrical connections are tight, clean, and dry. To prevent shock, it is advisable to keep work areas, equipment, and clothing dry at all times

CHAPTER 4

RESULT AND DISCUSSION

4.1 Maximum Wave Height and Wave Forces

Figure 4.1 below shows the P-M model and the wave energy spectrum distribution for H_s equal to 6.3 m in 100 years storm condition.

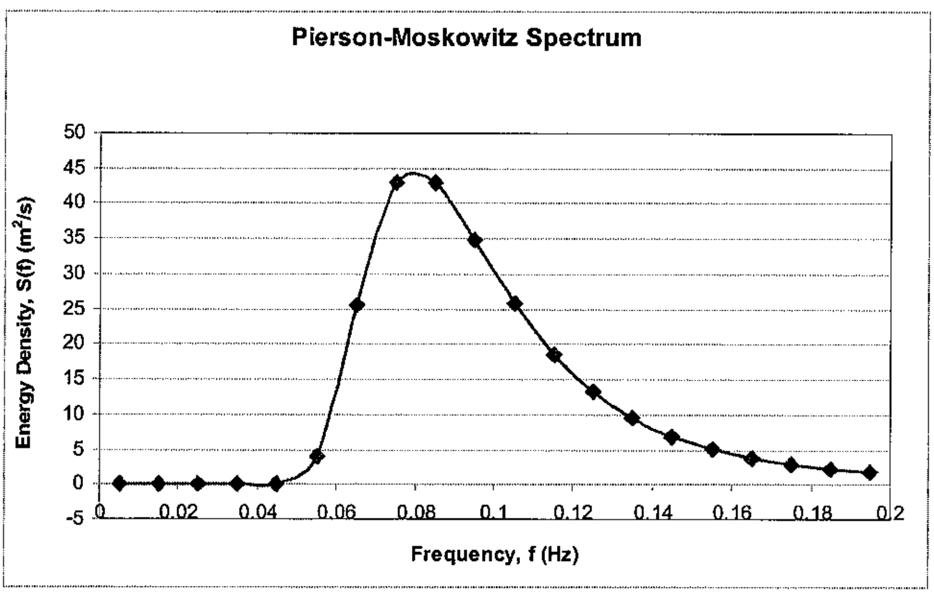


Figure 4.1: Wave Energy Spectrum

Based on Figure 4.1, total area below the spectrum is denoted as m_o and is used to compute total number of waves and the maximum wave height throughout the target service life of the spar (20years). The maximum wave height obtained from this P-M model is 18.745 m. Basically, this P-M model is very useful in representing a severe storm wave in offshore structure design.

Based on that maximum wave height, total wave forces coming from x-direction, F_t (for surge) and upward forces, F_y (for heave) is computed by using the Morison's equation and dynamic pressure equation respectively. From the design spreadsheet in **Appendix C**, the total horizontal wave force, F_t for hard tank and main leg truss system is 47674.75 kN the and the upward forces, F_y toward the hard tank base is 6926.04kN. The moment of inertia, MI about the center of gravity, COG of the structure is equal to 1110689.47kN.m.

4.2 Regular and Random Wave Profile

Figure 4.2 below shows the regular wave profile, η with respect to time, t = 0 until t = 100 sec for a single wave design of frequency, ω in spar location. This graph basically represents the ocean wave pattern in its simplest form which is pure sinusoidal oscillation.

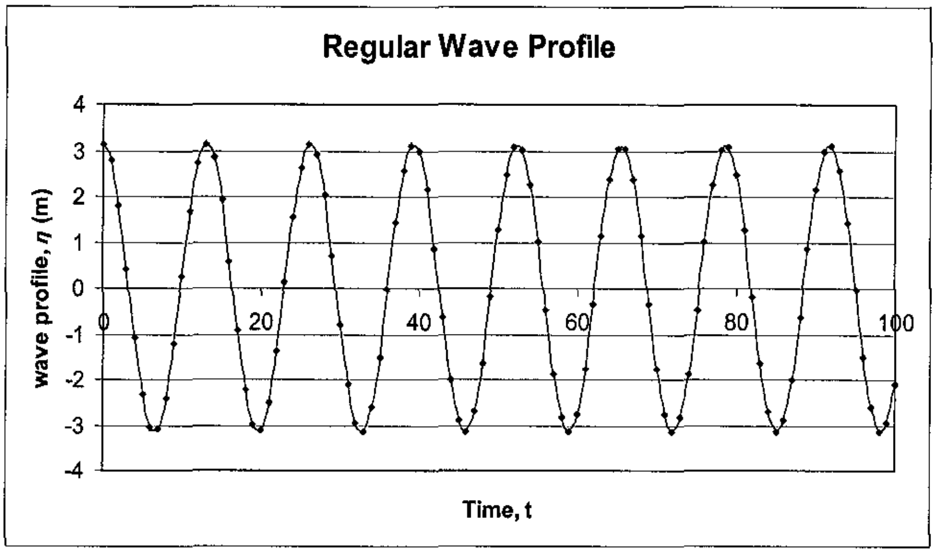


Figure 4.2: Regular Wave Profile

In real situation however, nonlinear regular wave is often used instead of regular wave. The random wave profile is generated by considering a regular wave and a sufficient range of the fundamental frequencies covered by the spectrum in the P-M model. Refer to Figure 4.3 for the random wave profile with respect to time, t = 0 until t = 200sec.

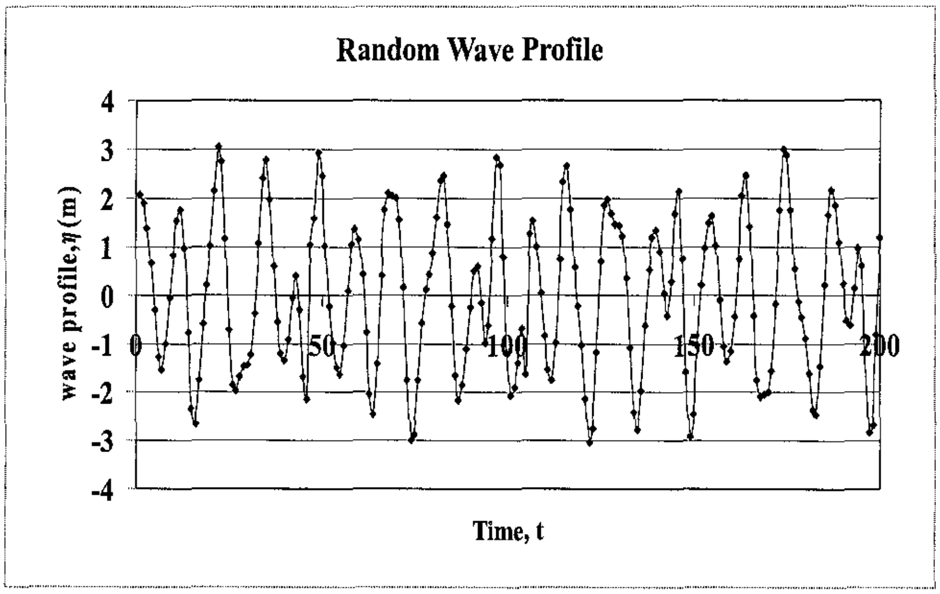


Figure 4.3: Random Wave Profile

Both graphs represent the wave profile for 100 years storm condition with significant wave height of 6.3 m and wave period of 13.1 sec. By comparison, it is observed that the wave profile in figure 4.2 shows uniform pattern and its wave amplitude is almost same throughout the time, t. In contrast, the random wave profile in figure 4.3 shows irregular wave pattern and the wave amplitude also varies throughout the time, t.

4.3 Surge, Heave and Pitch Response

Based on **Appendix D**, the Response-Amplitude Operator (RAO) obtained for surge, heave and pitch is 0.2485, 0.0757 and 0.0049 respectively. These values represent the ratio amplitude of response to the amplitude of wave. Using those values, the surge, heave and pitch response are computed and the response graph with time are shown in Figure 4.4, Figure 4.5 and Figure 4.6 respectively for t = 0 until t = 33 seconds.

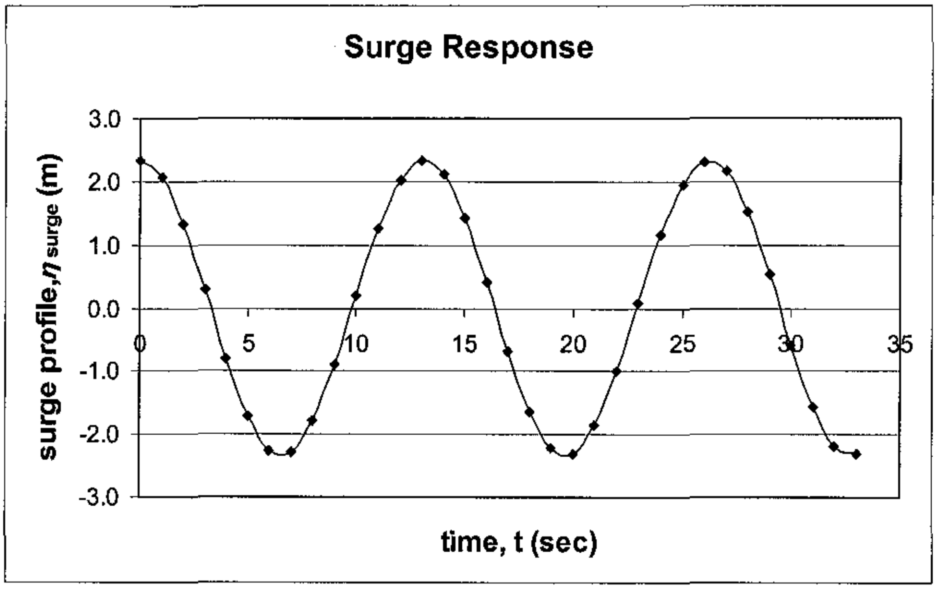


Figure 4.4: Surge Response in 100 Years Storm Condition

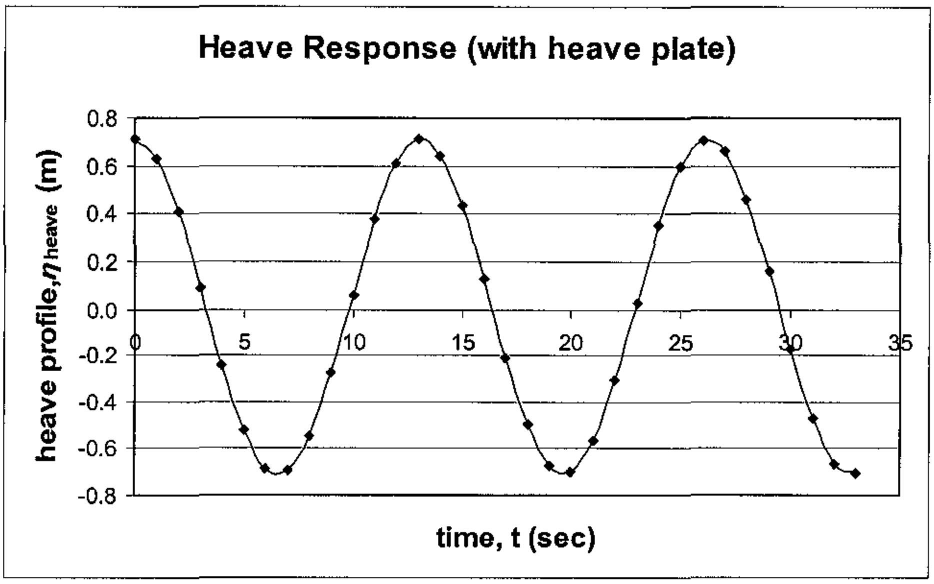


Figure 4.5: Heave Response in 100 Years Storm Condition

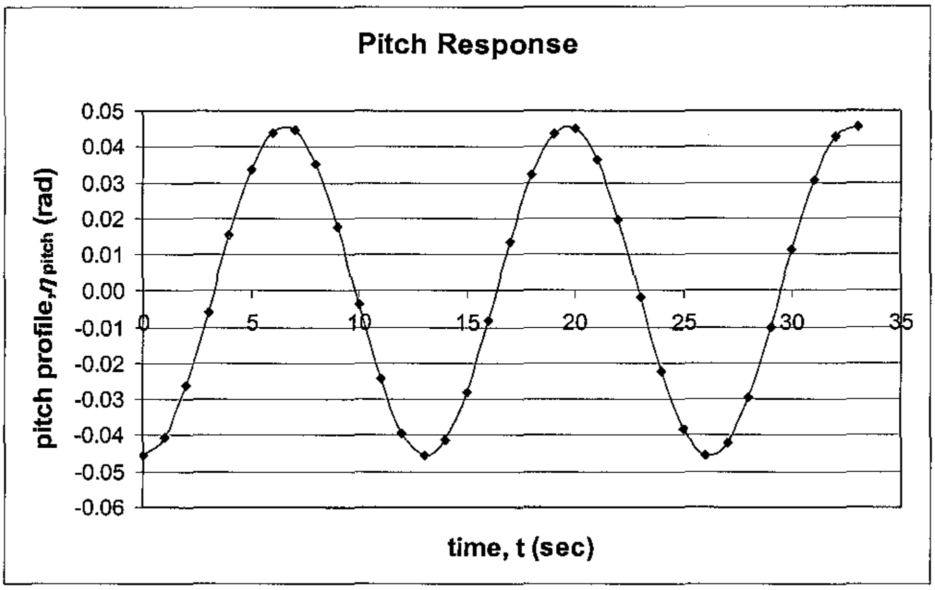


Figure 4.6: Pitch Response in 100 Years Storm Condition

Based on the above graphs, it can be observed that the surge, heave and pitch responses are in the form of sinusoidal which represent the regular wave effect. This is because the RAO values obtained are same throughout the time, t (refer to **Appendix D**). Thus, the amplitude of response is also same throughout the time, t similar in behavior with the amplitude of regular wave profile.

Other than that, the surge response is highest compare to heave and pitch where the max deflection or offset is 2.329 m from the original position. The maximum value for heave and pitch response is 0.709 m and 0.045 rad respectively. The greater value for surge response which is the horizontal motion along x-axis is due to the wave is assumed to come from x-direction. Furthermore the horizontal wave forces itself is higher compare to the upward forces. Therefore, the impact on the structures movement for surge is greater due to larger amount of wave forces strike directly on the hull part. However, the surge response during this storm condition is considerable and will not affect the spar performance since displacement in x-direction is allowed up to 5m.

4.4 Parametric Study

4.4.1 One Year, 10 Years and 50 Years Return Period

The dynamic responses of spar due to surge, heave and pitch for one year, 10 years, 50 years and 100 years is summarized in Table 4.1 below.

Table 4.1: Summarize of Dynamic Response for 1 Year, 10 Years, 50 Years and 100 Years Condition

Condition	Parameter		Maximum Response (m)		
	Wave height, H_s	Wave period, T	Surge	Heave	Pitch
1 year	3.50	12.20	1.280	0.237	0.027
10 years	4.90	12.70	1.822	0.442	0.037
50 years	5.90	13.00	2.188	0.629	0.042
100 years	6.30	13.10	2.329	0.710	0.045

Since the graphs obtained are also in sinusoidal pattern for all responses with different return period, thus the maximum value for each response is taken for comparison. From Table 4.1, it is observed that the overall dynamic responses are increasing as the wave height and the wave period increase from 1 year to 100 years return period. Besides that, in all environmental conditions the impact of surge response which is the translational along x-axis is most significant among the other. The reason has been discussed in previous part. Furthermore, the surge, heave and pitch response are highest for 100 years storm condition and hence represent the worst cases scenario. However, the values are still within the allowable limit.

4.4.2 Heave Plates Damping Features

Figure 4.7 illustrate the heave response for the spar without consider the heave plate. As observed, the maximum value for the dynamic heave response is 2.32 m. However, Figure 4.5 previously shows the heave motion of spar by considering the volume of the two heave plates in the vertical added mass. The maximum heave response obtained is 0.7096 m which is much lower than the 2.32m.

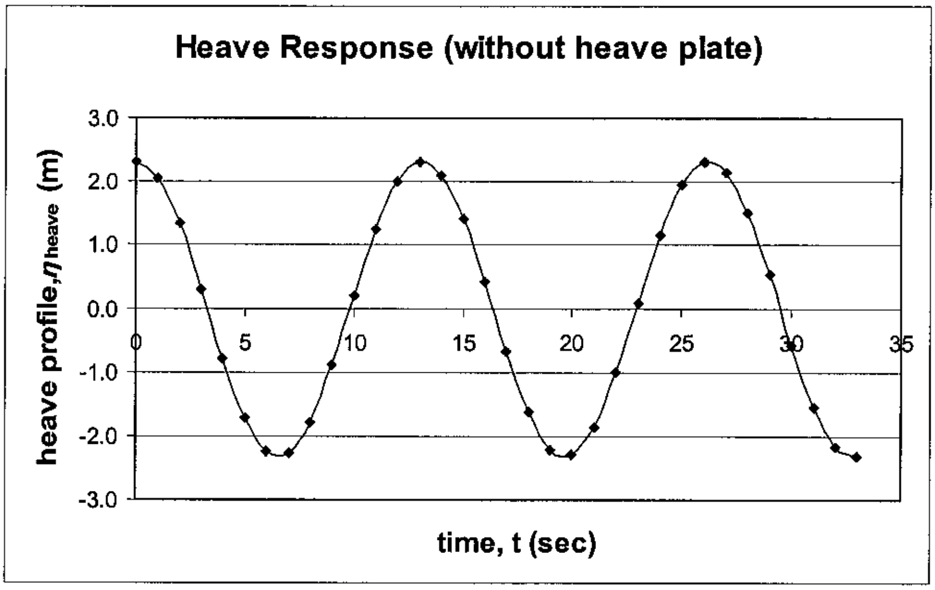


Figure 4.7: Heave Response without Heave Plate

Therefore, the two heave plates included in the Kikeh truss spar is very useful in minimizing the heave motion by increase the trapped mass in vertical direction. Other than that, the heave plates also act as damping devices since it increase the damping of the structure. It is important because small damping will cause large heave motion near its natural period. Thus, heave plates damping features is very effective for reducing the heave resonant motion and ensure the truss spar obtains its satisfactory heave motion performance.

4.4.3 Variation in Significant Wave Height, H_s

Table 4.2 below represents the maximum wave height, H_{max} and maximum response for surge, heave and pitch with respect to different significant wave height, H_s which vary from 1.9 to 7.9 m.

Table 4.2: Maximum Responses with Variation of Wave Height

H_s (m)	H_{max} (m)	η_{surge}	η_{heave}	η_{pitch}
1.9	4.831	0.654	0.214	0.013
2.9	8.139	1.078	0.327	0.021
3.9	11.314	1.470	0.439	0.029
4.9	14.431	1.840	0.552	0.036
5.9	17.516	2.192	0.665	0.043
6.9	20.584	2.529	0.777	0.049
7.9	23.642	2.851	0.890	0.055

Based on Table 4.2, it is observed that the maximum wave height, H_{max} increase significantly as the significant wave height increase. The effect of maximum wave height on the dynamic responses is shown in Figure 4.8, Figure 4.9, and Figure 4.10.

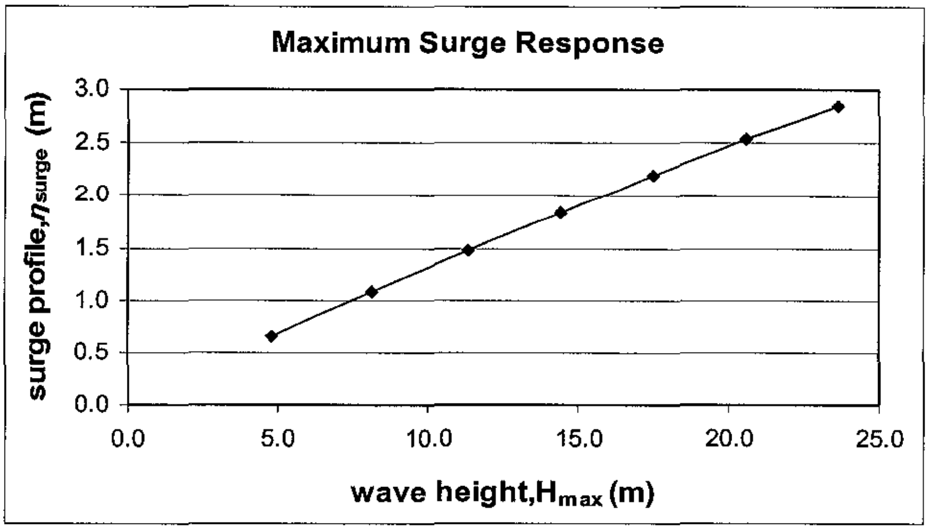


Figure 4.8: Surge Response Behavior with Variation Maximum Wave Height

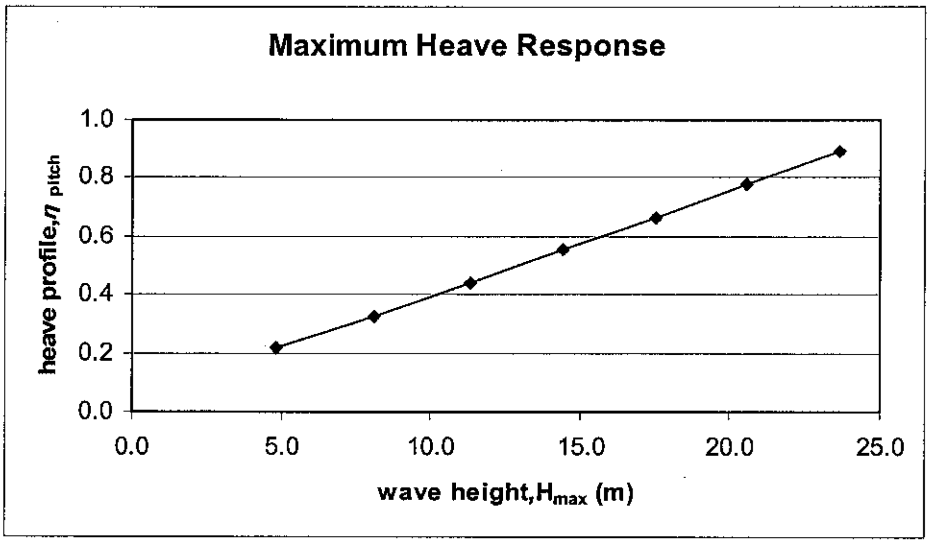


Figure 4.9: Heave Response Behavior with Variation Maximum Wave Height

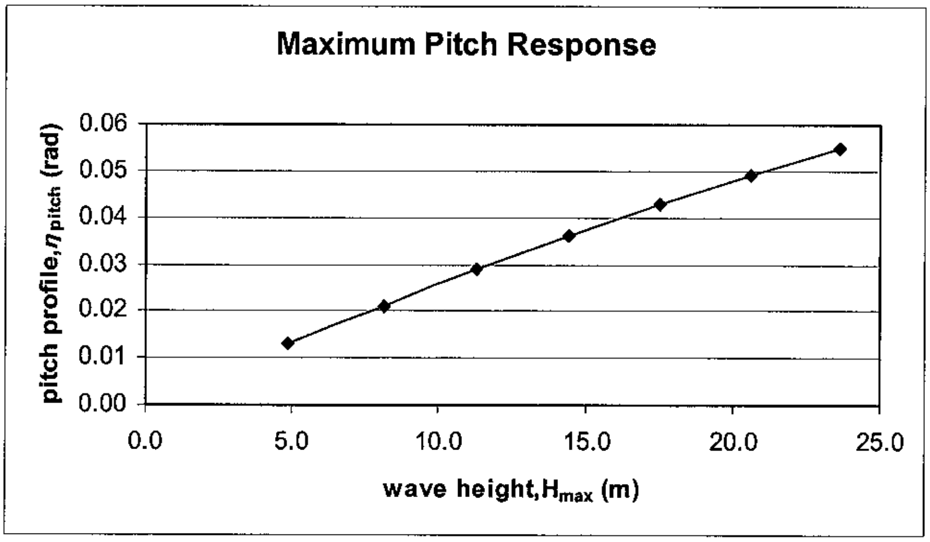


Figure 4.10: Pitch Response Behavior with Variation Maximum Wave Height

Based on Figure 4.8 till Figure 4.10, all three graphs show same pattern which is linear relationship. As observed, the maximum responses increases linearly as the maximum wave height, H_{max} increase. Therefore, the surge, heave and pitch response is directly proportionally to the H_{max} and thus the H_s.

4.4.4 Variation in Wave Period, T

Table 4.3 below shows the maximum wave height, H_{max} and the corresponding responses for surge, heave and pitch when wave period, T is varies from 3.2 till 15.2 sec.

Table 4.3: Maximum Responses with Variation of Wave Period

Wave Period, T (sec)	Max Wave Height, H_{max} (m)	η_{surge}	η_{heave}	η_{pitch}
3.2	19.454	0.374	1.5E-11	0.015
4.2	19.319	0.692	3.0E-07	0.026
5.2	19.212	0.992	4.3E-05	0.035
6.2	19.124	1.273	7.7E-04	0.042
7.2	19.049	1.533	5.1E-03	0.046
8.2	18.983	1.761	1.9E-02	0.049
9.2	18.925	1.950	5.3E-02	0.050
10.2	18.872	2.098	1.2E-01	0.049
11.2	18.825	2.207	2.3E-01	0.048
12.2	18.781	2.283	4.3E-01	0.047
13.2	18.741	2.333	7.5E-01	0.045
14.2	18.703	2.364	1.3E+00	0.044
15.2	18.668	2.382	2.2E+00	0.042

Based on table 4.3, it is observed that changes in wave period, T has small effect on the maximum wave height, H_{max} and hence its dynamic response. To observe the relationship between the wave period, T with the maximum wave height and also the maximum dynamic responses please refer to Figure 4.11, Figure 4.12, Figure 4.13 and Figure 4.14.

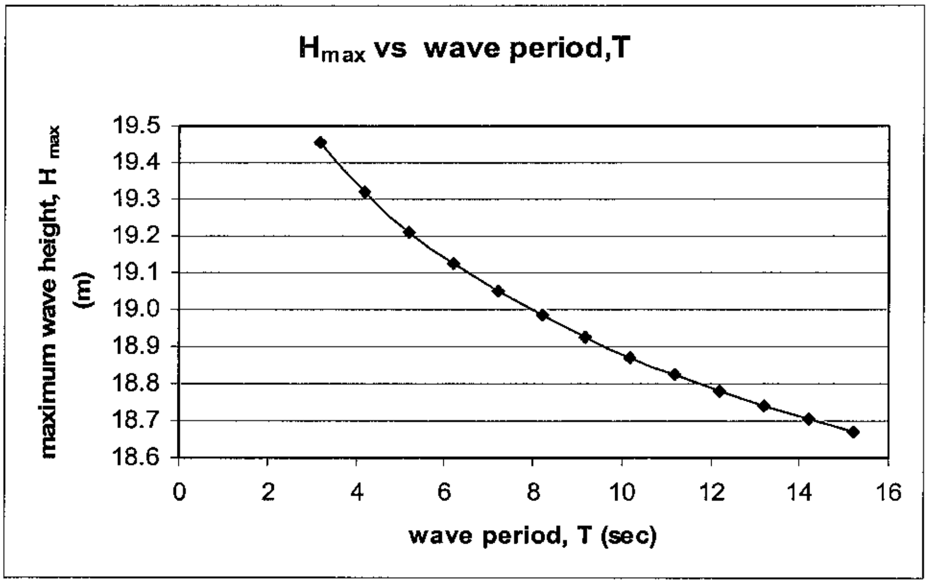


Figure 4.11: Maximum Wave height Behavior with Variation Wave Period

Referring to Figure 4.11, it is observed that the maximum wave height, H_{max} decreased exponentially with increasing of wave period, T.

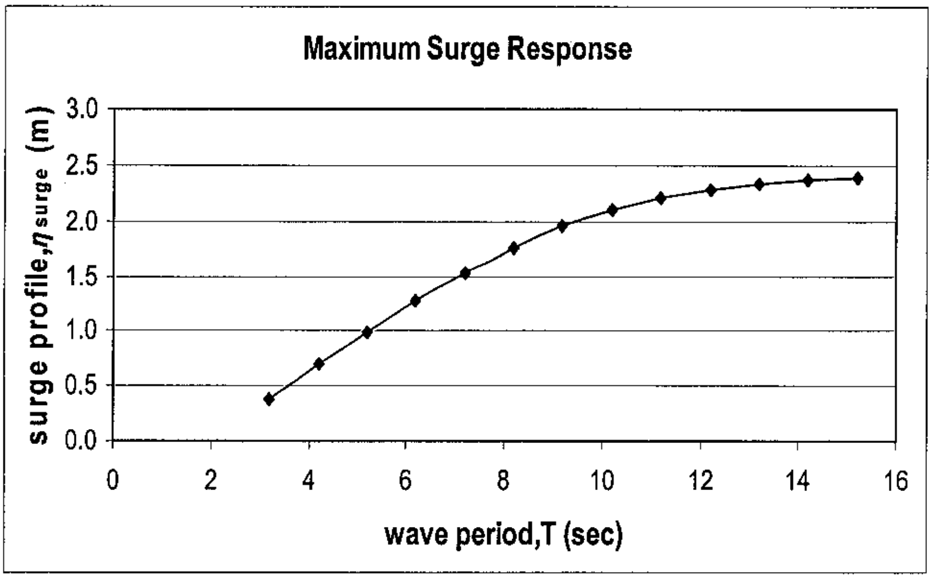


Figure 4.12: Surge Response Behavior with Variation Wave Period

Figure 4.12 shows that the surge profile increases exponentially with increase in wave period, T. This is because, increase in wave period, T will cause maximum wave height decrease exponentially so as to the total forces, F_t exerting on the hard tank. This will indirectly increase the motion RAO value which eventually causes the surge response increase exponentially with wave period, T.

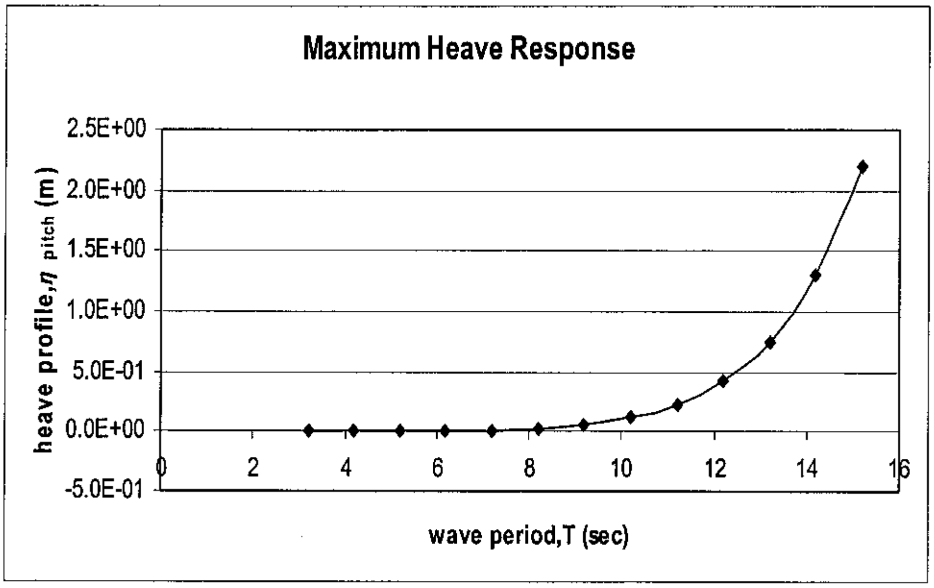


Figure 4.13: Heave Response Behavior with Variation Wave Period

Figure 4.13 also shows that the heave profile increases exponentially with changing in wave period, T. However the behavior is slightly different with surge profile. By comparing both surge and heave response, it is observed that the surge response increase almost equally from T = 3.2 sec till T = 11.2 sec and the increment become smaller after that point. This behavior is vice versa for the heave response where the increment is quite small at the beginning. However, after T= 11.2 sec the heave response increase significantly with wave period, T. Therefore, it can be said that changing in wave period, T has more significant effect on surge rather than heave response.

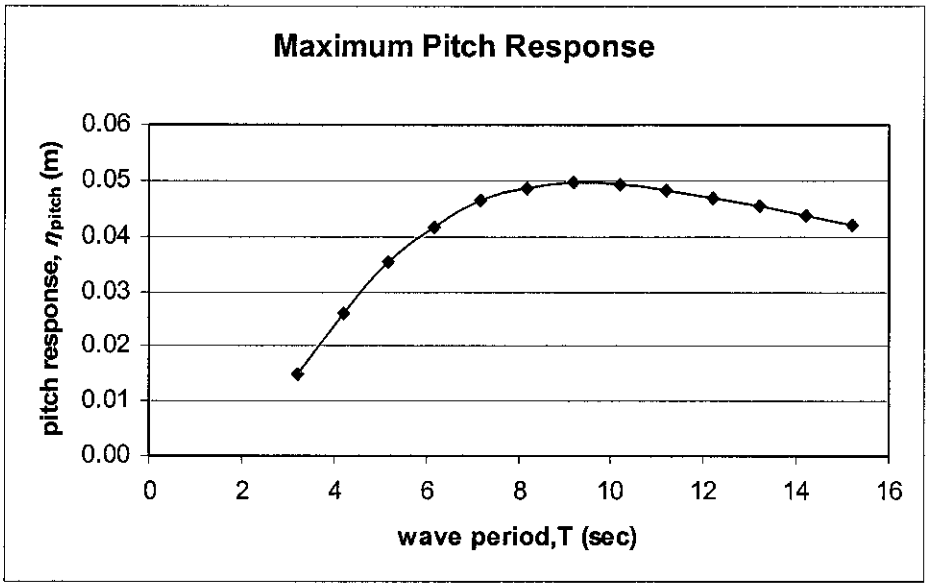


Figure 4.14: Pitch Response Behavior with Variation Wave Period

While in Figure 4.14 the pitch profile is increase exponentially from T = 3.2 till T = 9.2 which is the maximum pitch response. After that point, the pitch profile decrease exponentially with wave period, T. This is because as the wave period, T increases the maximum wave height decrease exponentially. The moment of inertia is also decrease. From T = 3.2 till T = 9.2 the motion RAO is rapidly increase which resulting increase in pitch response. However, after T = 9.2 the motion RAO is decrease which cause the pitch response to decrease.

4.4.5 Variation in Hard Tank Diameter, D

Table 4.4 represents the maximum response for surge, heave and pitch with changing parameter which is the hard tank diameter, D. The values of D vary from 23.3 to 37.3 m with increment of 2 m.

Table 4.4: Maximum Responses with Variation of Hard Tank Diameter

Hard Tank Diameter, D (m)	η_{surge}	η_{heave}	η_{pitch}
23.3	1.564	3.0E-01	0.023
25.3	1.749	3.7E-01	0.027
27.3	1.926	4.5E-01	0.032
29.3	2.094	5.4E-01	0.037
31.3	2.253	6.5E-01	0.042
33.3	2.402	7.8E-01	0.048
35.3	2.542	9.2E-01	0.054
37.3	2.672	1.1E+00	0.060

Based on the information in Table 4.4, the graph of maximum response for surge, heave and pitch with respect to the hard tank diameter, D is shown in Figure 4.15, Figure 4.16 and Figure 4.17 respectively.

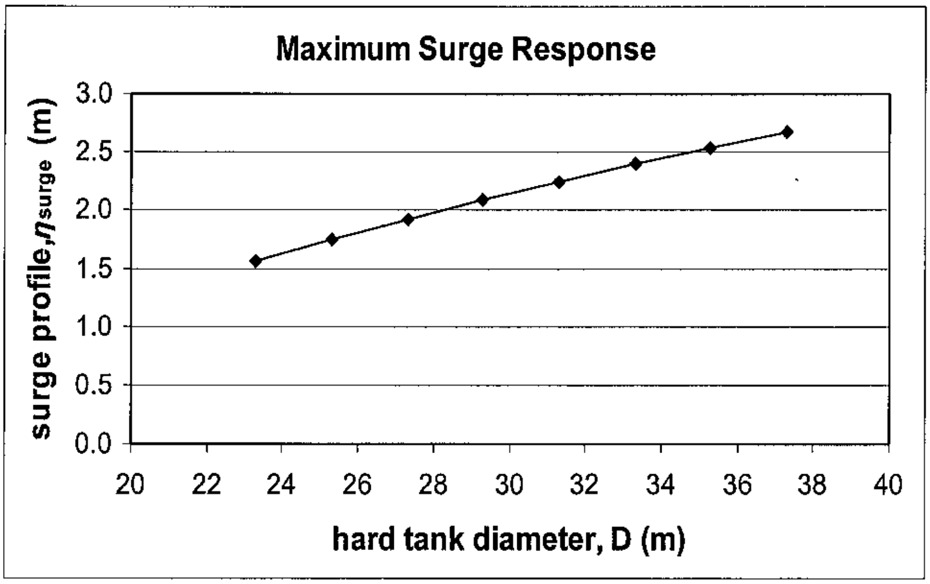


Figure 4.15: Surge Response Behavior with Variation Hard Tank Diameter

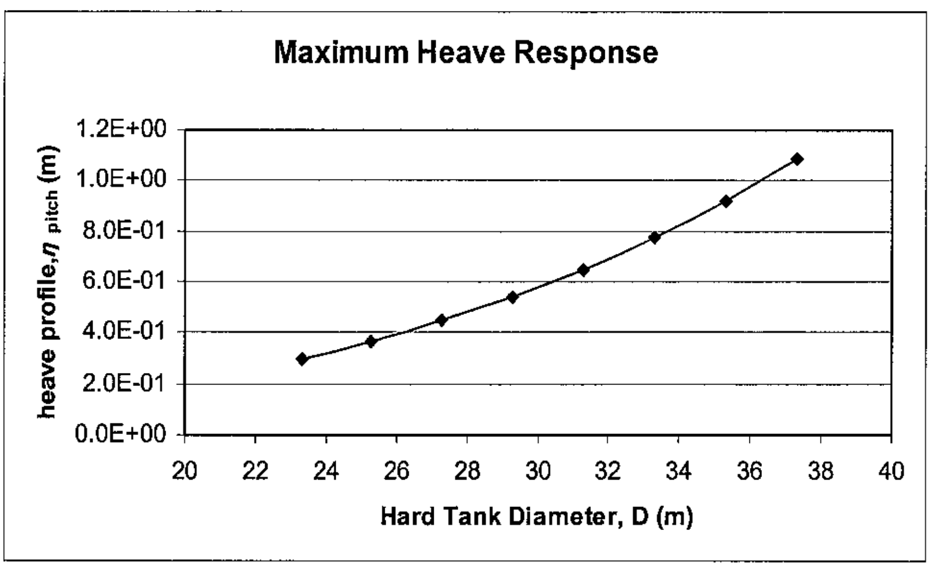


Figure 4.16: Heave Response Behavior with Variation Hard Tank Diameter

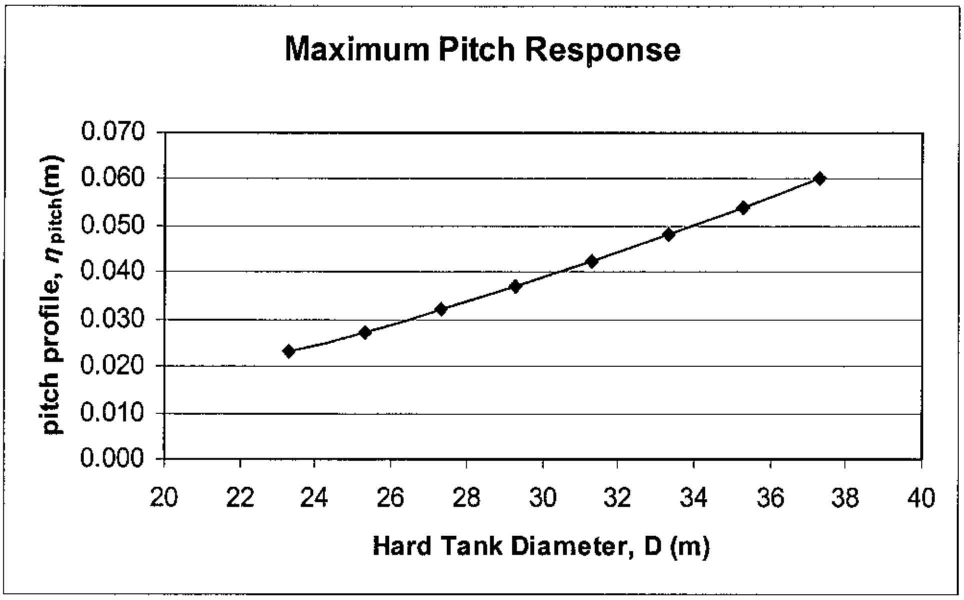


Figure 4.17: Pitch Response Behavior with Variation Hard Tank Diameter

Based on Figure 4.15, Figure 4.16 and Figure 4.17, the graphs show almost a straight line for all cases. As the hard tank diameter increase, the dynamic response will also increase. Therefore, the surge, heave and pitch response is directly proportional to the hard tank diameter.

4.5 Comparison with Wave Response Program Output

Figure 4.18, Figure 4.19 and Figure 4.20 below show the dynamic responses that obtained from SACS Software by using the Wave Response program module. The deflection is taken at one joint (joint 1000) which located at the hard tank and represent the structures dynamic movement.

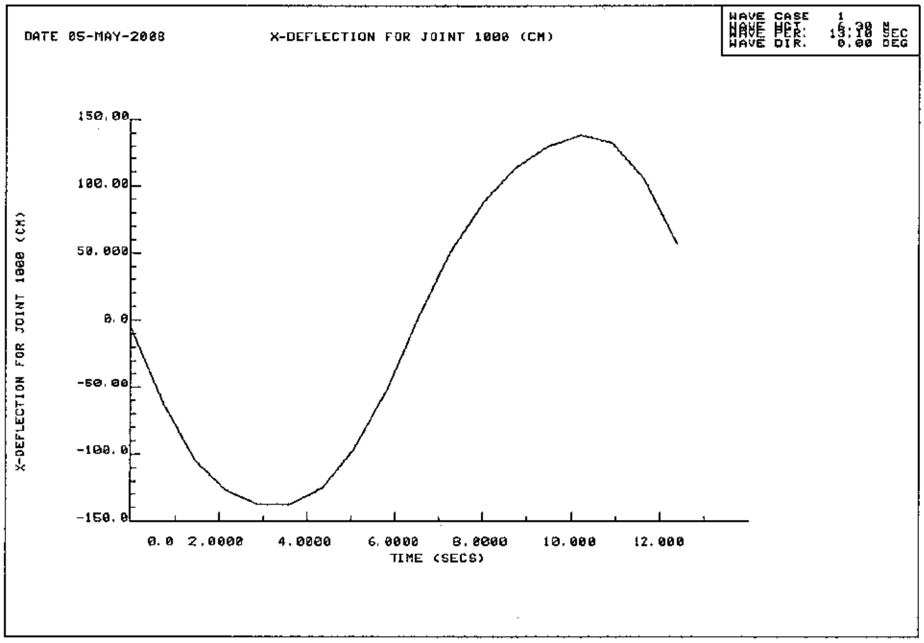


Figure 4.18: Surge Response using SACS Software

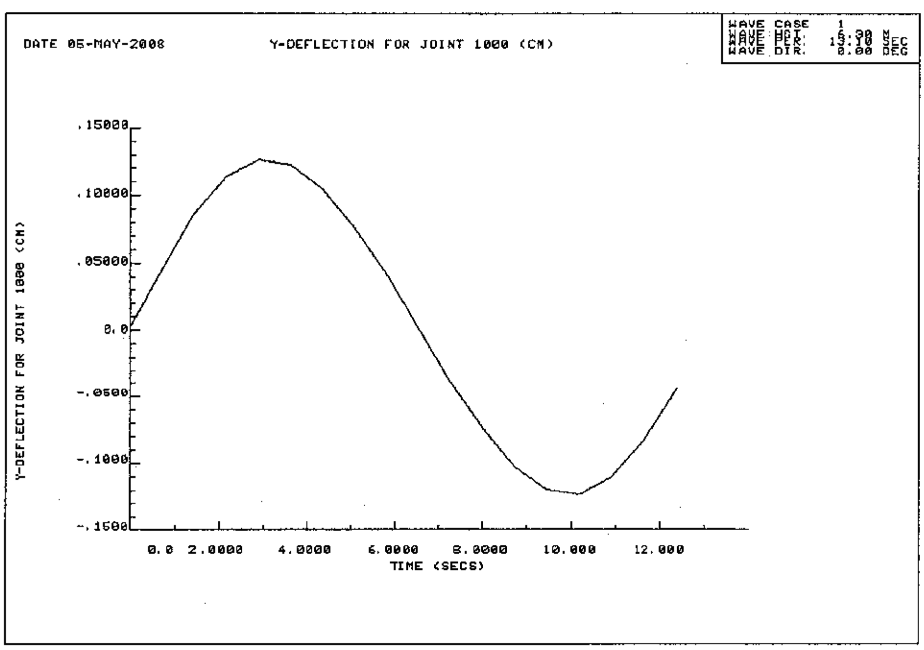


Figure 4.19: Heave Response using SACS Software

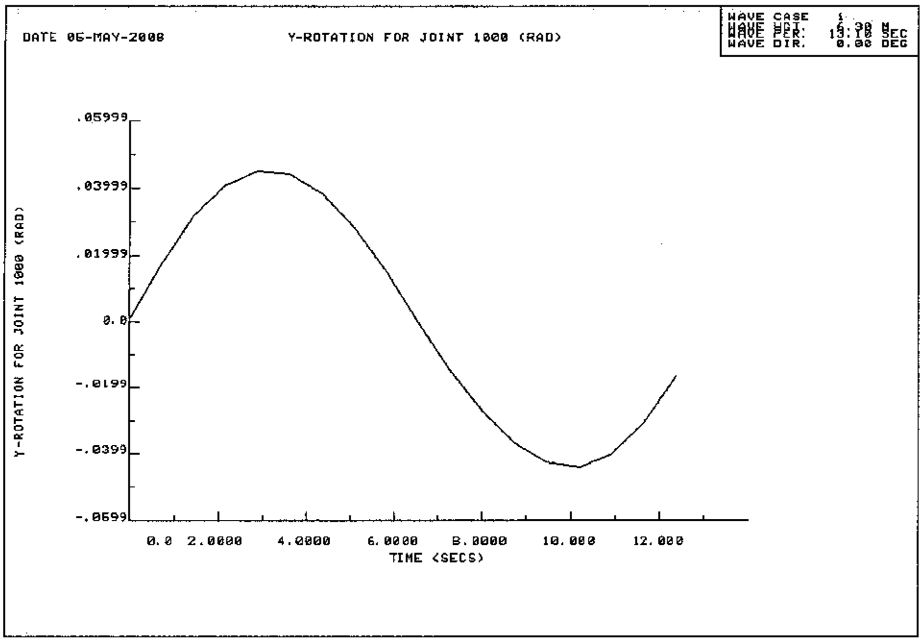


Figure 4.20: Pitch Response using SACS Software

Based on the above figures, the dynamic responses obtained from the SACS Software are compared with the responses obtained from frequency domain analysis and the results is shown in table 4.5.

Table 4.5: Dynamic Responses Comparison between Frequency Domain Analysis and Wave Response Program

Dynamic Responses	Frequency Domain Analysis	Wave Response Program (SACS Software)
Surge	2.329 m	1.400 m
Heave	0.709 m	0.013 m
Pitch	0.045 rad	0.043 rad

From the above table, it is observed that the dynamic responses obtained for surge and pitch are slightly different between two approaches where the values in frequency domain is slightly higher than the values in Wave Response Program. For heave response otherwise, the values is significantly different where the heave in frequency domain is much greater than the value in Wave Response Program.

The results obtained from the Wave Response Program basically act as parameter for determining the accuracy of the results obtained from the frequency domain analysis. It is because, the analysis done by using software such as the SACS Software is more accurate and reliable. Therefore, the different values from the Wave Response program might due to presence of errors while conducting the frequency domain analysis. For example, the error might occur because of incorrect value taken for the computation. Furthermore, in the frequency domain analysis, there are many assumptions and simplifications were used due to lack of certain data and information.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Discussion on overall dynamic response of the Kikeh Truss Spar has been made based on results obtained. The following conclusions were drawn from the frequency domain analysis which was conducted:

1. Regular wave profile represented uniform pattern throughout the time, t and was easier to be analyzed while random wave profile showed irregular characteristics and the amplitudes varied throughout the time, t.
2. The spar response due to three main degree of freedom motions surge, heave and pitch were within allowable values for all environmental conditions which was 1 year, 10 years, 50 years and 100 years return period.
3. The maximum responses among all environmental conditions were 2.33 m for surge, 0.709 m for heave and 0.045 rad for pitch which taken from 100 Years return period.
4. The steel heave plates between the truss system was very useful in reducing the heave resonant motion by increasing both added mass and damping for the structure.
5. From parametric study, it was determined that the dynamic response of the structure was directly proportional to the significant wave height, H_s and the hard tank diameter, D while exponentially increased with the wave period, T.
6. The overall dynamic responses obtained from the frequency domain analysis were slightly different from the results obtained in Wave Response program (SACS Software) due to some errors.

In order to improve the accuracy of the projects outcome, below are some recommendations for further work that could be made in the future:

1. The analysis should proceed with time-domain technique by using some iteration schemes such as the iterative incremental Newmark's Beta approach.
2. Appropriate software should be used such as Matlab 7.0 for doing iteration in time-domain analysis.
3. Model study should be conducted to obtain the experimental data for comparison purposes.

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APPENDIX A

Calculation Spreadsheet for Pierson-Moskowitz Spectrum

H_s	6.30	m	ω_o	0.501	rad/sec
α	0.0081		f_o	0.080	Hz
ω_o^2	0.2506		T	13.1	sec
D	32.3	m	ζ	0.10	

f (Hz)	α	f_0	H(f) (m)	S(f) (m^2.s)	Area S(f)Δf (m^2)
0.005	0.0081	0.07967	0.000	0.000	0.000
0.015	0.0081	0.07967	0.000	0.000	0.000
0.025	0.0081	0.07967	0.000	0.000	0.000
0.035	0.0081	0.07967	0.000	0.000	0.000
0.045	0.0081	0.07967	0.032	0.013	0.000
0.055	0.0081	0.07967	0.569	4.041	0.040
0.065	0.0081	0.07967	1.432	25.632	0.256
0.075	0.0081	0.07967	1.852	42.866	0.429
0.085	0.0081	0.07967	1.853	42.916	0.429
0.095	0.0081	0.07967	1.669	34.800	0.348
0.105	0.0081	0.07967	1.439	25.873	0.259
0.115	0.0081	0.07967	1.221	18.629	0.186
0.125	0.0081	0.07967	1.032	13.323	0.133
0.135	0.0081	0.07967	0.875	9.577	0.096
0.145	0.0081	0.07967	0.746	6.957	0.070
0.155	0.0081	0.07967	0.640	5.119	0.051
0.165	0.0081	0.07967	0.553	3.818	0.038
0.175	0.0081	0.07967	0.480	2.886	0.029
0.185	0.0081	0.07967	0.420	2.209	0.022
0.195	0.0081	0.07967	0.370	1.712	0.017
				Total =	2.404

Design life = 20 years

Number of waves, N = (20 x 365 x 24 x 3600) / 13.1

= 48146564.89 waves

H_s = $4 (m_o)^{0.5}$ Where m_o is total area under P-M spectrum

= 6.202 m

H_{rms} = $2\,(2xm_o)^{0.5}$

= 4.385 m

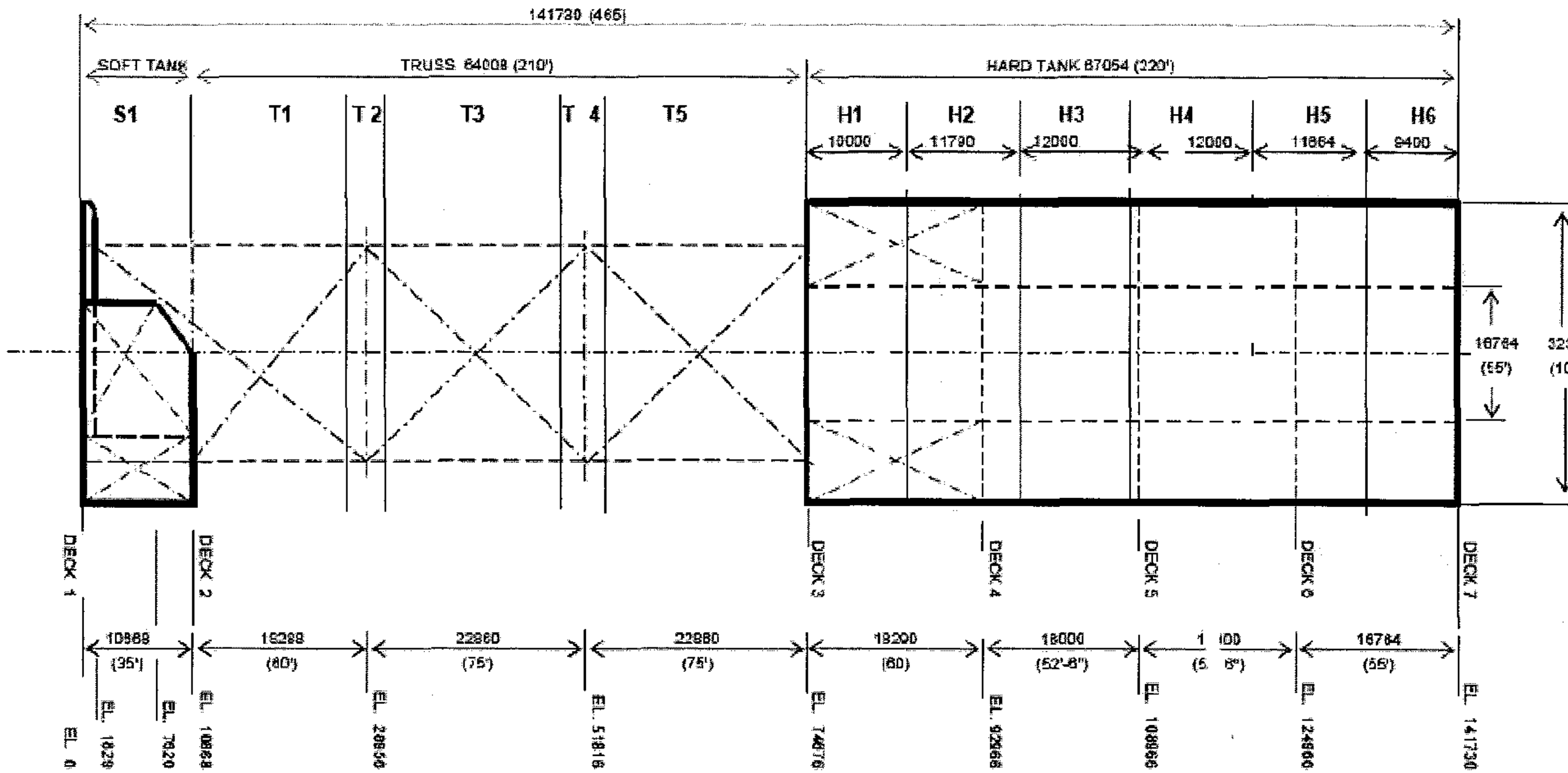
H_{max} = $[\sqrt{(\ln N)} + (0.2886 / \sqrt{(\ln N)}\,]\,H_{rms}$

= 18.745 m

APPENDIX B

Drawing Details

Kikeh Truss Spar Dimension



APPENDIX C

Calculation Spreadsheet for Wave Forces and Moment of Inertia

Wave forces on Hard Tank

Depth, d		=	1330.0 m
Wave Period, T		=	13.1 sec
Wave Height, H		=	18.7 m
Water Density, ρ		=	1030.0 kg/m^3
Diameter Cylinder, D		=	32.3 m
Inertia Coefficient, C_m		=	2.0
Drag Coefficient, C_d		=	1.0
Length of cylinder		=	56.4 m
t		=	1.0 sec
COG	x	=	0.7
	y	=	-46.3
	z	=	0.0

a) Find wavelength, L

L0	=	267.827 m
d/L0	=	4.966

From Wave Table

d/L	=	0.981
L	=	267.827 m

b) Wave Number, k

k	=	0.023

c) Wave Frequency, ω

ω	=	0.480 rad

y	s	k	ks	kd	ω	Θ	u	v	u'	v'	F/m	Fx (kN)	Moment (kN.m)
-0.5	1329.5	0.02346	31.18987241	31.2016	0.4796	-0.480	3.942	-2.050	-0.983	-1.890	1401378.935	**1401.379**	**-64146.719**
-1.5	1328.5	0.02346	31.16641256	31.2016	0.4796	-0.480	3.850	-2.003	-0.961	-1.847	1374738.555	**1374.739**	**-61552.544**
-2.5	1327.5	0.02346	31.14295271	31.2016	0.4796	-0.480	3.761	-1.956	-0.938	-1.804	1348447.597	**1348.448**	**-59026.945**
-3.5	1326.5	0.02346	31.11949286	31.2016	0.4796	-0.480	3.674	-1.911	-0.916	-1.762	1322510.256	**1322.510**	**-56569.054**
-4.5	1325.5	0.02346	31.09603300	31.2016	0.4796	-0.480	3.588	-1.867	-0.895	-1.721	1296930.065	**1296.930**	**-54177.957**
-5.5	1324.5	0.02346	31.07257315	31.2016	0.4796	-0.480	3.505	-1.823	-0.874	-1.681	1271709.939	**1271.710**	**-51852.701**
-6.5	1323.5	0.02346	31.04911330	31.2016	0.4796	-0.480	3.424	-1.781	-0.854	-1.642	1246852.213	**1246.852**	**-49592.300**
-7.5	1322.5	0.02346	31.02565345	31.2016	0.4796	-0.480	3.345	-1.740	-0.834	-1.604	1222358.675	**1222.359**	**-47395.735**
-8.5	1321.5	0.02346	31.00219360	31.2016	0.4796	-0.480	3.267	-1.699	-0.815	-1.567	1198230.608	**1198.231**	**-45261.963**
-9.5	1320.5	0.02346	30.97873375	31.2016	0.4796	-0.480	3.191	-1.660	-0.796	-1.531	1174468.816	**1174.469**	**-43189.916**
-10.5	1319.5	0.02346	30.95527390	31.2016	0.4796	-0.480	3.117	-1.621	-0.778	-1.495	1151073.661	**1151.074**	**-41178.509**
-11.5	1318.5	0.02346	30.93181404	31.2016	0.4796	-0.480	3.045	-1.584	-0.760	-1.460	1128045.092	**1128.045**	**-39226.640**
-12.5	1317.5	0.02346	30.90835419	31.2016	0.4796	-0.480	2.974	-1.547	-0.742	-1.427	1105382.669	**1105.383**	**-37333.194**
-13.5	1316.5	0.02346	30.88489434	31.2016	0.4796	-0.480	2.905	-1.511	-0.725	-1.394	1083085.594	**1083.086**	**-35497.047**
-14.5	1315.5	0.02346	30.86143449	31.2016	0.4796	-0.480	2.838	-1.476	-0.708	-1.361	1061152.736	**1061.153**	**-33717.067**
-15.5	1314.5	0.02346	30.83797464	31.2016	0.4796	-0.480	2.772	-1.442	-0.692	-1.330	1039582.652	**1039.583**	**-31992.117**
-16.5	1313.5	0.02346	30.81451479	31.2016	0.4796	-0.480	2.708	-1.409	-0.676	-1.299	1018373.613	**1018.374**	**-30321.056**
-17.5	1312.5	0.02346	30.79105494	31.2016	0.4796	-0.480	2.645	-1.376	-0.660	-1.269	997523.623	**997.524**	**-28702.745**
-18.5	1311.5	0.02346	30.76759508	31.2016	0.4796	-0.480	2.584	-1.344	-0.645	-1.239	977030.440	**977.030**	**-27136.043**
-19.5	1310.5	0.02346	30.74413523	31.2016	0.4796	-0.480	2.524	-1.313	-0.630	-1.211	956891.595	**956.892**	**-25619.816**
-20.5	1309.5	0.02346	30.72067538	31.2016	0.4796	-0.480	2.465	-1.282	-0.615	-1.183	937104.411	**937.104**	**-24152.929**

-21.5	1308.5	0.02346	30.69721553	31.2016	0.4796	-0.480	2.408	-1.253	-0.601	-1.155	917666.019	**917.666**	**-22734.258**
-22.5	1307.5	0.02346	30.67375568	31.2016	0.4796	-0.480	2.352	-1.224	-0.587	-1.128	898573.374	**898.573**	**-21362.683**
-23.5	1306.5	0.02346	30.65029583	31.2016	0.4796	-0.480	2.298	-1.195	-0.573	-1.102	879823.270	**879.823**	**-20037.095**
-24.5	1305.5	0.02346	30.62683598	31.2016	0.4796	-0.480	2.245	-1.168	-0.560	-1.077	861412.355	**861.412**	**-18756.393**
-25.5	1304.5	0.02346	30.60337612	31.2016	0.4796	-0.480	2.193	-1.140	-0.547	-1.052	843337.146	**843.337**	**-17519.486**
-26.5	1303.5	0.02346	30.57991627	31.2016	0.4796	-0.480	2.142	-1.114	-0.534	-1.027	825594.037	**825.594**	**-16325.296**
-27.5	1302.5	0.02346	30.55645642	31.2016	0.4796	-0.480	2.092	-1.088	-0.522	-1.003	808179.317	**808.179**	**-15172.759**
-28.5	1301.5	0.02346	30.53299657	31.2016	0.4796	-0.480	2.044	-1.063	-0.510	-0.980	791089.176	**791.089**	**-14060.819**
-29.5	1300.5	0.02346	30.50953672	31.2016	0.4796	-0.480	1.996	-1.038	-0.498	-0.957	774319.720	**774.320**	**-12988.439**
-30.5	1299.5	0.02346	30.48607687	31.2016	0.4796	-0.480	1.950	-1.014	-0.486	-0.935	757866.976	**757.867**	**-11954.594**
-31.5	1298.5	0.02346	30.46261702	31.2016	0.4796	-0.480	1.905	-0.991	-0.475	-0.914	741726.908	**741.727**	**-10958.273**
-32.5	1297.5	0.02346	30.43915717	31.2016	0.4796	-0.480	1.861	-0.968	-0.464	-0.892	725895.418	**725.895**	**-9998.483**
-33.5	1296.5	0.02346	30.41569731	31.2016	0.4796	-0.480	1.817	-0.945	-0.453	-0.872	710368.362	**710.368**	**-9074.245**
-34.5	1295.5	0.02346	30.39223746	31.2016	0.4796	-0.480	1.775	-0.923	-0.443	-0.851	695141.552	**695.142**	**-8184.597**
-35.5	1294.5	0.02346	30.36877761	31.2016	0.4796	-0.480	1.734	-0.902	-0.433	-0.832	680210.766	**680.211**	**-7328.591**
-36.5	1293.5	0.02346	30.34531776	31.2016	0.4796	-0.480	1.694	-0.881	-0.423	-0.812	665571.756	**665.572**	**-6505.298**
-37.5	1292.5	0.02346	30.32185791	31.2016	0.4796	-0.480	1.655	-0.861	-0.413	-0.794	651220.249	**651.220**	**-5713.806**
-38.5	1291.5	0.02346	30.29839806	31.2016	0.4796	-0.480	1.616	-0.841	-0.403	-0.775	637151.961	**637.152**	**-4953.219**
-39.5	1290.5	0.02346	30.27493821	31.2016	0.4796	-0.480	1.579	-0.821	-0.394	-0.757	623362.594	**623.363**	**-4222.658**
-40.5	1289.5	0.02346	30.25147835	31.2016	0.4796	-0.480	1.542	-0.802	-0.385	-0.740	609847.849	**609.848**	**-3521.261**
-41.5	1288.5	0.02346	30.22801850	31.2016	0.4796	-0.480	1.506	-0.784	-0.376	-0.723	596603.426	**596.603**	**-2848.185**
-42.5	1287.5	0.02346	30.20455865	31.2016	0.4796	-0.480	1.471	-0.765	-0.367	-0.706	583625.030	**583.625**	**-2202.601**
-43.5	1286.5	0.02346	30.18109880	31.2016	0.4796	-0.480	1.437	-0.748	-0.359	-0.689	570908.374	**570.908**	**-1583.700**
-44.5	1285.5	0.02346	30.15763895	31.2016	0.4796	-0.480	1.404	-0.730	-0.350	-0.673	558449.187	**558.449**	**-990.689**
-45.5	1284.5	0.02346	30.13417910	31.2016	0.4796	-0.480	1.371	-0.713	-0.342	-0.658	546243.212	**546.243**	**-422.792**
-46.5	1283.5	0.02346	30.11071925	31.2016	0.4796	-0.480	1.340	-0.697	-0.334	-0.643	534286.213	**534.286**	**120.749**
-47.5	1282.5	0.02346	30.08725939	31.2016	0.4796	-0.480	1.309	-0.681	-0.326	-0.628	522573.977	**522.574**	**640.676**
-48.5	1281.5	0.02346	30.06379954	31.2016	0.4796	-0.480	1.278	-0.665	-0.319	-0.613	511102.319	**511.102**	**1137.714**
-49.5	1280.5	0.02346	30.04033969	31.2016	0.4796	-0.480	1.249	-0.649	-0.312	-0.599	499867.080	**499.867**	**1612.571**
-50.5	1279.5	0.02346	30.01687984	31.2016	0.4796	-0.480	1.220	-0.634	-0.304	-0.585	488864.134	**488.864**	**2065.940**
-51.5	1278.5	0.02346	29.99341999	31.2016	0.4796	-0.480	1.191	-0.620	-0.297	-0.571	478089.388	**478.089**	**2498.495**
-52.5	1277.5	0.02346	29.96996014	31.2016	0.4796	-0.480	1.164	-0.605	-0.290	-0.558	467538.786	**467.539**	**2910.896**
-53.5	1276.5	0.02346	29.94650029	31.2016	0.4796	-0.480	1.137	-0.591	-0.284	-0.545	457208.306	**457.208**	**3303.787**
-54.5	1275.5	0.02346	29.92304043	31.2016	0.4796	-0.480	1.110	-0.578	-0.277	-0.533	447093.970	**447.094**	**3677.795**
-55.5	1274.5	0.02346	29.89958058	31.2016	0.4796	-0.480	1.085	-0.564	-0.271	-0.520	437191.836	**437.192**	**4033.532**
-56.5	1273.5	0.02346	29.87612073	31.2016	0.4796	-0.480	1.060	-0.551	-0.264	-0.508	427498.009	**427.498**	**4371.595**
											SUM	**47538.374**	**-1110689.470**

APPENDIX D

Calculation Spreadsheet of RAO and Dynamic Response

Surge Response

Mass of structure, m	**5.09E+07**	kg
Added mass, m_{a11}	**5.35E+07**	kg
Total mass, m_{11} ($m+m_{a11}$)	**104372644.3**	kg
Stiffness, k_{11}	**3622029.8**	N/m
ω_N	**0.1863**	rad/sec
Damping ratio, ξ	**0.1**	
Damping, c ($2m\xi\omega_N$)	**3888654.41**	N-sec/m

t	f	ω	Hmax, m	Fx (N)	$(k-m\omega^2)^2$	$(c\omega)^2$	RAO_{surge}	H_{surge} (m)	η_{surge} (m)
0	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.32858
1	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.06583
2	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.33689
3	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	0.30625
4	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-0.79351
5	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-1.71419
6	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.24803
7	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.27455
8	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-1.78778
9	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-0.89755
10	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	0.19522
11	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.24394
12	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.01194
13	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.32590
14	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.11498
15	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.42676
16	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	0.41657
17	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-0.68763
18	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-1.63665
19	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.21633

20	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.29585
21	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-1.85726
22	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-0.99954
23	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	0.08375
24	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.14813
25	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.95342
26	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.31787
27	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	2.15925
28	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	1.51335
29	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	0.52593
30	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-0.58018
31	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-1.55536
32	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.17954
33	0.076336	0.479632	18.745	47674753.800	415695641113669	3478690909459	0.2485	4.65716	-2.31186

Heave Response

Mass of structure, m			**50870895.37**	kg
Added mass, m_{a22}			**51627291.63**	kg
Total mass, m22 ($m+m_{a22}$)			**102498187.00**	kg
Stiffness, k_{22}			**14549607.4**	N/m
ω_N			**0.3768**	
Damping ratio, ξ			**0.1**	
Damping, c ($2m\xi\omega_N$)			**7723492.433**	N-sec/m

t	f	ω	Hmax, m	Fy (N)	(k-mω2)2	(cω)2	RAO_{heave}	H_{heave} (m)	η_{heave} (m)
0	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.70962
1	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.62955
2	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.40741
3	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.09333
4	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.24182
5	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.52239
6	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.68508
7	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.69316
8	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.54482
9	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.27353
10	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.05949
11	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.37909
12	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.61313
13	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.70881
14	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.64453
15	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.43480
16	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.12695
17	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.20955
18	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.49876

19	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.67542
20	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.69965
21	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.56599
22	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.30460
23	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.02552
24	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.34989
25	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.59530
26	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.70636
27	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.65802
28	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.46119
29	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	0.16028
30	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.17681
31	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.47399
32	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.66420
33	0.076336	0.479632	18.745	6926044.019	81537721553428	13722858847397	0.0757	1.41925	-0.70453

Pitch Response

Mass of structure, m		**8.10E+10**	kg
Added mass, m_{a11}		**3.34E+10**	kg
Total mass, m_{11} ($m+m_{a11}$)		**1.14E+11**	$kg.m^2$
Stiffness, k_{11}		**2000000000**	N.m/rad
ω_N		**0.1322**	rad/sec
Damping ratio, ξ		**0.1**	
Damping, c ($2m\xi\omega_N$)		**3025528267.63**	N-m-sec

t	f	ω	Hmax, m	Moment (N.m)	$(k-m\omega^2)^2$	$(c\omega)^2$	RAO_{pitch}	H_{pitch}	η_{pitch} (rad)
0	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.04558
1	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.04044
2	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.02617
3	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.00600
4	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.01553
5	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.03356
6	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.04401
7	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.04453
8	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.03500
9	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.01757
10	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.00382
11	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.02435
12	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.03939
13	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.04553
14	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.04140
15	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.02793
16	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	-0.00815
17	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.01346
18	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.03204
19	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.04339
20	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.04494
21	0.07634	0.479632	18.745	-1110689469.576	591591241255423000000	210581189842048000	-0.0049	-0.09117	0.03636

22	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	0.01957
23	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.00164
24	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.02248
25	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.03824
26	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.04537
27	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.04227
28	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.02963
29	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	-0.01030
30	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	0.01136
31	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	0.03045
32	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	0.04267
33	0.07634	0.479632	18.745	-1110689469.576	5915912412554230000000	2105811898420480000	-0.0049	-0.09117	0.04526

APPENDIX E

Wave Response Program Input Files

SACS Model File

```
LDOPT  IN NF+Z  1.030   9.03-1330.00 1330.00   MN DYN        NPNP
OPTIONS    MN      SDUCJT 5 5          PTPT   PT   PT
LCSEL DY        1   2
LCFAC DY  1.000  1   2
UCPART    0.00 0.70 0.70 1.00 1.00
SECT
SECT SPAR    TUB                         3200.0100.0
GRUP
GRUP CBL        10.795 3.000T1.+04 8.0034.50 1    1.001.00      0.50N1.0E-9
GRUP DUM          152.40 6.000 200.0 8.0034.50 1    1.001.00     0.50N1.0E-9
GRUP SPR SPAR                 20.00 8.0034.50 1    1.001.00        F1.0E-9
MEMBER
MEMBER 10021008 CBL   000000000111
MEMBER 10031007 CBL   000000000111
MEMBER 10041009 CBL   000000000111
MEMBER 10051010 CBL   000000000111
MEMBER 10171012 CBL   000000000111
MEMBER 10161013 CBL   000000000111
MEMBER 10181014 CBL   000000000111
MEMBER 10191015 CBL   000000000111
MEMBER 10061007 DUM
MEMBER 10061008 DUM
MEMBER 10061009 DUM
MEMBER 10061010 DUM
MEMBER 10061012 DUM
MEMBER 10061013 DUM
MEMBER 10061014 DUM
MEMBER 10061015 DUM
MEMBER 10001006 SPR
MEMBER 10061001 SPR
JOINT
JOINT 1000     0.     0.   -56.             -38.800 222000
JOINT 1001     0.     0.    10.              66.800 222000
JOINT 1002  -783.     0. -1330.-88.000                 111111
JOINT 1003   783.     0. -1330.  88.000                111111
JOINT 1004     0.   783. -1330.        88.000          111111
JOINT 1005     0.  -783. -1330.       -88.000          111111
JOINT 1006     0.     0.   -50.                  - 90.160 222000
JOINT 1007    16.     0.   -50.                   -90.160 222000
JOINT 1008   -16.     0.   -50.                   -90.160 222000
JOINT 1009     0.    16.   -50.                   -90.160 222000
JOINT 1010     0.   -16.   -50.                   -90.160 222000
JOINT 1012    11.    11.   -50. 31.400 31.400-90.200 222000
```

```
JOINT 1013   -11.   11.  -50.-31.400 31.400-90.200 222000
JOINT 1014    11.  -11.  -50. 31.400-31.400-90.200 222000
JOINT 1015   -11.  -11.  -50.-31.400-31.400-90.200 222000
JOINT 1016  -779.  779. -1330.-18.903 18.903       111111
JOINT 1017   779.  779. -1330. 18.903 18.903       111111
JOINT 1018   779. -779. -1330. 18.903-18.903       111111
JOINT 1019  -779. -779. -1330.-18.903-18.903       111111
LOAD
**************************************************************************
******
LOADCN  1
LOAD  1001            -4.98+5              GLOB JOIN  DEAD
**************************************************************************
******
LOADCN  2
LOAD  1001            520359.              GLOB JOIN  BOUYNCY
END
***SPMB** 10061012   1006101210061013   1006101310061014   10061014
***SPMB** 10061015   10061015
END
```

Seastate Input

```
LDOPT  IN   +Z  1.030  9.028-1330.00 1330.00   MN DYN        NPNP
FILE S
CDM
CDM AP
MGROV
MGROV    0.000  10.000   2.500
MGROV   10.000  45.000   5.000
GRPOV
GRPOV      SPR F
LOAD
LOADCN 200
WAVE
WAVE1.00AIRY  06.3      13.1       0.00     D  0.00  20.0  18MS10 1 0 7
```

Wave Response Input

```
WROPT  MNPSL  MAXSES              20   -1
*PSEL          JO MF OM BS
PSEL  SPBGFBMCBMVBMABJOBMFBOMBBSBHFBWSBWVB                          S
*PLTTF            OMBBSB              PFS
PSJO  1000DX1000DY1000DZ1000VX1000VY1000VZ1000RX1000RY1000RZ
PSMF  10001006FYA10061001FYA
*WAVTIM  +Z  90.0 -90.0              0.5  30    ST       1.0
*WSPEC    PM   06.3   13.1            400.0
DAMP      2.0
*ELVSEL  -5.0 -10.0 -15.0 -25.0 -30.0 -35.0 -40.0
*PTSEL   1   25   50
END
```