University of Strathclyde Engineering

OPTIMAL DESIGN OF FPSO VESSEL S FOR EXTREME METOCEAN CONDITIONS

By

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DECLARATION OF AUTHENTICITY AND AUTHOR'S RIGHTS

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Date

ABSTRACT

The evaluation of principal dimensions of a Floating Production, Storage and Offloading (FPSO) system is one of the most critical tasks at the initial design stage of the vessel. It is therefore important to get this right from the onset. This work presents an integrated approach of determining the overall optimal principal dimensions of FPSO vessels of any specified oil storage capacity for a given sea state. An Optimal Design Programme (OPTIMAP) has therefore been developed to analyze and compare the various responses of floating production vessels with the aim of selecting the best possible design to ensure not only a reduction in cost of construction, but also to maintain a safe operation and overall optimal performance of the vessel with regards to her dynamic responses in deep sea waves.

Furthermore, FPSOs in harsh environment are often vulnerable to green water. It is therefore necessary to consider the vulnerability of the floating vessel to green water in the design stage. One of the objectives of this research is to determine the optimal principal dimensions of FPSO vessel necessary to prevent or mitigate the effects of green water even in extreme wave environmental conditions. A computer-aided design tool for analysing the susceptibility of FPSOs to green water (ProGreen) has also been incorporated to the optimal design programme (OPTIMAP) in order to select the overall best for any given extreme wave conditions. Also, results of the analysis of a survey of world-wide FPSOs show that the global average length, beam, and depth of the vessels are four, three-quarter, and one-third of the cube root of the cubic number (the overall volume) respectively. This can serve as a vital initial decision-making tool as per weather a given size will be suitable for a specified ocean region. This is because vessel dimensions are directly related to the critical wavelength. Close to the critical wavelength in high wave conditions, the vessel could be subjected to severe bending moments. This research provides the essential technical design solution (in addition to the numerous useful data obtained) which helps to ensure good performance during operation (needed to reduces downtime, and increase uptime), safety and operability of the vessel even under the some harsh or extreme meteorological and oceanographic (metocean) conditions.

Keywords: FPSO, principal dimensions, optimal design, extreme metocean conditions, freeboard exceedance.

DEDICATION

I hereby dedicate this work to the King of kings and Lord of lords, who alone has absolute power over the stormy waves of the seas.

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NOMENCLATURE

a	Horizontal component of line tension divided by weight of unit length
A_3	Effective heave area
A_{jk}	Elements of the added mass matrix
$A_{11}^{(2D)}$	2-D virtual added mass in surge
$A_{33}^{(2D)}$	2-D virtual added mass in heave
B	Beam or breadth of vessel
BM	Wave bending moment
C_{33}	Coefficient of hydrostatic restoring heave force
C_{55}	Coefficient of hydrostatic restoring pitch moment
C_B	Block coefficient
C_f	Conversion factor from bbl to m^3 ($C_f = 6.28981077$)
C_{jk}	Elements of the stiffness matrix
C_n	Cubic number (or the overall volume of the vessel)
C_{nr}	Cube root of the Cubic number
c_{m1}	Virtual added mass coefficient in surge
c_{m3}	Virtual added mass coefficient in heave

c_v	Virtual added mass coefficient in heave
D	Draught
D_m	Vessel molded depth or height
d_k	Damping factor in k^{th} mode of motion
d_{jk}	Elements of the linear damping matrix
e	Maximum permissible green water exceedance
E	Green water exceedance; Modulus of elasticity
ϵ	Energy coefficient, Spectral bandwidth parameter
E_s	Oil storage efficiency
f	Wave frequency in Hz
F_j	complex amplitudes of the wave exciting forces and moments
f_1, f_2, f_3, f_4:	Dimensionless factors
F_{3a}	The amplitudes of the heave force
F_{5a}	The amplitudes of the pitching moment
FPSO	Floating Production, Storage and Offloading vessel
FSU	Floating Storage Unit
FSO	Floating Storage and Offloading vessel
g	Acceleration due to gravity
GM_T	Transverse metacentric height
ProGreen	Green water analysis programme
h	Water depth
H_s	Significant wave height
ISSC	International Ship Structures Congress
ITTC	International Towing Tank Conference
k	Wave number
KB	Distance from the keel to the center of buoyancy

KG	Distance from the keel to the center of gravity
κ_i	Factor for application of green water constraint to i^{th} vessel
L	Vessel length between perpendiculars
l_s	Minimum length of cable
L_5	Effective pitching lever
λ	Wavelength
λ_{cr}	Critical wavelength
M	Displacement (in tonne) of vessel (FPSO)
M_{jk}	Elements of the generalized mass matrix for the structure
m_n	n^{th} spectral moment
m_0	Zeroth moment or variance of the wave elevation (σ^2)
m_1, m_2, m_4:	First, second and forth spectral moments respectively
OPTIMAP	Optimal design programme
PDP	Principal Dimensions Programme
ProMot	Programme for Motion analysis
Q_1	Surge magnification factor
Q_3	Heave magnification factor
Q_5	Pitch magnification factor
RAO_1	Surge response amplitude operator
RAO_3	Heave response amplitude operator
RAO_5	Pitch response amplitude operator
ρ	Density of sea water
S_c	Required oil storage capacity
S_{min}	Minimum separation of heave- and-pitch zeros
$S(\omega)$	Wave spectrum
T	Wave period; Line tension

T_H	Horizontal component of line tension
T_{max}	Maximum line tension
$T_{n}3$	Heave natural period
$T_{n}5$	Pitch natural period
T_s	Significant wave period
T_p	Peak period
T_z	Zero up-crossing period
$\bar{T}$	Mean wave period
U	Wind speed
U_x	Horizontal wave particle velocity
U_z	Vertical wave particle velocity
Φ	Velocity potential
σ	Root mean square water surface elevation
τ	Shape parameter (See JONSWAP Spectrum)
ω	Wave frequency in rad/s
ω_n	Zero up-crossing frequency
ω_z	Zero up-crossing frequency
ω_o	Spectral peak or modal frequency
ω_z	Zero up-crossing frequency
$\bar{\omega}$	Mean wave frequency
w	Weight per unit length of mooring line
WavBem	Wave Bending Moment programme
w_j	Weighting factors for $1\ to\ j$ responses
x_b	Variable length-breadth ratio

y	Vertical distance above average sea level (approximately 19.5m)
y_d	Variable breadth-depth ratio
$\zeta_{i(j)}$	Responses for 1 $to\ i$ vessels
$\zeta_{min}^{(j)}$	Minimum responses in j characteristic modes for i vessels
ζ_a	Wave amplitude
Ω_i	Relative goodness or the Optimap number of i^{th} vessel
z_m	Draught to depth ratio

CHAPTER 1

1 INTRODUCTION

1.1 Historical Background

The conceptualization and creation of floating storage vessels became imperative and feasible when the offshore oil industry began to grow in the second half of the twentieth century. The first floating storage vessels were then installed to reduce the cost of transporting oil ashore for storage before shipping it elsewhere. These first floating storage units (FSU) were tankers that stayed moored for a few days to weeks. They were developed with the single point mooring system which allows for the vessel to be positioned such that environmental impacts are minimized.

Subsequently, platform operators began to look into vessels that would remain on station for periods of months to years. This type of vessel would have to be offloaded by a shuttle tanker. The logical progression was to convert mid-sized tankers into the floating, storage and offloading (FSO) vessels. These vessels however, still did not produce the oil. Thus, the oil had to be processed on a platform. Later, companies saw removing the platform as a way to reduce the cost of production. This led to the idea of putting production topsides on the FSO vessels. These developed into floating production, storage, and offloading (FPSO) vessels. See Figure 1.1. The early FPSO vessels were tanker conversions which eventually led to drastic reduction in available fleet of tankers and so provoking the designing and building of new ones.

Generally, the needs related to the use of ship-shaped offshore units (FSU, FSO, and FPSO etc.) and their technical challenges for the development of offshore oil and gas in deep water are given by Henery and Inglis (Henery and Inglis, 1995), Bensimon and Delvin (Bensimon and Delvin, 2001) and Hollister and Spokes (Hollister and Spoke, 2004) among others.

These offshore units have proven to be reliable and cost-effective solutions for the development of offshore fields in deep waters of more than 1,000m depth, as they have successfully been applied for more than 30 years in such harsh environments.

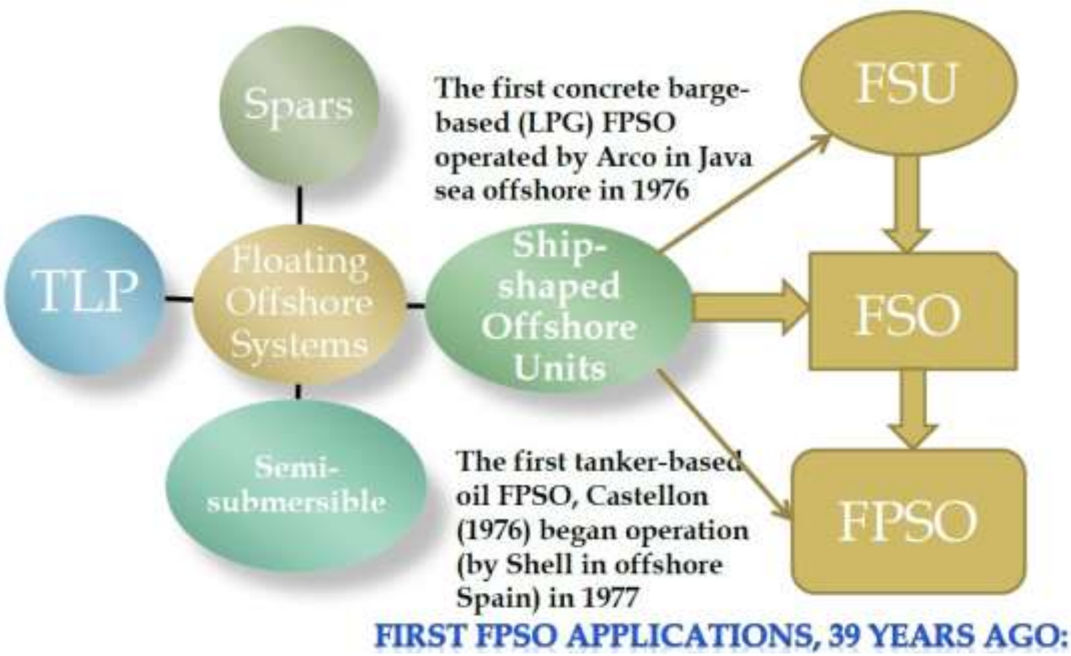


Figure 1.1: Floating Offshore Systems and FPSO development

It is note-worthy that a concrete barge with steel tanks became the first dedicated FPSO application and it was operated by Arco in the Ardjuna field in the Java Sea offshore Indonesia in 1976 (D'Souza et al., 1994), while the first tanker-based single-point moored FPSO facility is the FPSO Castellon for Shell offshore Spain in 1976. It however began operation in 1977. Since then, the application of FPSOs and other related offshore structures has grown very rapidly, and will remain a mainstay in the oil and gas industry for many years to come as they provide the flexibility and sound economics of producing and storing at the offshore well sites. Thus the oil is produced, safely stored and then directly transported to the refinery.

1.2 The Aim and Objectives of the Research

This research aims at investigating the impact of harsh or extreme environmental forces on FPSO and establishes reliable methods and tools for prediction of environmental loads and structural responses to enable a preliminary optimisation of the principal dimensions. The dynamic behaviour, induced motions or responses of the vessel under the influence of these metocean forces are vital to the stability and safety of both the vessel and crew and so will be evaluated. This design of FPSO is very imperative as it gives the design solution required for unrestricted offshore operations. To achieve this main objective, the extreme metocean forces, associated extreme motion responses as well as the shear forces and bending moments for the design environments such as the North Sea will be determined. That is, the specific objectives include the following:

- Select the wave spectral models suitable for design of floating production, storage and offloading system.

- Predict extreme vessel motion responses associated with some specified marine environments (North Sea and West African) and the vessel dimensions/size.

- Develop simpler methodology and programs for quick determination of design data. The design of the vessel's principal dimensions required for the development of any given oil field will be carried out based on the specified required storage capacity of the vessel.

- Evaluate the dynamic wave bending moment amidships. This is required in order to ensure that the hull girder has sufficient strength to withstand the induced stress.

- Predict the optimal design suitable for the avoidance or mitigation of green water occurrence due to extreme wave (of phenomenally high amplitude).

This study, on successful completion, will (or has the potential to):

- Lead to better understanding of environmental loading, and ways of enhancing the safety of crew and vessel in operation in extreme cases.

- Help in extending knowledge in offshore design and hydrodynamics, and develop some innovative approaches that could lead to a safer and more simplified design.

- Help in developing oil and gas fields (including marginal oil fields) more efficiently and so reducing downtime. The use of FPSO in field development in deep water cannot be over emphasized.

- The results will be relevant inputs for detailed FPSO design.

- Bring high economic benefits through reduction in the cost of production, products sales, and employment generation. Hence, this study is intended to help in bringing a sustainable oil and gas development

1.3 Summary of Research findings or Achievements

The following is a brief summary of the findings from this research:

(i) Computer-aided design tools or software have been developed to evaluate most probable maximum responses, and possible green water exceedances. The Optimal design programme (Optimap) enables users or FPSO manufacturing industries to make the best (Optimal) selection of the principal dimensions of the vessel given some defined functional and geometric constraints. It applies proposed relative goodness number and the specified constraint(s) to select the optimal design.

(ii) The programme is also equipped with the capability to optimise an already existing FPSO. For instance, Seven FPSO vessels (Aoka Mizu, Asgard A, Yuum Ka'Ak Naab, Aker Smart 2, Frade, Abo and Agbami) operating in different ocean regions have been optimized (See Table 8.4 and Table 8.5).

(iii) The effects of different extreme sea states on a particular FPSO vessel (such as Asgard A, 243.65kTon displacement, located in Asgard in the Norwegian part of the North Sea) have also been given (Table 8.14 and Figure 8.10). Also presented is the effects of those extreme sea states on the optimal dimensions of the FPSO Please, see Figure 8.11. The programmes have several subroutines which handle different subject areas.

(iv) Principal Dimensions Analysis Programme (PDP) makes use of the fact that the principal dimensions are directly proportional to the cube root of the cubic number (the overall volume which is a function of the required oil storage capacity). See Eqns. (4.8), (4.9) and (4.10).

(v) From the analysis carried out on some vessels selected from 2010 worldwide survey of FPSO, it has been found that the global average length, breadth, and depth of FPSO vessels are four, three-quarter, and one-third of the cube root of the required cubic number. These relationships are simpler, more generic and more accurate than those of MacGregor and Smith (1994). This has been discussed in section 4.4 (See Figure 4.6).

(vi) The motion analysis programme (ProMot) computes all the required motion characteristics of the vessels using the simplified and more explicit formulations which make it easier to compute.

(vii) The amplitudes of heave force and pitch moment have been further simplified: The amplitude of the heave force can be simply expressed as: $F_{3a} = \rho g \zeta_a A_3$;

$$A_3 = \left[\left(\frac{\mathrm{B}\lambda}{\pi}\right) - c_v \pi \left(\frac{B}{2}\right)^2\right](\mathrm{e}^{-\mathrm{kD}}) \sin\left(\frac{\mathrm{k}L}{2}\right)$$

While the amplitude of pitch moment is simplified as $F_{5\mathrm{a}} = F_{3\mathrm{a}} L_5$

Where the effective pitching lever is: $L_5 = \frac{1}{k}\left[\left(\frac{kL}{2}\right)\cot\left(\frac{kL}{2}\right) - 1\right]$

and the virtual heave added mass coefficient is given by:

$$c_v = c_{m3} = 1.014\left(\frac{B}{D}\right)^{(-0.2692)} + 0.674$$

(viii) The green water analysis programme (ProGreen) investigates the effects of green water and also helps to select the optimal design needed to avoid a given exceedance threshold or maximum permissible freeboard exceedance. The freeboard exceedance increases as length-breadth increases (with improvement in the heave and pitch motions). The optimal design for mitigating the effects of green water tends to require larger depths (i.e. lower breadth-depth and larger length-breadth ratios) which ensure that there are both sufficient freeboard and wider disparity from the critical wavelength.

(ix) The critical wavelength has been introduced and may be described as the wavelength at which the induced kinetic energy coefficient $\in_{kj}$ is maximum. The first and most important critical wavelength is approximately equal to the length of the vessel. Generally, critical wavelength is a prime factor of the vessel length. At that frequency, the wave bending moment per unit wave amplitude tends to maximum. See Figure 6.2. In nature, it may occur in form of a swell.

(x) The wave bending moment programme (WavBem) was implemented using the derived formulae (Eqns. 6.24 and 6.25). At a given wave period (or with slight differences in wave period, the induced wave bending moment is directly proportional to the significant wave height. At amidships, the slope is ¾ for this particular vessel, i.e. maximum BM (in GNm) is ¾ H_s +0.13. See Figure 6.4. It is also interesting to note that the wave bending moment distribution follows a Fourier series (of preferably, the forth degree). Furthermore, an approximate prediction of wave bending moment distribution has been given.

(xi) The n[th] spectral moment of the general spectral model has been obtained: $m_n = \left(\frac{A}{q}\right)\frac{\Gamma(c_n)}{B^{(c_n)}}$; where: $c_n = \left(\frac{p-n-1}{q}\right)$.
For details, please see Eqns. (3.9) and (3.48).

(xii) It has also been found that the natural heave and pitch period can be expresses as a function of beam and draught only. It can be estimated using: $T_{n3}, T_{n5} \cong 2\left\{D\left[1 + 0.4\left(\frac{B}{D}\right)^{0.7} + 0.3\left(\frac{B}{D}\right)\right]\right\}^{\frac{1}{2}}$.
For length-breadth ratios between 4.5 and 5.8, and breadth-depth ratios between 1.4 and 2.4 of rectangular-shaped vessel, the natural heave or pitch periods only range between 14.3 and 15.5s.

(xiii) Also see List of Publications from this Research in Appendix H.

1.4 Design Methodology

The design of floating structures is usually carried out following a welldefined design spiral as a guide. This project therefore follows a simplydefined design spiral to accomplish the desired goal(s). The FPSO Design Spiral (FDS) shown below (Figure 1.2) starts with the identification of the vessel owner's requirements. The spiral includes the following steps: (i) Owner's Requirements, (ii) Environments, (iii) Hydrostatics, (iv) Motions, and (v) Structure. In order to meet the owner's requirements such as the required storage capacity, it is important to ensure that the right principal dimensions of the vessel are evaluated as demonstrated in the following sections.

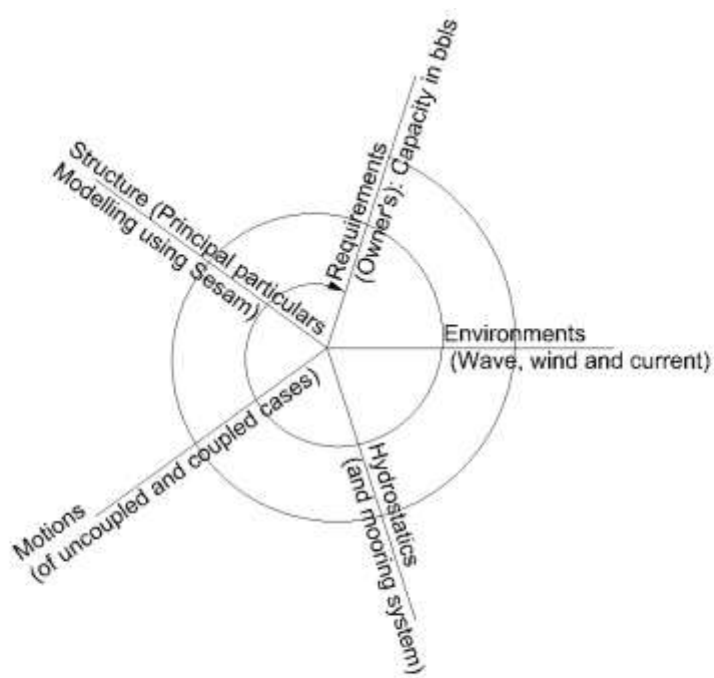


Figure 1.2: FPSO Design Spiral (FDS)

In a complex design analysis such as this, it is worthwhile to be mindful of some preliminary design objectives for optimal design of vessels which are to be operated in the harsh wave environment such as the North Sea:

(i) The storage capacity or volume must be capable of taking the output during the average interval of shuttle tanker calls plus about 3 days.

(ii) The value of the transverse metacentric height, GM_T, must be around 3m or more, in the fully-loaded condition.

(iii) The natural rolling period must be greater than 12 seconds. Also, the natural pitching and heaving periods, which should definitely be longer, must be as long as possible. Usually, a good design has the natural motion periods longer than the peak period of the spectrum which is exceeded for less than 2% of the time and low heave forces and pitch moments at all shorter periods. Table 1.1 gives the wave periods and wavelengths for four sea areas which illustrate the problems involved. For instance, the peak periods exceeded 2% of the time in the Central and Northern North Seas are 12.3s and 15.4s respectively.

(iv) In order to give a better motion response, the zero force frequencies for heave and pitch must be spread out as much as possible.

(v) The ratio L/D_m must be less than 13 (from structural point of view).

(vi) In order to accommodate the segregated ballast and produced water storage capacity, the underdeck volume should not exceed 1.8 times the displacement. This implies that: $D_m/D \leq 1.8$, i.e. $D \geq 0.56D_m$.

(vii) The required external surface areas should be as small as possible, which implies low L/B and B/D_m ratios.

Table 1.1: Wave Periods and Wavelengths for a Number of Sea Areas

Periods and Wavelengths Exceeded 2% of Time					
		Pierson-Moskowitz		JONSWAP	
Area	T_z	T_p [s]	λ_p [m]	T_p [s]	λ_p [m]
Central North Sea	8.7	12.3	236	11.2	196
Northern North Sea	10.9	15.4	370	14.1	310
West of Shetland	11.3	15.9	395	14.6	333
Brazil	10	14.1	324	12.9	260

Examples of wave spectral models are given in Chapter 3. See Figure 3.1. Spectral Analyses are carried out for each of the vessels with above preliminary objectives being applied as design constraints in the computer programmes written in MATLAB. The programmes (PD Programme, ProMot, WavBem, ProGreen and Optimap) have been carefully written to evaluate the effects of extreme conditions, and proffer corresponding solutions using the required storage capacity and the constraints posed by the above preliminary objectives as major inputs to the programmes.

The design environments (which is expressed as wave spectral models), hydrostatic/hydrodynamic analyses, and response computations are carried out using MATLAB programming and Spectral techniques as earlier stated.

The programmes yield useful solutions to the vessel's critical dynamic problems with a view to improving the applicable theories.

The structural modelling and analyses are carried out using Sesam software or MATLAB (which is a suitable Language of highly Technical Computing). Sesam GeniE and HydroD analyses of the vessel may also be vital validation tools in the design process, if necessary.

This method, when fully implemented will yield a very good preliminary design of the Floating Production, Storage and Offloading vessel with reasonable emphasis on the three major focal areas: FPSO Modelling; Environments; and Vessel Dynamics. See the design focal areas in Figure 1.3 below.

FPSO

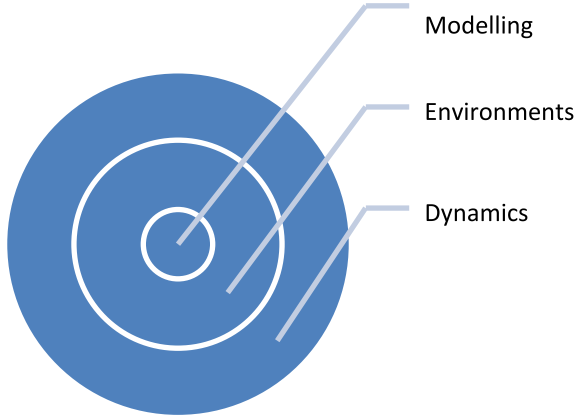


Figure 1.3: Design Focal areas

Therefore, the above method can be summarized as an optimisation-based frequency domain spectral analysis along a well-defined design spiral. The programmes developed following this method include PDP, ProMot, WavBem, ProGreen (for green water susceptibility analysis and optimisation), and Optimap (for overall optimal design analysis with the introduction of the Relative Goodness, Ω, which is a measure of the overall performance of the vessel in caparison with the others in the analysis).

1.5 Owner's Design Requirements

Vessels are often designed to perform specific function(s). The FPSOs are used mainly for production and storage of crude oil (and periodically offloaded to shuttle tankers for transportation to the refinery or market). Therefore, most vessel owners require reasonably high storage capacity and large deck area for topside installation.

Major oil fields in the Niger Delta area of Nigeria have oil reserves up to 1000 million bbls of oil. Agbami, Bonga, Forcados-Yokri, and Erha fields have oil reserves of 1000, 600, 1235, and 1200 million bbls respectively (Adebola et al., 2006). See Table 1.2. Therefore, most vessel owners would require FPSOs that would be capable of storing up to 2 million bbls. Agbami FPSO has storage capacity of 2.2 million bbls. It is therefore important to have a specific storage capacity in mind as an initial design requirement. In this project, we will be considering a storage capacity of 2 million bbls.

Table 1.2: Major Oil Fields in the Niger Delta

Operator	Fields	Reserves (mmbbls)
Shell	Bonga	600
	Bonga South west	600
	Bomu	875
	Cawthorne Channel	750
	Forcados-Yokri	1235
	Imo River	875
	Jones Creek	900
	Nembe Creek	950
Mobil	Edop	733
	Erha	1200

	Ubit	945
Chevron Texaco	Agbami Delta Meren Apoi-North-Funiwa Okan	1000 300 1100 500 800
Agip	Ebegoro	160
Total	Amenam-Kpono	500

1.6 General Arrangement of FPSOs

1.6.1 The Deck Area

The area of the deck required is a function of the size of the process plant, footprint and other relevant complexities. The process plant capacity is usually project-specific and field economics dependent. Other factors that affect the deck area and general arrangement are:

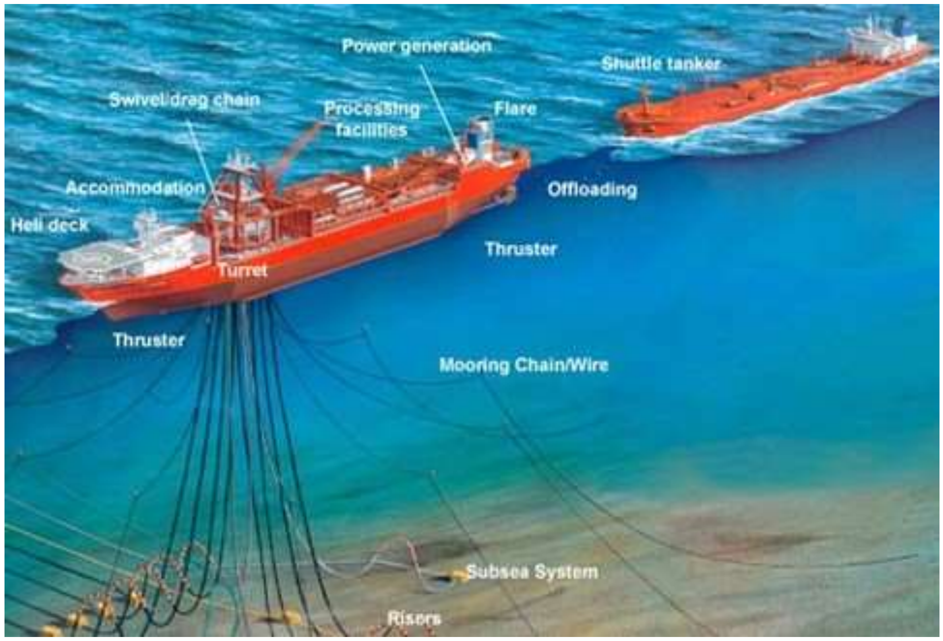
(1) Hull form
(2) Turret size and location
(3) Accommodation and its location
(4) Ballast capacity and distribution
(5) Double-side or double-bottom requirements
(6) Offloading arrangements
(7) Margins for future expansion

1.6.2 The Layout

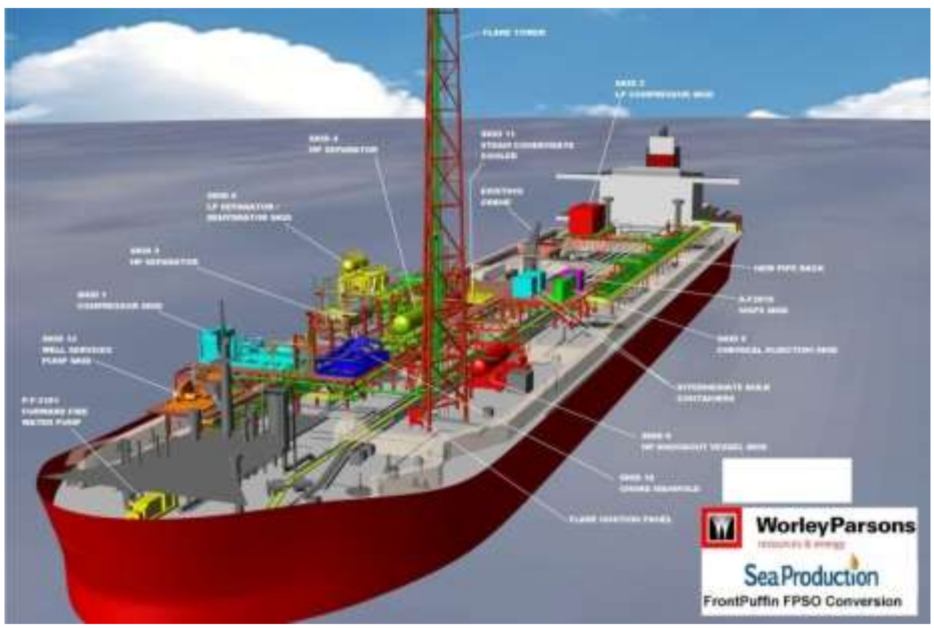
The layout of an FPSO may be divided into:

(1) Main deck
(2) Topsides deck
(3) Mooring system
(4) Accommodation
(5) Machinery room
(6) Cargo and Ballast tanks
(7) Offloading system

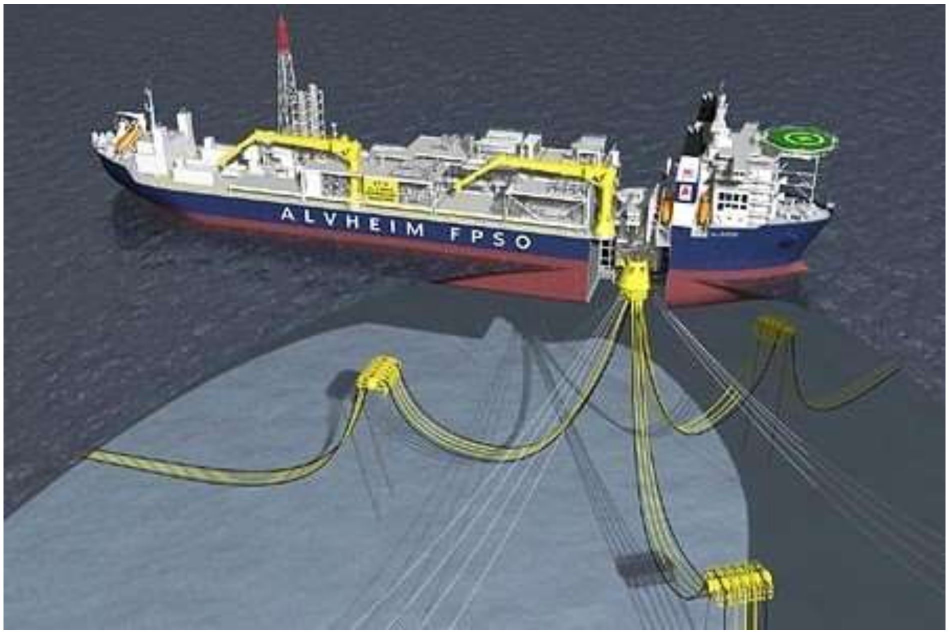
(a) FPSO with accommodation aft and internal turret



(b) FPSO with accommodation forward and internal turret



(c) FPSO with accommodation aft and internal turret



(d) FPSO with accommodation forward and internal turret

Figure 1.4: Typical Layouts of FPSO Topsides Facility

(Source: https://www.google.co.uk/search?q=fpso+pictures).

Figures 1.4(a)-(d) show typical layouts of FPSO topsides facility. There is one basic and easily observable distiction which is the exchange in position of accommodation and helipad on one side, with the process modules (including the power generation of the production system) and the flare tower on the other side. The underlying principle in the arrangement is to maximise the separation between the accommodation and the major hydrocarbon hazards for health and safety reasons.

As shown in Figures 1.4 (a) and (c), the accommodation and the helideck are located aft while the flare tower and process modules are sited forward of amidship.

On the other hand, the accommodation and the helideck are located forward of amidship while the flare tower and process modules are aft as shown in Figures 1.4 (b) and (d). The turret is usually located as far forward as possible to give the thrusters an easy and active heading control capability. When a large turret is required, it is usually necessary to locate it 0.2L0.35L from the forward end to allow enough cargo region length after the turret to be maximised.

1.6.3 Initial Determination of the Principal Dimensions of the FPSO Vessel

It is important to express the principal dimensions as a function of the cubic number if the proportions or ratios of the main dimensions are known.
These ratios have been estimated by some authors (MacGregor and Smith, 1994; DeLuca and Belfore, 1999). A cubic number is a perfect cube. The overall hull volume (LBD_m) is therefore equivalent to a certain cubic number.

Take: L: Length between perpendiculars; B: Breadth; D_m: Moulded Depth; and D: Draught.

Let: $L/B = x_b$; $B/D_m = y_d$; $D/D_m = z_m$

$$LBD_m = \frac{L^3}{(L/B)^2(B/D_m)} = \frac{L^3}{{x_b}^2 y_d}$$

$$L = (x_b{}^2 y_d)^{1/3}(LBD_m)^{1/3} \tag{1.1}$$

$$LBD_m = \frac{B^3(L/B)}{(B/D_m)} = \frac{B^3 x_b}{y_d}$$

$$B = (x_b/y_d)^{-1/3}(LBD_m)^{1/3} \tag{1.2}$$

$$LBD_m = D^3(L/B)(B/D_m)^2 = D_m{}^3 x_b y_d{}^2$$

$$D_m = (x_b y_d{}^2)^{-1/3}(LBD_m)^{1/3} \tag{1.3}$$

$$D = z_m D_m \tag{1.4}$$

Where: $LBD_m = \frac{Sc}{Es \times 6.28981077}$; $1m^3 = 6.28981077 bbls\ of\ oil$

Sc: Required Storage Capacity in barrels of oil (bbls)

Es: Oil storage Efficiency.

Example: Given: $Sc = 2000000$; $Es = 0.58$

$L/B = x_b = 5.4$; $B/D_m = y_d = 1.8$; $D/D_m = z_m = 0.7$. The principal dimensions can be fully evaluated and are all directly proportional to the cube root of the cubic number or the overall volume.

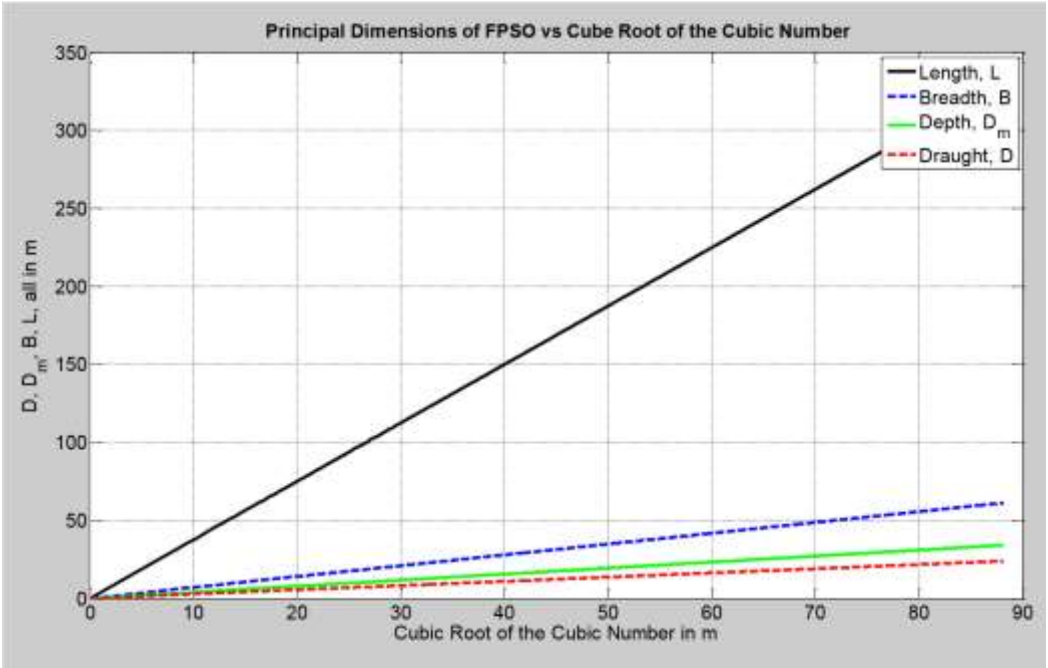


Figure 1.5: Principal Dimensions vs cube root of the Cubic Number

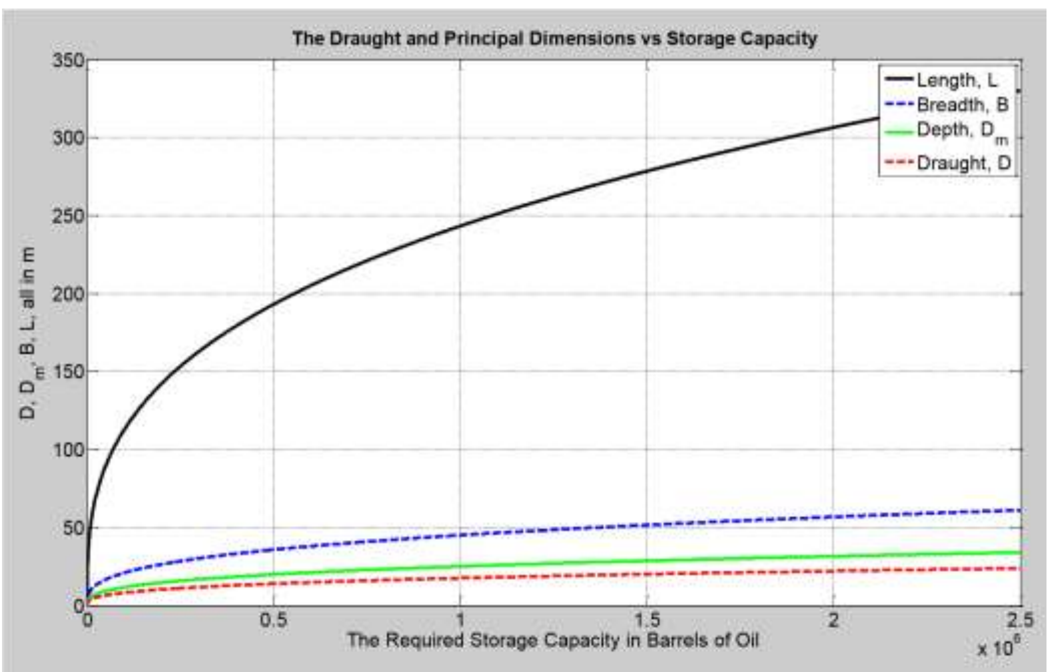


Figure 1.6: Principal Dimensions vs Storage Capacity

The solution gives the following principal particulars: L=306.4372m; B=56.7476m; D_m=31.5265m; and D=22.0685m. A more detail design of these principal dimensions will be presented in Chapter 5.

CHAPTER 2

2 BRIEF REVIEW OF RELEVANT LITERATURES

2.1 Trading Tankers and Ship-Shaped Offshore Units

The trading tankers and the ship-shaped offshore units such as the FPSOs have many design and operational features in common. However they differ from each other in a number of ways as shown in Table 2.1

Table 2.1: Differences between Trading Tankers and Ship-shaped Offshore Units

S/N	Trading Tankers	Ship-shaped Offshore Units

(i)	Design Condition: North Atlantic wave environment	Design Condition: Site- and towroute-specific environments
(ii)	20- to 25-year return period	100-year return period
(iii)	Wave action is predominant	Current, wind and wave actions
(iv)	Limited number of loading conditions	Variety and higher number of loading conditions
(v)	Limited number of loading and offloading cycles	More frequent loading/offloading cycles
(vi)	Operate in open sea for about 70% of the time	Operate offshore for 100% of the time
(Vii)	Weather in any direction, but possible to avoid rough weather	Highly directional weather and weathervaning, with rough weather avoidance impossible
(viii)	No topsides	With topsides and associated interaction effects on the hull
(ix)	Requires regular dry-docking every 5 years	Operates continuously without dry-docking
(x)	With propulsion power plants	Without propulsion power plants

The design environmental condition is one of the key criteria which must be considered in the design of any marine vessel and can also be used in differentiating them. Trading tankers are normally designed based on the North Atlantic wave environment for possibility of unrestricted worldwide travel. However, the design of ship-shaped offshore units is based on the environmental conditions prevalent in their operational sites, mode of transportation to field for installation, type of mooring, time of commencement of operation in that field (Paik and Thayamballi, 2007).

The return period of waves for the hull girder strength design of shipshaped offshore units is, for historical reasons, taken as 100 years, while that of trading tankers is usually between 20 and 25 years.

Whereas waves are the predominant source of environmental actions on trading tankers at sea, winds and currents among other factors also induce significant actions and action effects on offshore units.

2.2 FPSO Designs for Exploration in Adverse Coasts

Haveman et al (2006) designed an FPSO to accommodate a 1.6 million barrel storage facility and to be used in harsh cyclonic coast of China. This facility is self-contained and processes, stores and offloads crude oil products.

Team West Africa (Banda et al., 2003) worked on Design of an FPSO System and Oil Off-take System for Offshore West Africa. They compared the ship-shaped and square shaped FPSOs and found that the environmental load on the square-shape option was much greater than the conventional ship-shaped FPSO. Though the square-shaped FPSO had lower draught which was advantageous for the shallow water (of about 27 m of depth) oil field where it is designed to operate, they however preferred and recommended the ship-shaped FPSO because of its environmentally friendly disposition in terms of the hydrodynamic forces acting on it and the operational cost when compared to the square-shaped option.

Analysis of the rapidly growing FPSO worldwide fleet, showing the industrial trends over recent years had recently been carried out by Wyllie and Johnson (2006). The trends analysed included processing capacity, process complexity and water depth which are all on the increase. Their emphasis was more on the relationship between shape of the hull and the cost of producing of the vessel. The environmental forces are very critical when dealing with the extreme responses, stability and safety of the vessel and her crew.

2.3 The Low Frequency Motions

The low frequency motions of moored floating vessels had been investigated by a number of researchers in the last few decades. Havelock (1942), Maruo (1960), Newman (1974), Remery and Hermans (1972) made some background studies, empirical measurements and gave some theoretical explanations of the drift forces acting on a moored floating vessel in waves. Furthermore, an analytical procedure for calculating the slow drift oscillations and peak mooring forces which are extremely essential in practice was illustrated by Hsu and Blenkarn (1970). Very extensive studies on the slowly drifting moored vessel were also undertaken by Pinkster (1975; 1979; 1980). Pinkster reviewed the methods of calculating the low-frequency-wave drifting forces on an object in irregular waves using the existing method in which he applied the drifting force in regular waves. The influence of the force on the motions of moored vessels and the loads in the mooring system were favourably compared to the results of model tests in irregular waves. Pinkster's works undoubtedly enhanced the understanding of the phenomenon, with vital formulations deemed to be very invaluable in both the frequency and time domain computations. Though his formulations are based on linear assumptions, they are more suitable and preferable to model-test measurements at the initial design stage.

Apparently, a reasonably accurate estimate of the surge motion of a bargetype vessel under the influence of the low-frequency drifting force in irregular waves can therefore be made as demonstrated by Remery and Hermans (1972). Also, Hsu and Blenkam (1972) suggested a method in which the spectral density of the drifting force is calculated directly from the spectral density of irregular waves using the mean drifting force coefficients in regular waves.

The responses of a ship to irregular waves can be considered as the summation of the responses to regular waves of all frequencies (St. Denis and Pierson, 1953). This hypothesis is based on the principle of superposition which is considered to be valid for evaluation of sea loads and ship motions.

The validity has been proven, particularly for vertical motions and loads (Ogilvie, 1964; Salvesen et al., 1970).

For more accurate evaluation and predictions of the behaviour of a moored vessel due to slowly varying drift forces, several other authors had carried out further studies especially on the related damping components (Wichers and Sluijs, 1979; Hearn and Tong, 1986; Standing et al., 1987; Faltinsen and Zhao, 1989).

The hydrodynamic damping components may be divided into four categories according to their sources or origin:

(a) Still water (both potential and viscous origin),
(b) Wave drift damping,
(c) Mooring lines damping and
(d) Damping due to other environmental components such as wind and current.

Furthermore, comparative analyses of linear and non-linear computer simulations carried out by (Herfjord and Nielsen, 1991) indicated that the first order hydrodynamic quantities and the first order motion responses can be computed with a high level of accuracy using methods available today. However, the prediction of second-order forces and associated responses show a considerable amount of deviation.

These large deviations could have been caused by other properties of the moored vessel such as the turret location (in the case of turret mooring), mooring system or configuration. The influence of turret location on the dynamic response of the vessel and the loads on the mooring-lines had been investigated (Liu and Brown, 1998; Thiagarajan, 1998).

Researches on the dynamic responses of moored vessel in waves began in the early seventies. The main cause of these late studies on this area is that earlier traditional naval architects dealt with mooring designs at that time only for the purpose of moored ships to a quayside, which was considered as a static problem. The studies on the dynamic responses of moored ships in waves gained momentum with the advent of offshore industries (Hsu and Blenkarn, 1970). Interestingly, progress in this area of research have been accelerated by steady developments in numerical techniques like the three dimensional source technique (Oortmersen, 1977).

Other relevant works in this field include the study of dynamic wave induced loads acting on the hull girder of an FPSO which has been investigated and found to be adequate for the purpose of the preliminary design using linear or nonlinear hydrodynamic modelling (Incecik et al., 2002; Korvin-Kroukovsky and Jacobs, 1957; Jacobs, 1958; Gerritsma and Beukelman, 1967), etc.

However, further work is required to account for the influence of the principal dimensions of the vessel, and the higher-order wave forces on the low-frequency wave drift.

2.4 Effects of Extreme Wave Conditions

Green water is the flow of the unbroken waves which overtop the bow, side or even stern part of the deck of a ship or floating offshore structure. It depends on the relative motion between the vessel and the waves, velocity, freeboard, and the harshness or flow intensity of the wave. It occurs when the relative motion exceeds the freeboard. The bow is most susceptible to green water occurrence especially for a turret-moored offshore unit due to its weathervaning characteristics, although it sometimes occurs at the stern (HSE, 2001). This problem is a very important design issue because of its great potential to cause damage to deck-mounted equipment. It poses a tremendous threat to both crew and deck facilities such as accommodation, watertight doors, walk-way ladders and cable trays (HSE, 1997; HSE, 2000). Also, it may lead to deck flooding which is hazardous and constitutes a threat to the workforce and could result in downtime depending on its severity.

The FPSOs in the North Sea are highly vulnerable to green water. Between 1995 and 2000, about seventeen green water incidents on twelve FPSOs in UK waters of the North Sea have been reported (Morris et al., 2000; Ersdal and Kvitrud, 2000).

Problems associated with green water and wave slamming at the bottom of the bow which are directly related to the freeboard and flare have remained unresolved by most of the available software, although they have been quite helpful in design and analysis of ships and offshore floating structures. Most of the available software cannot account for the influence of freeboard and flare which are essential geometric characteristics responsible for deck wetness and water impact forces on deck equipment.

Because of the criticality of these phenomena, this study will analyse and discuss ways of addressing the challenges of the green water susceptibility of a Floating Production Storage and offloading Vessel and predict the required principal dimensions with respect to a given storage capacity for a specified wave environment (Chapter 7). In other words, the objective of this research is to determine the optimal principal dimensions of FPSO vessel necessary to prevent or mitigate these undesirable effects of green water.

The influence of geometric changes upon the behaviour of a ship or a moored floating offshore vessel (such as FPSO or Floating Storage Unit, FSU) in sea wave is very imperative. The parameters may be categorized as follows:

(i) Displacement, Principal Dimensions (length L, breadth B, depth D_m, and draught D), and the Block Coefficient.

(ii) The Coefficients which define the hull form details. These are the Waterplane Area Coefficient, the Longitudinal Centres of Buoyancy and Flotation (LCB and LCF). For simplicity, a rectangular form is considered in this research.

Generally, extreme wave environments often induce high motion which in turn leads to high stress load and bending moments which could cause fatigue failure. However, selection of optimal principal dimension could lead to significant reduction in (a) motion (b) bending moment (c) Green water loading and (c) bow slamming.

Xia (2012) and Khaw et al. (2005) discussed the importance of selecting principal dimensions to optimise the natural periods of FPSO as a way of improving motion performance which is necessary to minimise operational downtime due to the adverse effects of the meteorological and oceanographic conditions.

CHAPTER 3

3 DESIGN WAVE ENVIRONMENT

3.1 Wave Spectrum Models

3.1.1 Phillips Spectrum

In 1958, Phillips (1958) proposed an approximate range of the fullydeveloped sea. Fully-developed sea is a sea state where the waves generated by the wind are as large as they can be under the prevailing condition of wind and fetch. Philips Spectrum is however independent of wind speed and fetch and therefore not normally applied in practice.

$$\left.\begin{aligned} S(\omega) &= A\omega^{-5} \\ A &= \alpha g^2 \end{aligned}\right\} \tag{3. 1}$$

Where $\alpha (= 0.0081)$ is Philips' constant and g is the acceleration due to gravity.

3.1.2 General Spectral Form

The general form of the wave spectrum model may be written as

$$S(\omega) = A\omega^{-p} \exp(-B\omega^{-q}) \tag{3. 2}$$

Where A, B, p, q are four parameters of the Spectrum.

Since the two common wave parameters used to describe wave are the significant wave height H_s and the mean wave period, T, the n[th] moment of the spectrum becomes very useful in obtaining them as follows:

$$m_n = \int_0^{\infty} \omega^n S(\omega) d\omega \tag{3. 3}$$

The zeroth moment (n=0, m_n=m_0) or the variance of the wave elevation is defined as the area under the Spectral curve. The mean wave frequency $\bar{\omega}$ is the ratio of the first moment to the zeroth moment. The zero-crossing frequency ω_z is the square root of the ratio of the second moment to the zeroth moment.

$$H_s = 4\sqrt{m_0} \tag{3. 4}$$

$$\left.\bar{\omega} = \frac{m_1}{m_0}; \quad \bar{T} = \frac{2\pi}{\bar{\omega}} \right\} \tag{3. 5}$$

$$\omega_z = \sqrt{\frac{m_2}{m_0}} \tag{3.6}$$

The spectral peak frequency can be obtained by differentiating $S(\omega)$ with respect to ω and equating the result to zero.

$$\frac{dS(\omega)}{d\omega} = A\omega^{-p} \times qB\omega^{-q-1} \exp(-B\omega^{-q}) - pA\omega^{-p-1} \exp(-B\omega^{-q}) = 0$$

$$A{\omega_0}^{-p} \times qB{\omega_0}^{-q}{\omega_0}^{-1} \exp(-B{\omega_0}^{-q}) = pA{\omega_0}^{-p}\,{\omega_0}^{-1}\exp(-B{\omega_0}^{-q})$$

$${\omega_0}^{-q} = \frac{p/q}{B}$$

Therefore, the spectral peak or modal wave frequency ω_0 is given by:

$$\left.\begin{matrix} \omega_0 = \left(\frac{B}{p/q}\right)^{\frac{1}{q}}; \quad B = \frac{p/q}{{\omega_0}^{-q}}; \\ \frac{p/q}{B{\omega_0}^{-q}} = 1; \quad B{\omega_0}^{-q} = p/q \end{matrix}\right\} \tag{3.7}$$

$$m_n = \int_0^\infty \omega^n\, S(\omega) d\omega = \int_0^\infty \omega^n\, A\omega^{-p} \exp(-B\omega^{-q}) d\omega$$

Substituting $u = B\omega^{-q} \quad \Rightarrow \quad du = -qB\omega^{-q-1}d\omega \quad ; \quad d\omega = -\frac{du}{qB\omega^{-q-1}}$

$$\omega = \left(\frac{B}{u}\right)^{1/q} \quad ; \; \omega^{n} = \left(\frac{B}{u}\right)^{n/q} \quad ; \quad \omega^{-p} = \left(\frac{B}{u}\right)^{-p/q} \; ; \; \omega^{q+1} = \left(\frac{B}{u}\right)^{(q+1)/q}$$

$$\therefore \qquad m_n = \int_{\infty}^{0} \left(\frac{B}{u}\right)^{\frac{n}{q}} A \left(\frac{B}{u}\right)^{-\frac{p}{q}} \exp(-u) \left(-\frac{du}{qB\omega^{-q-1}}\right)$$

$$= \int_{\infty}^{0} \left(\frac{B}{u}\right)^{\frac{n}{q}} A \left(\frac{B}{u}\right)^{-\frac{p}{q}} \omega^{q+1} \exp(-u) \left(-\frac{du}{qB}\right)$$

$$= \int_{0}^{\infty} \left(\frac{B}{u}\right)^{n/q} A \left(\frac{B}{u}\right)^{-p/q} \left(\frac{B}{u}\right)^{(q+1)/q} \exp(-u) \left(\frac{du}{qB}\right)$$

$$= \frac{A}{qB} \int_{0}^{\infty} \left(\frac{B}{u}\right)^{\left(\frac{q+1+n-p}{q}\right)} \exp(-u) du$$

$$\therefore \quad m_n = \left(\frac{A}{qB}\right) B^{\left(\frac{q+1+n-p}{q}\right)} \int_0^{\infty} u^{-\left(\frac{q+1+n-p}{q}\right)} \exp(-u) du \qquad (3.8)$$

If $c_n = \left(\frac{p-n-1}{q}\right)$; $\Gamma(c_n) = \int_0^{\infty} u^{(c_n - 1)} \exp(-u) du$;

then: $$m_n = \left(\frac{A}{q}\right) \frac{\Gamma(c_n)}{B^{(c_n)}} \qquad (3.9)$$

3.1.3 Neumann Spectrum

Neumann Spectrum is the first analytical spectrum model that was used for engineering design purpose (Neumann, 1953; Chakrabarti, 1987). It was developed in 1953 by Neumann and it is expressed in terms of wind speed, U.

$$\left.\begin{aligned} S(\omega) &= A\omega^{-6} \exp\left[-2\left(\frac{\omega U}{g}\right)^{-2}\right] \\ S(\omega) &= A\omega^{-6} \exp[-B\omega^{-2}] \end{aligned}\right\} \qquad (3.10)$$

Where:
$$B = 2\left(\frac{U}{g}\right)^{-2} \quad (3.11)$$

$$U = U_{10}\left(\frac{y}{10}\right)^{1/7} \quad (3.12)$$

y (commonly taken as 19.5m) is the vertical distance in meters above the average sea level.

$$\frac{dS(\omega)}{d\omega} = 0 \text{ at } \omega = \omega_0$$

$$\frac{dS(\omega)}{d\omega} = A\omega^{-6} \times 2B\omega^{-3}\exp[-B\omega^{-2}] - 6A\omega^{-7} \times \exp[-B\omega^{-2}] = 0$$

$$A\omega_0{}^{-6} \times 2B\omega_0{}^{-3}\exp[-B\omega_0{}^{-2}] = 6A\omega_0{}^{-7} \times \exp[-B\omega_0{}^{-2}]$$

$$\omega_0 = (B/3)^{1/2}$$

Alternatively, making use of Eqn. (3.7), we have:

$$\Rightarrow \quad \omega_0{}^{-q} = \frac{p/q}{B};\ p = 6;\ q = 2;\ \omega_0{}^{-2} = \frac{3}{B}$$

$$\omega_0 = (B/3)^{1/2} = \sqrt{\frac{2}{3}} \times \frac{g}{U} = 0.8165\frac{g}{U} \quad (3.13)$$

$$B = 3\omega_0{}^2 \quad (3.14)$$

Substituting this expression in Eqn. (3.10), we obtain:

$$S(\omega) = A\omega^{-6}\exp\left[-3\left(\frac{\omega}{\omega_0}\right)^{-2}\right] \quad (3.15)$$

The zeroth moment, m_0, is obtained by computing the area under the spectral curve. Generally, the n^{th} moment of the spectrum is defined as:

$$m_n = \int_0^\infty \omega^n S(\omega) d\omega$$

$$S(\omega) = A\omega^{-6} \exp[-B\omega^{-2}]$$

Put $u = B\omega^{-2} \quad \Rightarrow \quad du = -2B\omega^{-3}d\omega$

$$\omega = \left(\frac{B}{u}\right)^{1/2}; \ \ \omega^n = \left(\frac{B}{u}\right)^{n/2}; \ \ \omega^{-3} = \left(\frac{B}{u}\right)^{-3/2}; \quad \omega^{-3}d\omega = -\frac{du}{2B}$$

$$m_n = -\int_{u=\infty}^{u=0} \left(\frac{B}{u}\right)^{n/2} A \left(\frac{B}{u}\right)^{-3/2} \exp[-u] \frac{du}{2B}$$

$$m_n = \int_0^{\infty} \left(\frac{B}{u}\right)^{n/2} A \left(\frac{B}{u}\right)^{-3/2} \exp[-u] \frac{du}{2B}$$

$$m_n = \frac{AB^{\left(\frac{n-5}{2}\right)}}{2} \int_0^{\infty} u^{(3-n)/2} \exp[-u]\, du \tag{3. 16}$$

$$m_0 = \frac{AB^{-5/2}}{2} \times \frac{3\pi^{1/2}}{4} \tag{3. 17}$$

$$m_1 = \frac{AB^{-2}}{2} \tag{3. 18}$$

$$m_2 = \frac{AB^{-3/2}}{2} \times \frac{\pi^{1/2}}{2} \tag{3. 19}$$

$$m_4 = \frac{AB^{-1/2}}{2} \times \pi^{1/2} = \frac{A}{2}\sqrt{\frac{\pi}{B}} \tag{3. 20}$$

From Eqn. (3.17), 'A' can be obtained:

$$A = \frac{8B^{5/2}m_0}{3\pi^{1/2}} = \frac{8\left(3\omega_0{}^2\right)^{5/2}\left(H_s{}^2/16\right)}{3\pi^{1/2}} = 1.466H_s{}^2\omega_0{}^5 \tag{3. 21}$$

Therefore, the Neumann Spectrum model can be rewritten by substituting A and B in Eqn. (3.10) with $1.466H_s{}^2\omega_0{}^5$ and $3\omega_0{}^2$ respectively.

$$S(\omega) = 1.466H_s{}^2\omega_0{}^5\omega^{-6} \exp\left[-3\left(\frac{\omega}{\omega_0}\right)^{-2}\right] \tag{3. 22}$$

Where H_s and ω_0 are given in terms of the wind speed, U.

3.1.4 Pierson-Moskowitz Spectrum

Pierson and Moskowitz (1964) proposed a new relation for the spectrum distribution in terms of the wind speed. The spectrum is the most representative for waters all over the world and has also been found useful in representing a severe storm wave in offshore structural design.

$$\left.\begin{aligned} S(\omega) &= \alpha g^2 \omega^{-5} \exp\left[-0.74\left(\frac{\omega U}{g}\right)^{-4}\right] \\ S(\omega) &= A\omega^{-5}\exp[-B\omega^{-4}] \end{aligned}\right\} \tag{3. 23}$$

Where: $A = \alpha g^2$ (3. 24)

$$B = 0.74\left(\frac{U}{g}\right)^{-4} \tag{3. 25}$$

The spectrum can be represented in terms of spectral peak period, ω_0.

$$\frac{dS(\omega)}{d\omega} = 0 \ \text{ at } \ \omega = \omega_0$$

$$\frac{dS(\omega)}{d\omega} = A\omega^{-5} \times 4B\omega^{-5}\exp[-B\omega^{-4}] - 5A\omega^{-6} \times \exp[-B\omega^{-4}] = 0$$

$$A\omega_0^{-5} \times 4B\omega_0^{-5}\exp[-B\omega_0^{-4}] = 5A\omega_0^{-6} \times \exp[-B\omega_0^{-4}]$$

$$\omega_0 = (B/1.25)^{1/4}$$

Alternatively, using Eqn. (3.7).

$$\omega_0 = \left(\frac{B}{p/q}\right)^{\frac{1}{q}}; \quad B = \frac{p/q}{\omega_0^{-q}} \quad ; \quad p = 5; \quad q = 4$$

$$\omega_0 = \left(\frac{B}{5/4}\right)^{\frac{1}{4}}; \quad B = \frac{5/4}{\omega_0^{-4}} = \frac{1.25}{\omega_0^{-4}}$$

$$S(\omega) = A\omega^{-5} \exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right] \tag{3. 26}$$

Since $B = 1.25\omega_0{}^4 = 0.74\left(\frac{U}{g}\right)^{-4}$ (3. 27)

$$\omega_0{}^4 = \frac{0.74}{1.25}\left(\frac{U}{g}\right)^{-4} \; ; \qquad \omega_0 = 0.877\left(\frac{g}{U}\right) \tag{3. 28}$$

Since the n^th moment of the spectrum is defined as:

$$m_n = \int_0^\infty \omega^n S(\omega) d\omega$$

$$S(\omega) = A\omega^{-5} \exp[-B\omega^{-4}]$$

Put $u = B\omega^{-4} \quad \Rightarrow \quad du = -4B\omega^{-5}d\omega$

$$\omega = \left(\frac{B}{u}\right)^{1/4}; \;\; \omega^n = \left(\frac{B}{u}\right)^{n/4}; \;\; \omega^{-5} = \left(\frac{B}{u}\right)^{-5/4}; \quad \omega^{-5}d\omega = -\frac{du}{4B}$$

$$m_n = -\int_{u=\infty}^{u=0} \left(\frac{B}{u}\right)^{n/4} A \exp[-u] \frac{du}{4B}$$

$$m_n = \int_0^\infty \left(\frac{B}{u}\right)^{n/4} \left(\frac{A}{4B}\right) \exp[-u]\, du$$

$$m_n = \frac{AB^{\left(\frac{n-4}{4}\right)}}{4} \int_0^\infty u^{-n/4} \exp[-u]\, du \tag{3. 29}$$

$$m_0 = \frac{AB^{-1}}{4} = \frac{A}{4B} \tag{3. 30}$$

$$m_1 = \frac{AB^{-3/4}}{4} \times \Gamma\left(\frac{3}{4}\right) = \frac{AB^{-3/4}}{4} \times 1.2254 \tag{3. 31}$$

$$m_2 = \frac{AB^{-1/2}}{4} \times \pi^{1/2} = \frac{A}{4}\sqrt{\frac{\pi}{B}} \tag{3. 32}$$

$$m_4 = \frac{A}{4} \times \infty = \infty \tag{3. 33}$$

The zeroth moment can also be expressed in terms of the root mean square water surface elevation, σ.

$$m_0 = \sigma^2 = \frac{A}{4B} = \frac{\alpha g^2}{4 \times (5/4){\omega_0}^4}$$

$$\sigma = \sqrt{m_0} = \sqrt{\frac{\alpha}{5}} \times \frac{g}{{\omega_0}^2} \tag{3. 34}$$

Significant wave amplitude ζ_s is given by:

$$\zeta_s = 2\sigma = \sqrt{\frac{\alpha}{5}} \times \frac{2g}{{\omega_0}^2} \tag{3. 35}$$

Significant wave height H_s is given by:

$$H_s = 4\sigma = \sqrt{\frac{\alpha}{5}} \times \frac{4g}{{\omega_0}^2} = 0.161\frac{g}{{\omega_0}^2} \tag{3. 36}$$

$$\omega_0 = \sqrt{\frac{0.161g}{H_s}} \tag{3. 37}$$

The P-M spectrum is broad banded:

Since $m_4 \longrightarrow \infty$;

$$\epsilon^2 = 1 - \frac{{m_2}^2}{m_0 m_4} \longrightarrow 1 \tag{3. 38}$$

Where ϵ is the spectral bandwidth parameter.

From Eqns. (3.26), (3.27) and (3.30), we obtain:

$$A = 4Bm_0 = 4(1.25\omega_0{}^4)\left(\frac{H_s{}^2}{16}\right) = \frac{1.25}{4}\omega_0{}^4 H_s{}^2$$

$$S(\omega) = \frac{1.25}{4}\omega_0{}^4 H_s{}^2 \omega^{-5} \exp\left[-1.25\left(\frac{\omega}{\omega_0}\right)^{-4}\right] \qquad (3.\ 39)$$

The above equation (3.39) may be referred to as the modified P-M spectrum.

To transform from frequency to period spectra and vice versa, we apply the following relations:

$$\omega = 2\pi f = F(f); \qquad f = \frac{\omega}{2\pi} = F(\omega)\ ;$$

$$\omega = 2\pi F(\omega)$$

$$F(f) = 2\pi F(\omega)$$

$$\therefore S(f) = 2\pi S(\omega)$$

$$S(\omega) = \frac{S(f)}{2\pi}$$

Also,

$$\omega = \frac{2\pi}{T} = 2\pi T^{-1} = F(T); \qquad T = \frac{2\pi}{\omega} = F(\omega)$$

$$d\omega = -2\pi T^{-2} dT$$

$$\frac{d\omega}{dT} = -2\pi T^{-2} = -\frac{2\pi T^{-1}}{T} = -\frac{\omega}{T}$$

$$\frac{\omega}{T} = 2\pi T^{-2}$$

$$\frac{F(T)}{F(\omega)} = \frac{2\pi}{T^2}$$

$$\therefore S(T) = \frac{2\pi}{T^2} S(\omega)$$

$$S(\omega) = \frac{T^2}{2\pi} S(T) = \frac{S(f)}{2\pi} \qquad (3.40)$$

The spectrum $S(T)$ has its maximum energy at a wave period of T_p while this maximum spectral energy is evaluated to be T_0 using the frequency spectrum $S(\omega)$. The significant wave period T_s which is defined as the average of the 1/3 highest wave recorded. Bretschneider found that it (T_s) falls between the peak period T_p and the modal period T_0.

$$T_0 = \left(\frac{5}{5}\right)^{\frac{1}{4}} T_0$$

$$T_s = \left(\frac{4}{5}\right)^{\frac{1}{4}} T_0 = 0.946 T_0 \qquad (3.41)$$

$$T_p = \left(\frac{3}{5}\right)^{\frac{1}{4}} T_0 = 0.880 T_0 \qquad (3.42)$$

$$\omega_s{}^4 = 1.25 \omega_0{}^4 = B \qquad (3.43)$$

Comparing this with Eqn. (3.37), we obtain:

$$\omega_s = \frac{1.3289}{H_s{}^{1/2}}; \qquad \omega_s H_s{}^{1/2} \cong 1.33 \qquad (3.44)$$

It is interesting to notice that $\omega_s{}^4$ is equivalent to B in the P-M spectrum expressed in Eqn. 3.23.

3.1.5 Bretschneider Spectrum

Bretschneider (1959; 1969) assumed that the spectrum is narrow-banded and the individual wave height and period follow the Rayleigh distribution and obtained the spectrum model of the form:

$$\left.\begin{array}{c} S(\omega) = A\omega^{-5}\exp[-B\omega^{-4}] \\ B = 67.5\%\ of\ \omega_s{}^4 \quad ; \quad A = 4Bm_0 \end{array}\right\} \tag{3. 45}$$

The significant wave heights obtained from the modified P-M spectrum (Eqn. 3.39) were smaller than those observed in reality; hence it is important to adjust *B* in spectral model to 67.5% of the original *B*. In other words, *B* is equated to $0.675\omega_s{}^4$. This gives rise to the new spectrum given by Eqn. (3.45).

Where

$$B = 0.675\omega_s{}^4 \quad ; \quad A = 4(0.675\omega_s{}^4)\left(\frac{H_s{}^2}{16}\right) = 0.1688\omega_s{}^4 H_s{}^2 \tag{3. 46}$$

This spectrum is derived for a fully-developed sea, but may be reasonably acceptable for partially developed sea.

Significant wave frequency $\omega_s = \frac{2\pi}{T_s}$;

Significant wave period $T_s = 0.857T_0$;

where $T_0 = \frac{2\pi}{\omega_0}$; $\omega_0 = (B/1.25)^{1/4}$

(Note: If the significant wave period $T_s = \left(\frac{4}{5}\right)^{-\frac{1}{4}} T_0 = 0.946T_0$, then we obtain $\omega_s{}^4 = 1.25\omega_0{}^4$ which is equivalent to *B* in the P-M spectrum. Results show that the significant wave period obtained from both P-M and Bretschneider spectra are equivalent.

Significant wave height is designated as H_s

The following were empirically derived: For fully developed sea

$$\frac{gH_s}{U^2} = 0.282, \quad and \quad \frac{gT_s}{U} = 6.776$$

For "nearly" developed sea

$$\frac{gH_s}{U^2} = 0.254 \;\rightarrow (90\%); \quad \frac{gH_s}{U^2} = 0.226 \;\rightarrow (80\%) \quad and \quad \frac{gT_s}{U} = 4.764$$

3.1.6 ISSC Spectrum

The International ship Structures congress (ISSC) in 1964 made slight modification to the Bretschneider Spectrum model. In order words, if you substitute $\omega_0 = \bar{\omega}/1.296$ into the modified P-M spectrum (Eqn. 3.39), the ISSC Spectrum is obtained:

$$\left.\begin{array}{c} S(\omega) = A_1\omega^{-5}\exp[-B_1\omega^{-4}] \\ A_1 = 0.1107\bar{\omega}^4 {H_s}^2 \;\;;\;\; B_1 = 0.4427\bar{\omega}^4 \end{array}\right\} \qquad (3.47)$$

Where the mean wave frequency $\bar{\omega} = 1.296\omega_0$ (See proof below).

Generally, $(\omega) = A\omega^{-p}\exp(-B\omega^{-q})$

$$m_n = \int_0^\infty \omega^n S(\omega) d\omega = \left(\frac{A}{qB}\right) B^{c_n} \int_0^\infty u^{-c_n} \exp(-u) du \quad ;$$

$$c_n = \left(\frac{q+n+1-p}{q}\right) = 1 - \left(\frac{p-n-1}{q}\right)$$

$$m_n = \left(\frac{A}{qB}\right) B^{c_n} \times \Gamma(1-c_n) = \frac{A}{q}\left[\frac{\Gamma(1-c_n)}{B^{(1-c_n)}}\right]$$

$$m_n = \frac{A}{q}\left[\frac{\Gamma\left(\frac{p-n-1}{q}\right)}{B^{\left(\frac{p-n-1}{q}\right)}}\right] \tag{3. 48}$$

For: $p = 5; \quad q = 4; \quad c_n = \left(\frac{n}{4}\right); \quad c_0 = 0;$

$$c_n = \left(\frac{1}{4}\right); \qquad \Gamma \text{ is a gamma function.}$$

$$\bar{\omega} = \frac{m_1}{m_0} = \frac{B^{1/4} \times \Gamma(3/4)}{\Gamma(1)} = \frac{(1.25\omega_0{}^4)^{1/4} \times 1.2254}{1}$$

$$\therefore \qquad \bar{\omega} = 1.296\omega_0$$

Alternatively, since $B_1 = 0.4427\bar{\omega}^4 = 1.25\omega_0^4$; $\quad \therefore \quad \bar{\omega} = 1.296\omega_0$ Eqn.

(3.47) may also be rewritten as:

$$\frac{S(\omega)}{H_s{}^2 T_1} = \frac{0.11}{2\pi}\left(\frac{\omega T_1}{2\pi}\right)^{-5} \exp\left[-0.44\left(\frac{\omega T_1}{2\pi}\right)^{-4}\right] \tag{3. 49}$$

$$\text{where } T_1 = \frac{2\pi}{\bar{\omega}}$$

3.1.7 ITTC Spectrum

The International Towing Tank Conference (1966; 1969; 1972) modified the P-M Spectrum in terms of the significant wave height H_s and zero crossing frequency ω_z.

$$\left.\begin{array}{c} S(\omega) = A_1 \omega^{-5} \exp[-B_1 \omega^{-4}] \\ A_1 = \alpha g^2 \quad ; \quad \alpha = \frac{0.0081}{k^4} \quad ; \quad B_1 = \frac{A_1}{4m_0} = 4A_1 H_s^{-2} = \frac{4\alpha g^2}{H_s^2} \end{array}\right\} \qquad (3.50)$$

$$\sigma = \sqrt{m_0} = H_s/4$$

$$\omega_z = \sqrt{\frac{m_2}{m_0}}$$

Since $m_2 = \frac{A_1}{4}\sqrt{\frac{\pi}{B_1}}$ *and* $m_0 = \frac{A_1}{4B_1}$ (See eqns. 3.30 and 3.32).

$$\omega_z = (\pi B_1)^{1/4} = \left(\frac{4\pi\alpha g^2}{H_s^2}\right)^{1/4} = \left(\frac{4\pi \times 0.0081 \times g^2}{16\sigma^2 k^4}\right)^{1/4}$$

$$= \frac{0.2824\left(\frac{g}{\sigma}\right)^{1/2}}{k}$$

$$\therefore \qquad k = \frac{\left(\frac{g}{\sigma}\right)^{1/2}}{3.54\omega_z} \qquad (3.51)$$

$$\therefore \qquad A_1 = \alpha g^2 = \frac{0.0081}{k^4} g^2 = \frac{124}{T_z^4} H_s^2 \qquad (3.52)$$

$$B_1 = \frac{A_1}{4m_0} = 4A_1 H_s^{-2} = \frac{496}{T_z^4} \qquad (3.53)$$

Therefore, Eqn. (3.50) can be rewritten in terms of significant wave height and zero crossing period as:

$$S(\omega) = \frac{124}{T_z^4} H_s^2 \omega^{-5} \exp\left[-\frac{496}{T_z^4}\omega^{-4}\right] \qquad (3.54)$$

3.1.8 JONSWAP Spectrum

During a joint North Sea wave project, Hasselmann et al. (1973) modified the Pierson-Moskowitz spectrum by multiplying it by a peakedness term, $(3.3)^{\gamma}$ and the resulting spectrum was named after the project. However, because of the need to express it in terms of wave height and period, the following JONSWAP (Joint North Sea Wave Project) spectrum has been recommended by the 7th International Towing Tank Conference, ITTC, for limited fetch:

$$S(\omega) = \frac{155}{{T_1}^4} {H_s}^2 \omega^{-5} \exp\left[-\frac{944}{{T_1}^4}\omega^{-4}\right](3.3)^{\gamma} \qquad (3.\ 55)$$

Where

$$\gamma = exp\left[-\frac{1}{2}\left(\frac{\omega-\omega_0}{\tau\omega_0}\right)^2\right] = exp\left[-\frac{1}{2}\left(\frac{0.191\omega T_1 - 1}{\tau}\right)^2\right]$$

The shape parameter, $\tau = \begin{cases} 0.07\,; & \omega \le \omega_0 \\ 0.09; & \omega > \omega_0 \end{cases}$

$\omega_0 = \frac{5.24}{T_1};\ \ T_0 = 1.199T_1 = 1.287T_z$

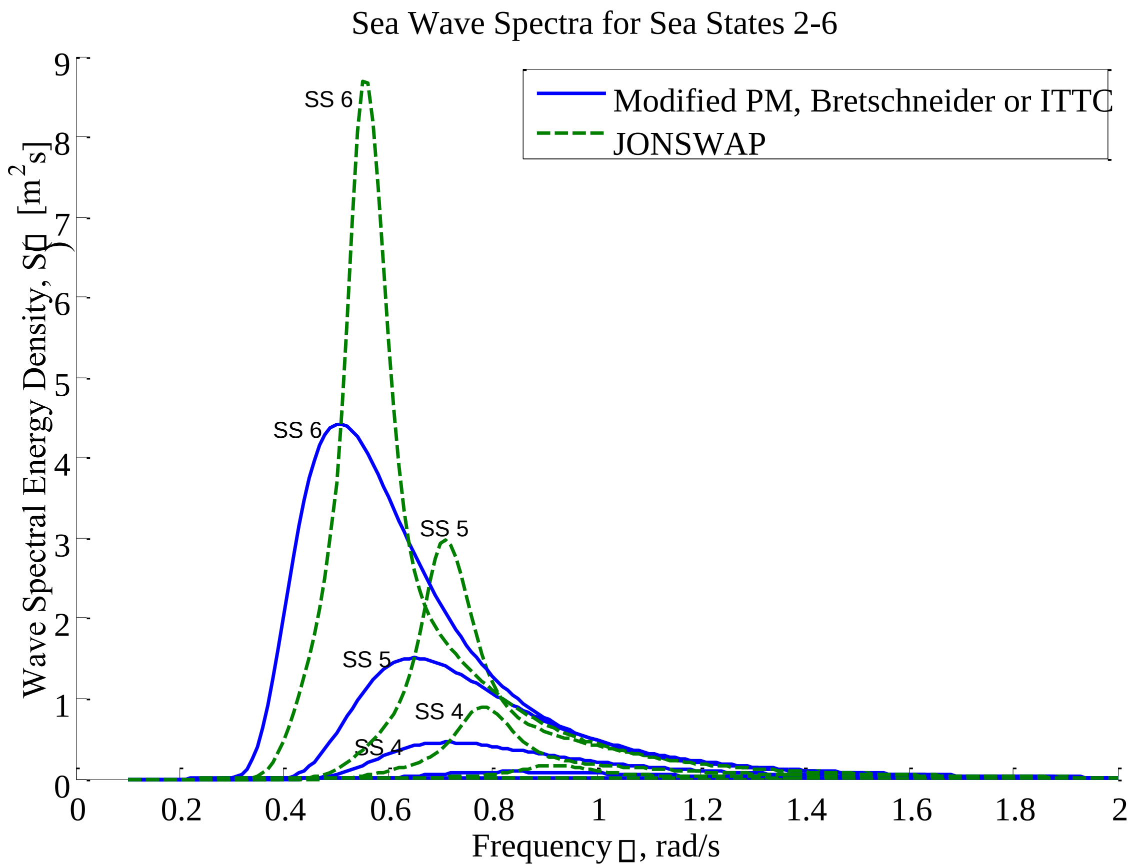


Figure 3.1: Examples of commonly used Wave Spectra plotted for Sea States 2-6

CHAPTER 4

4 THE PRINCIPAL DIMENSIONS OF FPSO

4.1 Introduction

One of the foremost challenges in the design of a floating production, storage and offloading (FPSO) system is centred on the determination of the principal dimensions of the floating vessel suitable for the development of the offshore oil field. FPSOs accounts for 65% of all floating production systems used worldwide(Wilhoit and Supan, 2010). It is therefore important for the size which largely affects its cost to be properly and accurately determined. MacGregor and Smith (1994) investigated the cost differentials between the trading tankers and various FPSOs operating in the North Sea. The reasons for the significant cost differentials were due to size and sophistication (e.g. forward accommodation, internal turret, double hull, 20% more ballast capacity and 60% more freeboard) of the FPSOs.

In this Chapter, a simple and computer-aided analysis of the principal dimensions will be presented, and the major factors that must be considered in the selection of relevant independent variables will be discussed.

4.2 Factors Affecting Sizing and Arrangement

The layout of an FPSO may be divided into about seven parts namely: The main deck; topsides deck; accommodation; mooring system; offloading system; machinery room; and cargo and ballast tanks (Paik, 2007). Also, there are three major factors that greatly influence the size and arrangements of these different parts of the Floating Production, Storage and Offloading system and its process plants. These are: (i) Provision of sufficient oil storage capacity, (ii) Provision of enough topside area or space for process plants, accommodation, helideck and other required topside equipment and (iii) Provision of displacement and ballast capacity.

4.2.1 Oil Storage Capacity:

The required oil storage capacity, S_c , must be known and made compatible with the production rate and offloading arrangements. The oil storage Efficiency, E_s , is the ratio of the required oil storage capacity to the overall cubic volume provided by the hull. The required storage capacity, in barrels of oil, is given by:

$$S_c = C_f \times E_s \times L \times B \times D_m \tag{4.1}$$

Where $\quad The\ conversion\ factor, C_f = 6.28981077$

$(ie. \quad 1m^3 = 6.28981077 bbl\ of\ oil)$

$E_s = Oil\ Storage\ Efficiency$

$L = Length\ between\ perpendiculars$

$B = Breadth$

$D_m = Depth\ moulded$

The storage capacity being the owner's requirement is fundamental. It is therefore the major contributory factor to the overall cubic number of the vessel. The cubic number of the vessel may be defined as a perfect cube or rather the cubic volume on which the principal dimensions of the vessel depend. In addition to the vessel's sophistication, the weight and cost of most marine vessels depend on this volume which must be provided, enclosed and supported by a watertight and corrosion-protected structure. The cubic number is therefore very relevant in FPSO design as the modern segregated vessels are "volume limited" since the hull design is determined by the need to provide sufficient internal volume to enclose the cargo tanks, ballast tanks and machinery spaces.

From Eqn. (4.1), the product of the three required principal dimensions which gives the cubic number may be determined from the expression:

$$C_n = L \times B \times D_m = \frac{S_c}{C_f \times E_s} \qquad (4.2)$$

Consider some vessels selected from 2010 worldwide survey of FPSO with storage capacity in barrels given as major owner's requirement as shown in Table 4.1. The volume (C_n) can therefore be easily computed.

However, when the design is "weight limited", careful checks are made to ensure that sufficient buoyancy (which is a measure of the weight of the displaced volume of water) is provided to carry the deadweight while leaving the predetermined safe freeboard.

Table 4.1: Oil Storage Capacities and Efficiencies of Some Selected FPSO Units

S/No	**Name of Vessel (FPSO)**	**Oil Storage Capacity (bbl)**	**Oil Storage Efficiency (%)**	**Cubic Number or Volume (m^3)**
1	Abo	932000	51.0038	290520
2	Agbami	1800000	48.3355	592064
3	Aker Smart 2	1300000	58.2273	354960
4	Aker Smart 3	1300000	55.2039	374400
5	Al Zaafarana	800000	58.2371	218400
6	Alvheim	560000	16.177	550368

7	Anoa Matuna	550000	64.7079	135135
8	Aoka Mizu	600000	43.6107	218736
9	Armada Perkasa	360000	25.6387	223238
10	Asgard A	920000	43.3041	337770
11	Azurite FDPSO	1300000	39.4314	524160
12	Baobab Ivoirien Mv 10	2000000	54.0773	588000
13	Belenak	880000	32.5536	429780
14	Berge Helena	1650000	56.4484	464724
15	Berge Okoloba Toru LPG	472000	53.7797	139536
16	Bohai Shiji (Bohai Century)	390000	19.8269	312732
17	Bonga	1400000	39.3199	566080
18	Brasil	1700000	57.4454	470496
19	Brotojoyo	400000	43.39	146566
20	Bunga KertasLukut	619000	51.6982	190361
21	BW Peace	1000000	61.8512	257048
22	BW Pioneer	600000	35.705	267168
23	Capixaba	2037000	63.0305	513810
24	Captain	849000	69.161	195168
25	Chang Qing Hao (CNOOC 102)	390000	51.6838	119970

4.2.2 Deck Area:

The provision of the correct area of space for safe layout of process plants, accommodation and utilities is very important. It largely depends on the selection of the length-breadth ratio (L/B). High ratio will ensure that sufficient separation is provided between the hazardous parts and the accommodation. This is further constrained by available transit channels.

4.2.3 Displacement and Ballast Capacity:

With the area of the topside fixed by the correct selection of the lengthbreadth ratio suitable for safe layout, the provision of sufficient displacement and ballast capacity can then be ensured by selecting appropriate breadth-depth ratio for the vessel. The stability and motion response can be improved by selecting sufficiently high and optimum breadth-depth ratio. Considering the transverse stability for instance, it can be shown that the transverse metacentric height of a rectangular vessel is largely dependent on the beam (and the ratio, breadth/depth). See Goldberg et al. (1988) and Tupper (1996).

$$GM_T = KB + \frac{B^2}{12DC_B} - KG \cong KB + \left(\frac{B}{8.4}\right)\left(\frac{B}{D_m}\right) - KG \quad (4.3)$$

(Assuming the draught, $D \cong 0.7D_m$; Block coefficient, $C_B = 1$)

GM_T is the transverse metacentric height

KB (=D/2) is the length from the keel to the centre of buoyancy

$KG \approx \left(\frac{D_m}{2} + 1\right)$, is the length from the keel to the centre of gravity of the vessel.

Based on these three factors, the following steps will therefore be taken in order to evaluate the appropriate principal dimensions:

(a) Consider the required storage capacity
(b) Select appropriate length-breadth ratio (c) Select appropriate breadth-depth ratio

(d) Compute the principal dimensions using the following relations:

Since, the Cubic number $C_n$is given by:

$$C_n = L \times B \times D_m$$

$$= \frac{L}{(L/B)^2 \times (B/D_m)} = \frac{B}{[(L/B)/(B/D_m)]^{-1}} = \frac{D_m}{[(L/B) \times (B/D_m)^2]^{-1}} = \frac{S_c}{C_f \times E_s} \qquad (4.4)$$

3 3 3

Let $\frac{L}{B} = x_b$ $\frac{B}{D_m} = y_d$

Therefore, the require Length,

$$L = (x_b{}^2 \times y_d)^{1/3} \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} = f_1 C_n{}^{1/3} \qquad (4.5)$$

The require Breadth,

$$B = (x_b / y_d)^{-1/3} \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} = f_2 C_n{}^{1/3} \qquad (4.6)$$

The required Depth,

$$D_m = (x_b \times y_d{}^2)^{-1/3} \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} = f_3 C_n{}^{1/3} = (f_1 f_2)^{-1} \, C_n{}^{1/3} \quad (4.7)$$

4.3 Principal Dimensions Programme

The first part of the MATLAB Principal Dimensions Programme (when it is run) requires the user to enter the required parameters: length to breadth ratio; breadth to depth ratio; depth to draught ratio; oil storage efficiency; and the required storage capacity in barrels of oil ($\frac{L}{B}$, $\frac{B}{D_m}$, z_m, E_s, and S_c) needed for the preliminary design of the floating system. An example is a ***1.8 million barrel capacity FPSO with storage efficiency of 48%*** (and other important design ratios given) which is needed to develop Agbami oil field in the Niger Delta region of Nigeria. The field, which was discovered in 1998 with reserves estimated at one billion barrels, ranks among the largest single deepwater discoveries in the West Africa sub-region (Adebola et al., 2006):

Please, enter the value of the length to breadth ratio, L/B: 5.5

Enter the value of the Breadth to Moulded depth ratio, B/D_m: 1.8

Enter the value of the Draught to Moulded depth ratio, D/D_m: 0.7

Please, enter the Oil Storage Efficiency, E_s: 0.48

Please, enter the required Storage Capacity, S_c: 1800000

L=319.0048m
B=58.0009m

D_m=32.2227m

D=22.5559m

M=427775.1904tonne

For a ***2 million barrel capacity FPSO with storage efficiency of 58%***, the vessel will be:

Please, enter the value of the length to breadth ratio, L/B: 5.4

Enter the value of the Breadth to Moulded depth ratio, B/D_m: 1.8

Enter the value of the Draught to Moulded depth ratio, D/D_m: 0.7

Please, enter the Oil Storage Efficiency, E_s: 0.58

Please, enter the required Storage Capacity, S_c: 2000000

L=306.4372m

B=56.7476m

D_m=31.5265m

D=22.0685m

M=393356.497tonne

Now, let us consider the set of FPSO vessels (Table 4.1) selected from the 2010 worldwide Survey of FPSOs. The vessels have specified oil storage capacities. We applied the proposed method to obtain the design parameters, and so computed the values of the cubic numbers and their respective principal dimensions. Table 4.2 shows resulting dimensions of the vessels.

Table 4.2: Principal Dimensions of the FPSO Units

S/No	Name of Vessel (FPSO)	$L/B=x_b$	$B/D_m=y_d$	Length	Breadth	Depth
1	Abo	5.0	2.7	269	54	20
2	Agbami	5.5	1.8	319	58	32
3	Aker Smart 2	5.7	2.1	290	51	24
4	Aker Smart 3	5.8	2.2	300	52	24
5	Al Zaafarana	6.5	1.9	260	40	21
6	Alvheim	6.0	0.8	252	42	52
7	Anoa Matuna	4.2	1.9	165	39	21

8	Aoka Mizu	5.9	2.0	248	42	21
9	Armada Perkasa	4.6	2.0	211	46	23
10	Asgard A	6.2	1.7	278	45	27
11	Azurite FDPSO	5.6	1.9	312	56	30
12	Baobab Ivoirien Mv 10	5.8	2.1	350	60	28
13	Belenak	4.9	2.2	285	58	26
14	Berge Helena	6.4	1.9	331	52	27
15	Berge Okoloba Toru LPG	6.4	1.8	216	34	19
16	Bohai Shiji (Bohai Century)	5.7	2.4	292	51	21
17	Bonga	5.3	1.8	305	58	32
18	Brasil	6.7	2.0	348	52	26
19	Brotojoyo	5.3	2.0	203	38	19
20	Bunga Kertas-Lukut	5.4	2.3	233	43	19
21	BW Peace	5.8	1.9	254	44	23
22	BW Pioneer	6.3	2.0	276	44	22
23	Capixaba	6.3	2.0	346	55	27
24	Captain	5.6	1.6	214	38	24
25	Chang Qing Hao (CNOOC 102)	6.9	1.7	215	31	18

4.4 The Effects of Cubic Number

Figure 4.1 shows a scatter diagram of the cubic numbers versus storage capacities, with 40, 50, 58 and 60% storage efficieencies superimposed on the diagram. This is to enable us determine the most commonly applied storage efficiency. The result shows that, for a given oil storage efficiency, the oil storage capacity is directly proportional to the cubic number (See Figure 4.1). Moreso, most modern FPSO vessels have storage efficiencies ranging between 40 and 60% while the most frequently applied is 58%.

Having obtained the expressions for the principal dimensions (Eqns. 4.5, 4.6, and 4.7), it is important to further analyse or rather simplify them. Let us consider the first set of terms or dimensionless factors (f_1, f_2 and f_3):

$$f_1 = (x_b^2 \times y_d)^{1/3}$$

$$f_2 = (x_b / y_d)^{-1/3}$$

$$f_3 = (x_b \times y_d^2)^{-1/3}$$

A careful study of these dimensionless factors shows that their variation about their respective mean values is relatively small. Figure 4.2 shows the variations of the factors (f_1, f_2 , and f_3) with the cube root of the cubic number, C_{nr}. There is a wide separation between f_3, f_2 , and f_1.

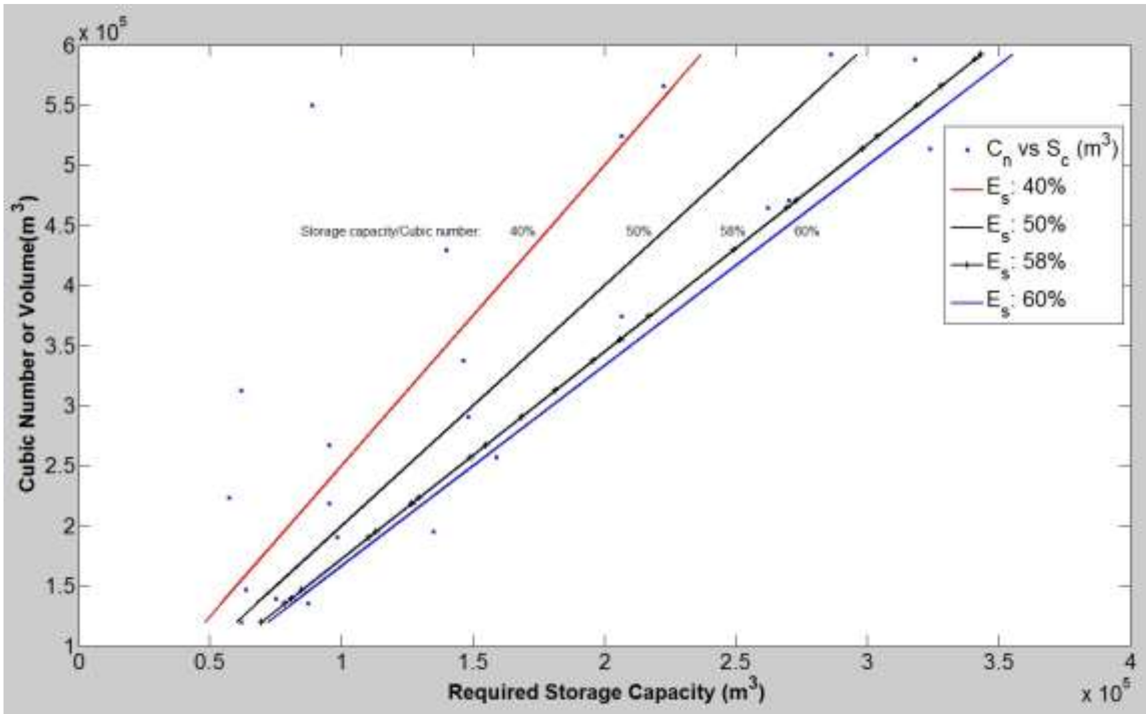


Figure 4.1: The Cubic Number versus the Required Storage Capacity

Figure 4.2 shows a scatter diagram of the dimensionless factors, f_1, f_2, f_3, versus the cube root of the cubic numbers. Now, these factors can easily be estimated using linear model curve fit tool.

Fit 1 (Linear model) gives:

$$f_1(C_{nr}) = p_1 C_{nr} + p_2$$

Coefficients (with 95% confidence bounds, i.e. the true mean of the sample is within 95% bounds, p_1 is the residual factor):

$$p_1 = -0.0004331 \ \ (-0.01396, 0.01309)$$

$$p_2 = 4.013 \ \ (3.081, 4.945)$$

$\therefore \quad f_1(\approx p_2) \approx 4.013 \;\; (3.081, 4.945)$

Fit 2 (Linear model) gives:

$$f_2(C_{nr}) = p_1 C_{nr} + p_2$$

Coefficients (with 95% confidence bounds):

$$p_1 = -0.0007543 \;\; (-0.002977, 0.001468)$$

$$p_2 = 0.7484 \;\; (0.5953, 0.9015)$$

$\therefore \quad f_2(\approx p_2) \approx 0.7484 \;\; (0.5953, 0.9015)$

Fit 3 (Linear model) gives:

$$f_3(C_{nr}) = p_1 C_{nr} + p_2$$

Coefficients (with 95% confidence bounds):

$$p_1 = 0.0007871 \;\; (-0.001577, 0.003151)$$

$$p_2 = 0.3132 \;\; (0.1504, 0.4761)$$

$\therefore \quad f_3(\approx p_2) \approx 0.3132 \;\; (0.1504, 0.4761)$

The factor, f_1 which ranges between 3 and 5 has a mean value of 4. The factor, f_2 with range from 0.6 to 0.9, has its mean value as 0.75, while f_3 has a mean value of 0.31 as it ranges from 0.16 to 0.48.

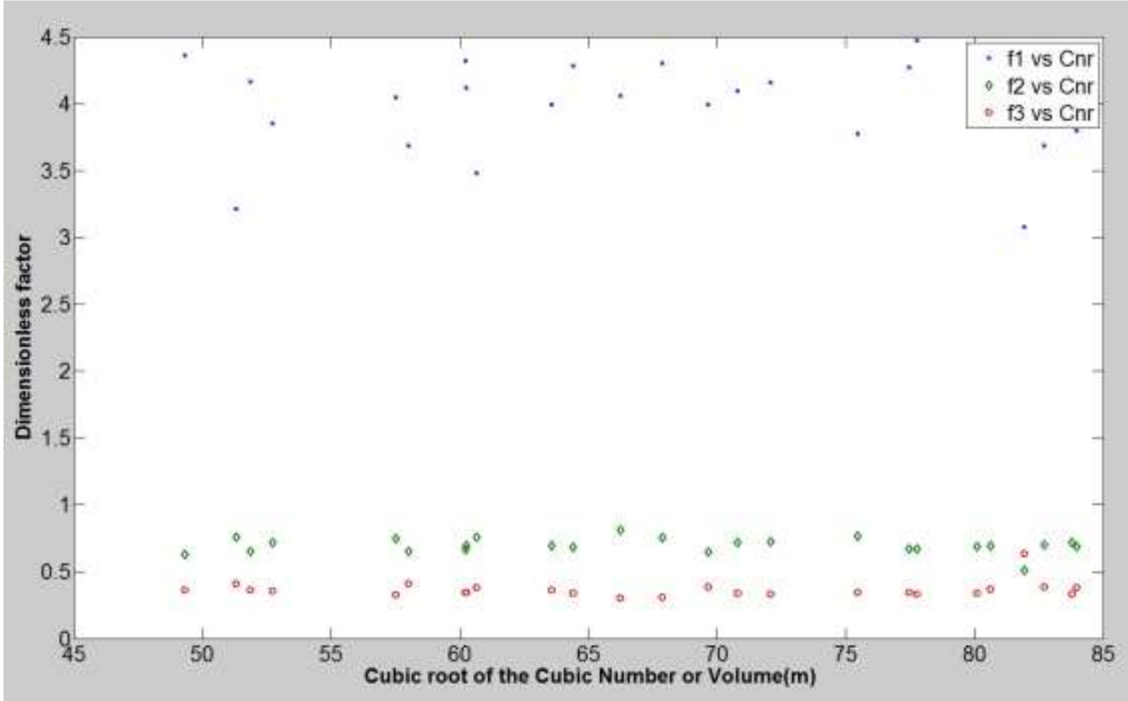


Figure 4.2: The Dimensionless Factor versus the Cube Root of the Cubic Volume

Therefore, Eqns. (4.5), (4.6), and (4.7) become:

$$L = f_1 C_{nr} = f_1 \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.8}$$

$$\{3.1 \leq f_1 \leq 4.9 \;\; i.e. \;\; f_1 = 4(\pm\, 0.9)\}$$

$$B = f_2 C_{nr} = f_2 \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.9}$$

$$\{0.6 \leq f_2 \leq 0.9 \;\; i.e. \;\; f_2 = 0.75(\pm\, 0.15)\}$$

$$D_m = f_3 C_{nr} = f_3 \left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.10}$$

$$\{0.18 \leq f_3 \leq 0.48 \;\; i.e. \;\; f_3 = 0.33(\pm\, 0.15)\}$$

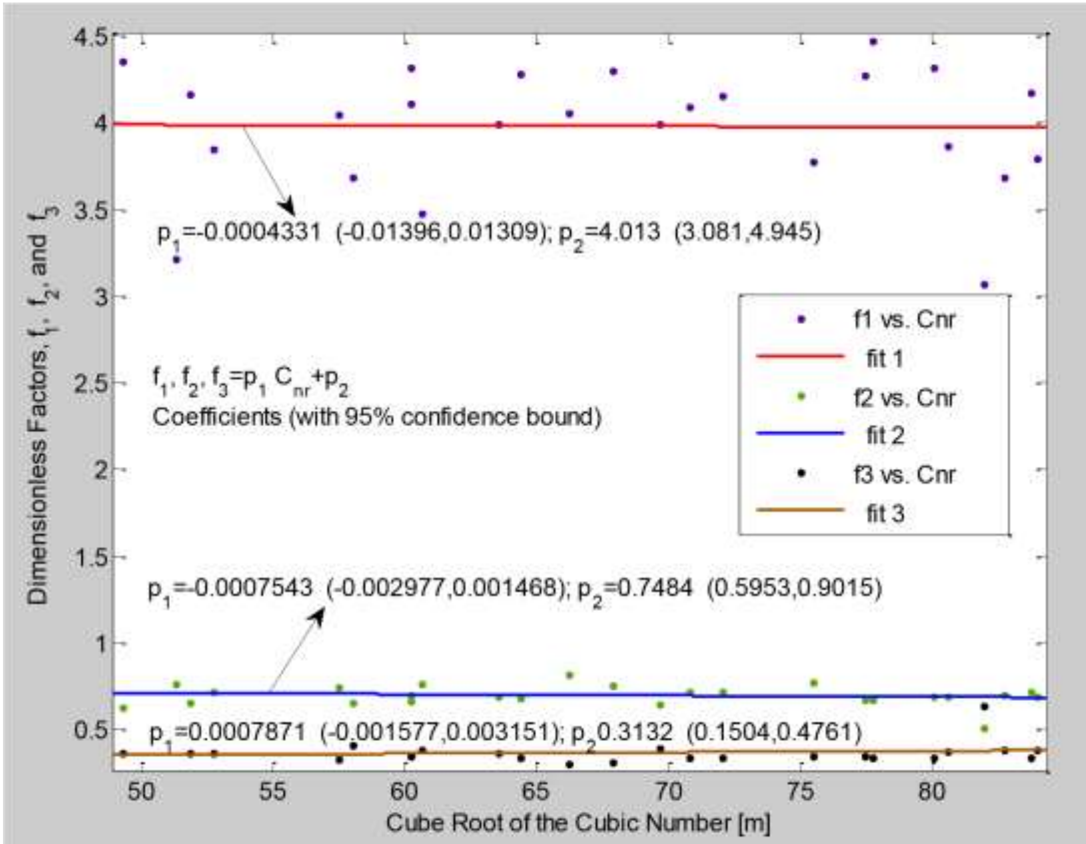


Figure 4.3: Using Curve Fit Tool to Evaluate the Dimensionless Factors

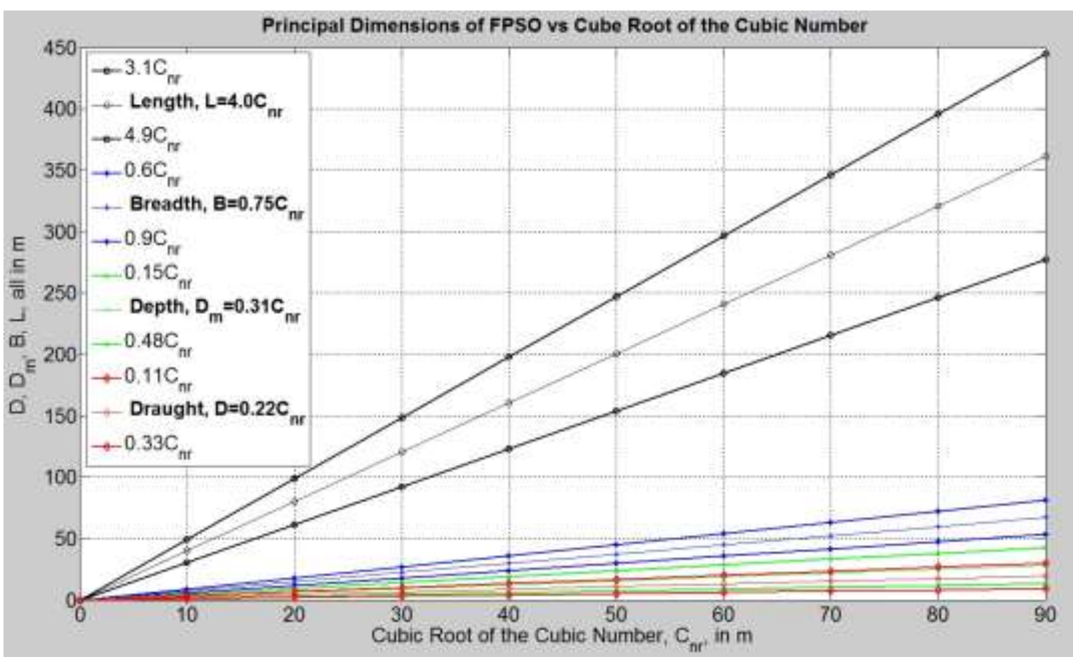


Figure 4.4: Principal Dimensions (mean values) of FPSOs vs Cube Root of the Cubic Number

The draught, D, may be given by:

$$D = z_m D_m; \quad f_4 = f_3 z_m; \qquad Assumption; z_m \approx 0.7$$

$$D = f_4 C_{nr} = f_4 \left(\frac{S_c}{C_f \times E_s}\right)^{\frac{1}{3}} \tag{4.11}$$

$$\{0.13 \leq f_4 \leq 0.33 \;\; or \;\; f_3 = 0.23(\pm\, 0.10)\}$$

As a very good guide or quick check, an estimate of the vessel dimensions can be obtained by using the mean values of these dimensionless factors as given below (Eqns. 4.12, 4.13, 4.14, and 4.15). Figure 4.5 shows a graphical representation of the effects of the cubic number on the vessel principal dimensions. Generally, the principal dimensions are directly proportional to the cube root of the cubic number. The lower, mean and upper values have been plotted (Figure 4.4) using their respective dimensionless factors.

$$\bar{L} = 4\left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.12}$$

$$\bar{B} = 0.75\left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.13}$$

$$\bar{D}_m = 0.33\left(\frac{S_c}{C_f \times E_s}\right)^{\frac{1}{3}} \tag{4.14}$$

$$\bar{D} = 0.23\left(\frac{S_c}{C_f \times E_s}\right)^{1/3} \tag{4.15}$$

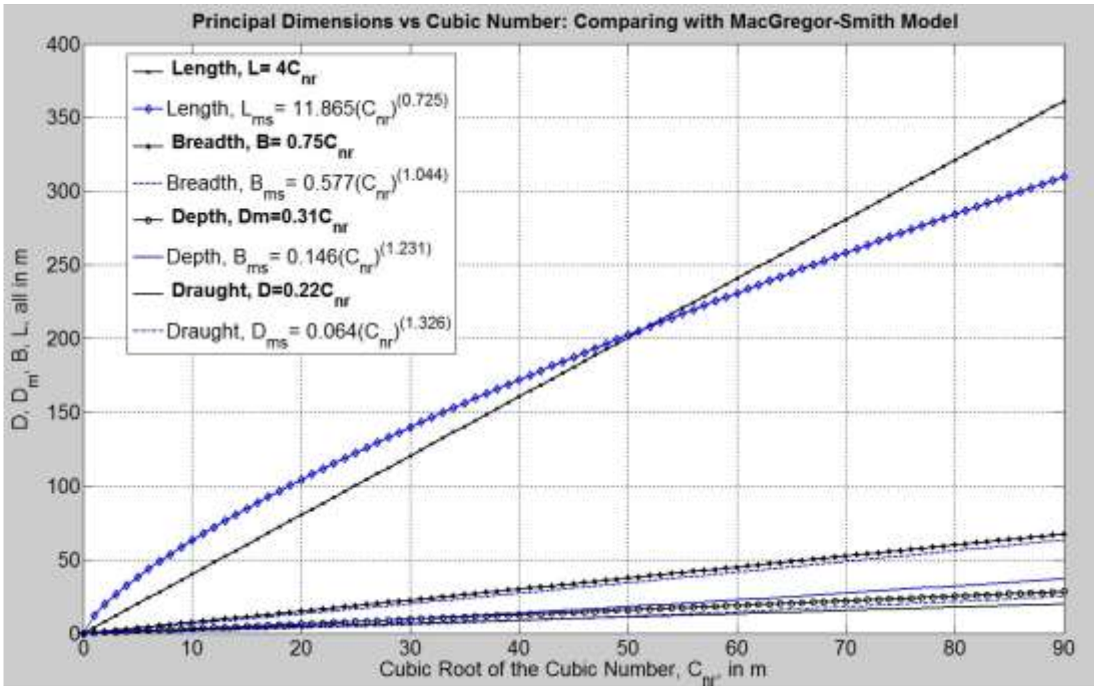


Figure 4.5: Principal Dimensions vs Cube Root of the Cubic Number: Comparism with MacGregor-Smith Model

For further simplification, Eqns. 4.8-4.10 may be rewritten as:

$$L = aC_{nr} \tag{4.16}$$

$$B = bC_{nr} \tag{4.17}$$

$$D_m = (ab)^{-1}C_{nr} \tag{4.18}$$

Where the average values of:

$$a = 4; \quad b = \frac{3}{4}; \ and \ C_{nr} = (C_n)^{1/3} = \left(\frac{S_c}{C_f \times E_s}\right)^{1/3}$$

The mean values of the principal dimensions compare favourably with those obtained using Macgregor and Smith model (See Figure 4.5 and Figure 4.6).

However, MacGregor-Smith's length is too low while its corresponding depth is too high. Therefore, the above proposed equations (4.16, 4.17 and 4.18 or 4.14) are recommended for estimations of the mean dimensions as they are better measures of the global averages and fit better than MacGregor-Smith's dimensions as shown in Figure 4.6.

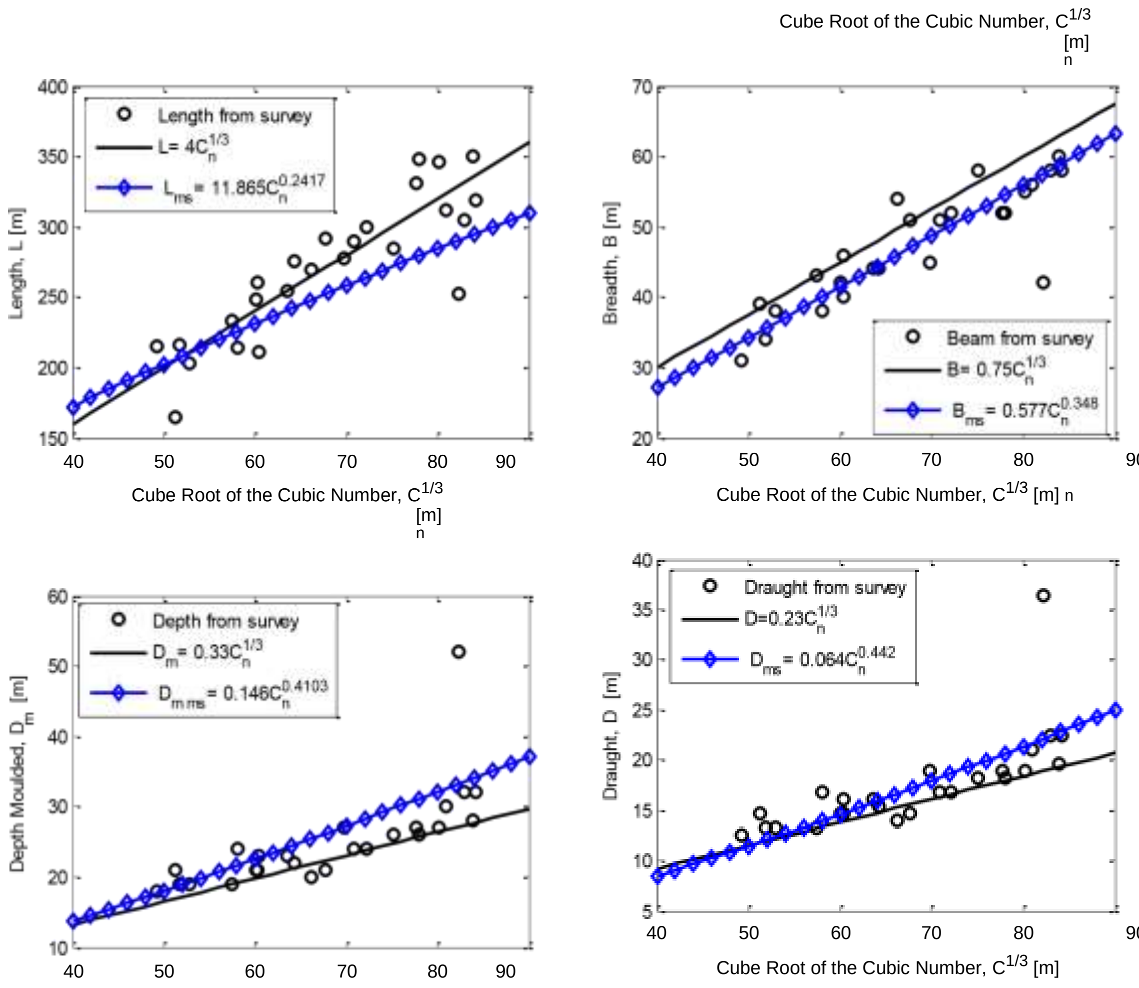


Figure 4.6: The relationship between the Principal Dimensions and the Cubic Number: Comparison of the new formulae (for L, B, D) with

MacGregor-Smith Models (L_{ms}, B_{ms}, D_{ms})

In order to accurately determine the required dimensions of any prospective Floating Production, Storage and Offloading system, the relevant factors which comprise first, the provision of required oil storage capacity, second, the provision of sufficient topside space for safe layout of the process plants, accommodation and the various utilities, and finally, the provision of the needed displacement and ballast capacity, must be correctly accounted for. Generally, the mean principal dimensions of the worldwide FPSOs have been found to be directly proportional to the cube root of the cubic numbers, which depend on the required storage capacities. The Length, Breadth, and Depth moulded are approximately 4, 3/4, and 1/3 of the cube root of the cubic number, respectively.

In order to reduce the environmental impacts on the vessel, it is important to optimise the principal dimensions by considering their effects on the dynamics of the floating system.

CHAPTER 5

5 DYNAMIC RESPONSES OF A MOORED FLOATING RECTANGULAR VESSEL

5.1 Equation of Motion

The floating Production, Storage and Offloading Vessel may be modelled as large rectangular floating structure or barge. The equation of motion of a moored rectangular barge with six degrees of freedom may be represented by:

$$\sum_{k=1}^{6}\left[\left(M_{jk}+A_{jk}\right)\ddot{\eta}_k+d_{jk}\dot{\eta}_k+C_{jk}\eta_k\right]=F_j \qquad (5.1)$$

Where

M_{jk} are the elements of the generalized mass matrix for the structure

A_{jk} are the elements of the added mass matrix d_{jk} are the elements

of the linear damping matrix

C_{jk} are the elements of the stiffness matrix

F_j are the wave exciting forces and moments, with the physical forces and moments. F_1, F_2 and F_3 are the amplitudes of the surge, sway, and heave exciting forces, while F_4, F_5 and F_6 are the amplitudes of roll, pitch and yaw exiting moments.

j and k indicate the directions of fluid forces and the modes of motions

η_k represents surge, sway, heave, roll, pitch and yaw responses respectively.

$\dot{\eta}_k$ and $\ddot{\eta}_k$ are the velocity and acceleration terms.

ω is the angular frequency of encounter.

If we consider a floating structure with lateral symmetry as in most cases, the six coupled equations of motions reduce to two sets of equations, each with three coupled equations; that is, one set of three coupled equations for surge, heave and pitch and the second set of three coupled equations for sway, roll and yaw. So, for structures with lateral symmetry, surge, heave and pitch are not coupled with sway, roll and yaw.

Now, let us consider the first set of equations of surge, heave and pitch, assuming that all the motions are uncoupled. The surge, heave and pitch equations become:

$$(M_{11} + A_{11})\ddot{\eta}_1 + d_{11}\dot{\eta}_1 + C_{11}\eta_1 = F_1 \quad (5.2)$$

$$(M_{33} + A_{33})\ddot{\eta}_3 + d_{33}\dot{\eta}_3 + C_{33}\eta_3 = F_3 \quad (5.3)$$

$$(M_{55} + A_{55})\ddot{\eta}_5 + d_{55}\dot{\eta}_5 + C_{55}\eta_5 = F_5 \quad (5.4)$$

Where

$M_{11}=M_{33}=M$

$M_{55}=I_5$ (i.e. mass moment of inertia about the y-axis)

If we now consider the coupling between the heave and pitch motions, then Eqns. (5.2), (5.3) and (5.4) become:

$$(M + A_{11})\ddot{\eta}_1 + d_{11}\dot{\eta}_1 + C_{11}\eta_1 = F_1 \qquad (5.5)$$

$$(M + A_{33})\ddot{\eta}_3 + d_{33}\dot{\eta}_3 + C_{33}\eta_3 + A_{35}\ddot{\eta}_5 + d_{35}\dot{\eta}_5 + C_{35}\eta_5 = F_3 \qquad (5.6)$$

$$(I_5 + A_{55})\ddot{\eta}_5 + d_{55}\dot{\eta}_5 + C_{55}\eta_5 + A_{53}\ddot{\eta}_3 + d_{53}\dot{\eta}_3 + C_{53}\eta_3 = F_5 \qquad (5.7)$$

The two sets are two possible cases. To obtain the required most probably maximum responses, the uncoupled case is a better choice, and therefore considered in the analysis. Also, unidirectional wave condition is chosen to maximize the effects of wave on the responses.

5.2 Linear Wave Properties

Linear wave theorem is one of the most important wave theorems and has wide range of applications in offshore structural dynamics. The following are some of characteristics of linear wave in deep sea:

5.2.1 Wave Number

The wave number is the ratio of the wave frequency, ω, to its celerity, c, and therefore given by:

$$k = \frac{\omega}{c} = \frac{2\pi}{\lambda} = \frac{\omega^2}{g} \qquad (5.8)$$

Where

λ is the wavelength g is the acceleration due to gravity

5.2.2 Wave Elevation

The wave profile or rather wave elevation, ζ_z, at any time, t, is

$$\zeta_z = \zeta_a \sin(kx - \omega t) \tag{5.9}$$

Where

x is the distance moved by the wave particle in horizontal direction of wave propagation.

ζ_a is the wave amplitude (that is, one half of the wave height, H).

5.2.3 Wave Velocity, Acceleration and Dynamic Pressure

The velocity potential, Φ, may be given as:

$$\Phi = -\zeta_a c e^{kz} \cos(kx - \omega t) = -\zeta_a \frac{g}{\omega} e^{kz} \cos(kx - \omega t) \tag{5.10}$$

Therefore, the horizontal wave velocity, U_x, is

$$U_x = \frac{\partial \Phi}{\partial x} = \zeta_a \frac{kg}{\omega} e^{kz} \sin(kx - \omega t) = \zeta_a \omega e^{kz} \sin(kx - \omega t) \tag{5.11}$$

And the vertical wave velocity, U_z, is

$$U_z = \frac{\partial \Phi}{\partial z} = -\zeta_a \frac{kg}{\omega} e^{kz} \cos(kx - \omega t) = -\zeta_a \omega e^{kz} \cos(kx - \omega t) \tag{5.12}$$

Wave Acceleration in the horizontal direction is

$$\dot{U}_x = \frac{\partial U_x}{\partial t} = -\zeta_a \mathrm{kg} e^{kz} \cos(kx - \omega t) = -\zeta_a \omega^2 e^{kz} \cos(kx - \omega t) \qquad (5.13)$$

Wave Acceleration in the vertical direction is

$$\dot{U}_z = \frac{\partial U_z}{\partial t} = -\zeta_a \mathrm{kg} e^{kz} \sin(kx - \omega t) = -\zeta_a \omega^2 e^{kz} \sin(kx - \omega t) \qquad (5.14)$$

The wave dynamic pressure, P_D, is given by

$$P_D = \rho g \zeta_z e^{kz} = \rho g \zeta_a e^{kz} \sin(kx - \omega t) \qquad (5.15)$$

5.3 Surge Motion

5.3.1 Added Mass in Surge

The hydrodynamic added mass in surge, A_{11}, of water as the vessel surges forward and backward can be taken as being approximately equivalent to mass of the cylindrical water column formed at both the stern and the bow as shown in Figure 5.1.

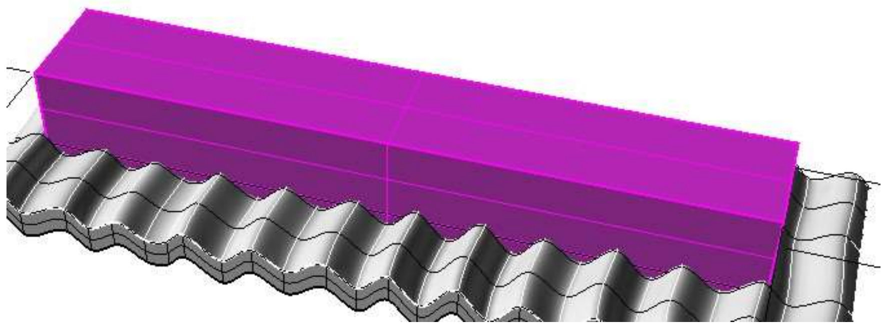


Figure 5.1: A Floating Rectangular Vessel encountering regular Wave

$$A_{11} = c_{m1}\rho\pi\left(\frac{D}{2}\right)^2 B \qquad (5.16)$$

$$A_{11}^{(2D)} = \frac{\pi}{8}c_{m1}\rho BD \qquad (for\ each\ side\ of\ the\ vessel) \qquad (5.17)$$

Where

c_{m1} is the added mass coefficient and its value depends on the ratio, $\frac{B}{D}$

When $\frac{B}{D} = 2.67$, c_{m1}=0.81

The added mass coefficient c_m may be estimated using:

$$c_{m1} = -0.4601\left(\frac{B}{D}\right)^{-0.7307} + 1.036 \qquad (5.18)$$

This equation (5.18) was obtained by plotting the analytical added mass coefficients of a 3-D rectangular flat (thin) plate oscillating in infinite fluid (from Table F. 2), and then applying power curve fit tool. So, the surge virtual added mass coefficient increases with increase in breadth-draught ratio as shown in Figure 5.2. Although surge added mass is small and often neglected, it has strong effect on the natural surge frequency of the vessel.

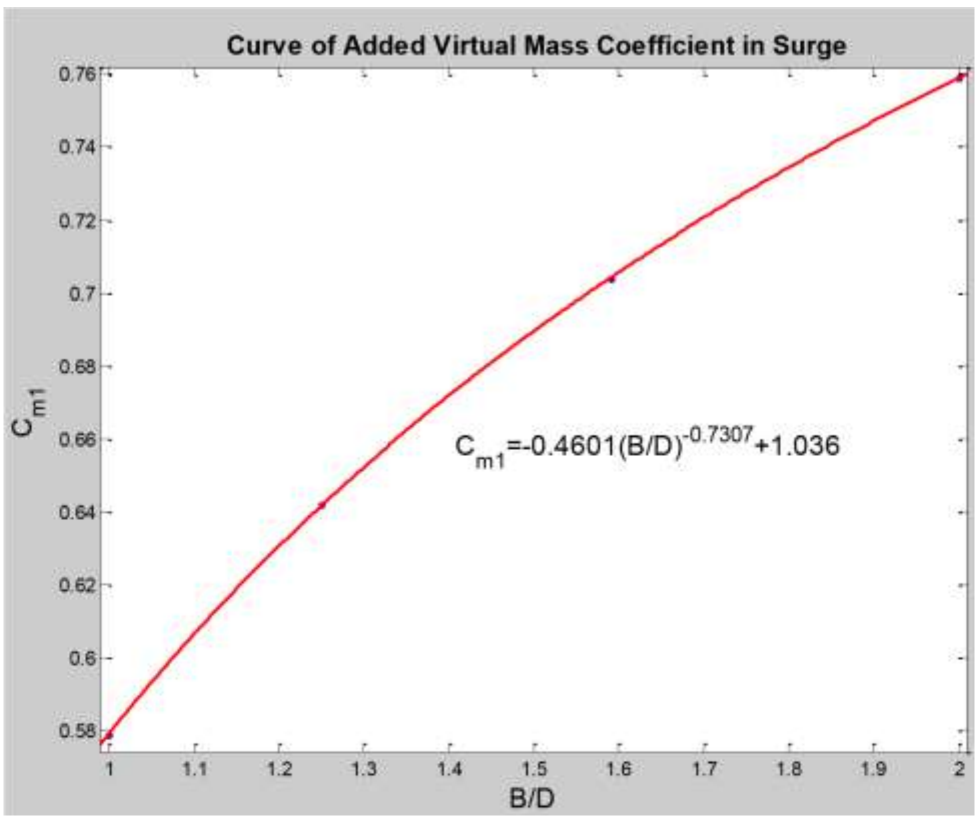


Figure 5.2: The effect of Breadth-Draught Ratio on Surge Added Mass Coefficient

5.3.2 The Natural Surge Frequency

The natural frequency in surge motion is:

$$\omega_{n1} = \sqrt{\frac{C_{11}}{M + A_{11}}} = \sqrt{\frac{C_{11}}{M + c_{m1}\rho\pi\left(\frac{D}{2}\right)^2 B}} \qquad (5.19)$$

Where

C_{11} is the stiffness or restoring force per unit length of mooring lines. It is calculated based on the Catenary mooring line formula (Faltinsen, 1993).

The frequency ratio is:

$$R_1 = \frac{\omega}{\omega_{n1}} \qquad (5.20)$$

5.3.3 Damping

Damping may be generated by waves which dissipate energy on the floating vessel. If the vessel is in motion, it creates waves and inertia wave forces. The wave radiation force is an important inertial wave force which consist of the decelerating added mass component and the damping (a function of velocity) component opposing the motion. This type of damping is called wave radiation (or potential) damping. Damping can also be caused by viscous effects such as skin friction, vortices etc. In most cases, including this present analysis, viscous effects are negligibly small and are often ignored in motion calculations of offshore structures especially in sway, heave, pitch and yaw motions of ships and offshore structures (Journee and Massie, 2001). In roll motion, viscous damping is more predominant than wave radiation damping (Barltrop, 1998).

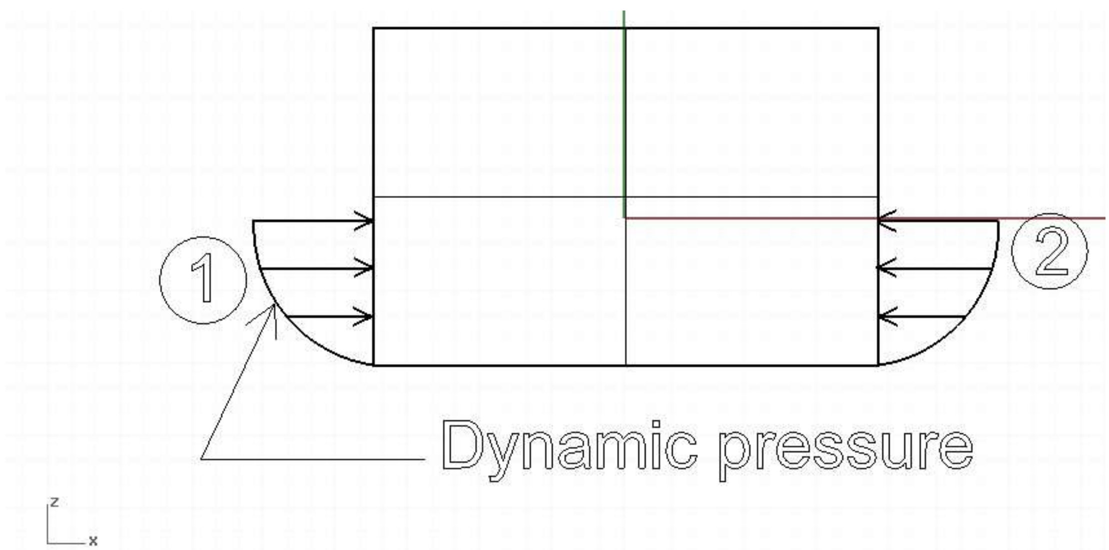
Generally, the hydrodynamic coefficients are small in surge motion. The surge damping coefficient is very small. However, the critical damping, d_{1cr}, can be computed using:

$$d_{1cr} = 2(M + A_{11})\omega_{n1} = 2\sqrt{C_{11}(M + A_{11})} \quad (5.21)$$

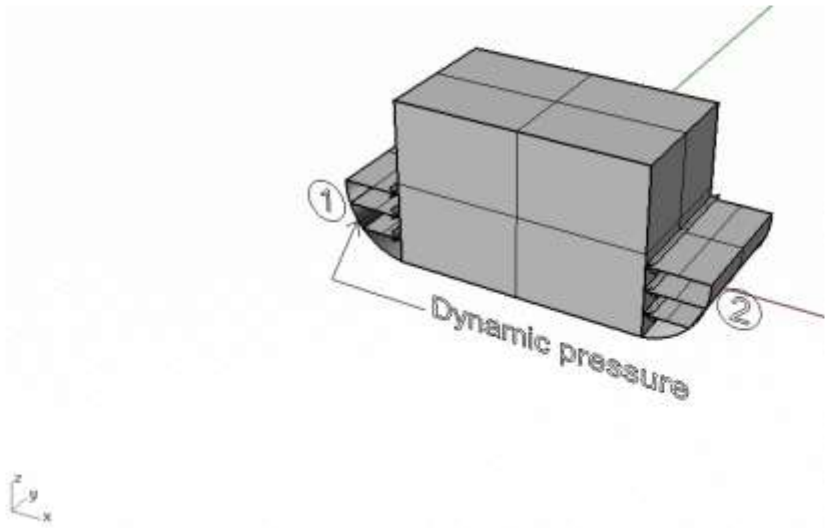
Let the surge damping be denoted by d_{11}. Then, the damping factor or ratio, d_1, is equal to:

$$\therefore \quad d_1 = \frac{d_{11}}{d_{1cr}} \quad (5.22)$$

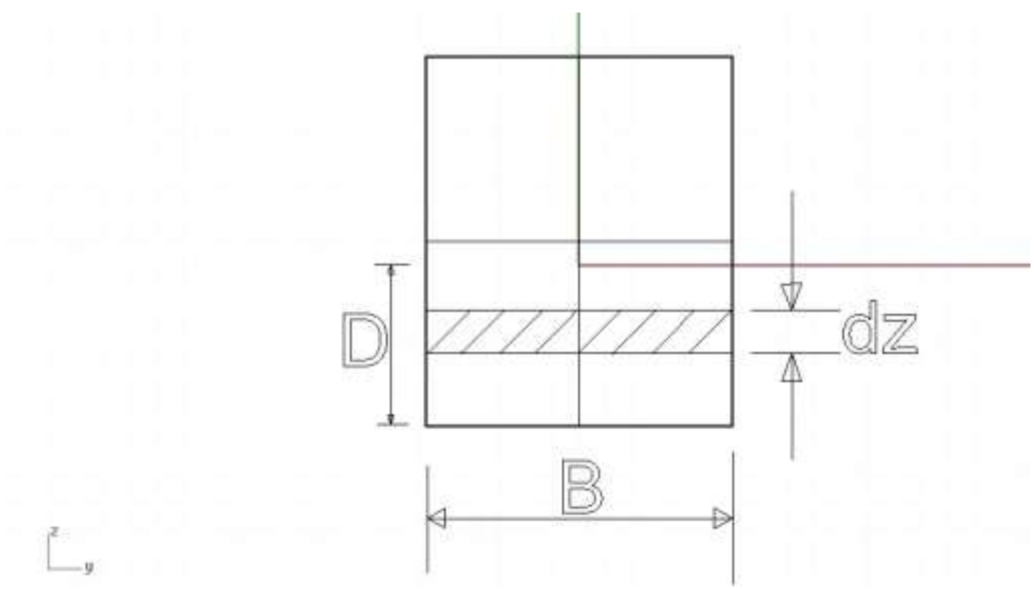
5.3.4 The Surge Force and Response Amplitude Operator



(a)



(b)



(c)

Figure 5.3: Dynamic pressure distribution on a floating rectangular vessel **Froude-Krilov Force:**

The wave dynamic pressure causing surge motion is given by:

$$P_D = \rho g \zeta_a e^{kz} \sin(kx - \omega t)$$

The dynamic pressure on the hatched elemental strip, 1, at the stern (where $x = -\frac{L}{2}$) is:

$$P_{D1} = \rho g \zeta_a e^{kz} \sin(-\frac{kL}{2} - \omega t)$$

The dynamic pressure force on this strip is therefore:

$$dF_{p1} = P_{D1} dA = P_{D1} B dz = \rho g \zeta_a B \sin(-\frac{kL}{2} - \omega t) e^{kz} dz$$

$$F_{p1} = \int_{-D}^{0} dF_{p1} = \rho g \zeta_a B \sin\left(-\frac{kL}{2} - \omega t\right) \int_{-D}^{0} e^{kz} dz$$

$$= \rho g \zeta_a B \sin(-\frac{kL}{2} - \omega t) \frac{1}{k} \left(1 - e^{-kD}\right)$$

The dynamic pressure on the hatched elemental strip, 2, at the bow (where $x = \frac{L}{2}$) is:

$$P_{D2} = \rho g \zeta_a e^{kz} \sin(\frac{kL}{2} - \omega t)$$

The dynamic pressure force on this strip is therefore:

$$dF_{p2} = P_{D2} dA = P_{D2} B dz = -\rho g \zeta_a B \sin(\frac{kL}{2} - \omega t) e^{kz} dz$$

$$F_{p2} = \int_{-D}^{0} dF_{p2} = -\rho g \zeta_a B \sin\left(\frac{kL}{2} - \omega t\right) \int_{-D}^{0} e^{kz} dz$$

$$= -\rho g \zeta_a B \sin(\frac{kL}{2} - \omega t) \frac{1}{k} \left(1 - e^{-kD}\right)$$

Hence, the Froude-Krylov or dynamic pressure force in the direction of the wave propagation is:

$$F_{FKx} = F_{p1} + F_{p2} = \rho g \zeta_a \,\mathrm{B} \sin\left(-\frac{kL}{2} - \omega t\right)\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)$$

$$-\rho g \zeta_a \,\mathrm{B} \sin\left(\frac{kL}{2} - \omega t\right)\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)$$

$$= \rho g \zeta_a \mathrm{B}\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\left[\sin\left(-\frac{kL}{2} - \omega t\right) - \sin\left(\frac{kL}{2} - \omega t\right)\right]$$

$$= \rho g \zeta_a \mathrm{B}\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\left[-2\cos(-\omega t)\sin\left(\frac{kL}{2}\right)\right]$$

$$= \rho g \zeta_a \mathrm{B}\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\left[-2\cos(\omega t)\sin\left(\frac{kL}{2}\right)\right]$$

$$\therefore \quad F_{FKx} = -2\rho g \zeta_a \mathrm{B}\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right)\cos(\omega t) \qquad (5.23)$$

$$F_{FKx} = F_{FK1}\cos(\omega t) \qquad (5.24)$$

So, the amplitude of the force is:

$$F_{FK1} = -2\rho g \zeta_a \mathrm{B}\frac{1}{\mathrm{k}}\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right)$$

This implies that the surge force amplitude per unit wave amplitude is:

$$\frac{F_{FK1}}{\zeta_a} = -2\left(\frac{\rho g \mathrm{B}}{\mathrm{k}}\right)\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right) \qquad (5.25)$$

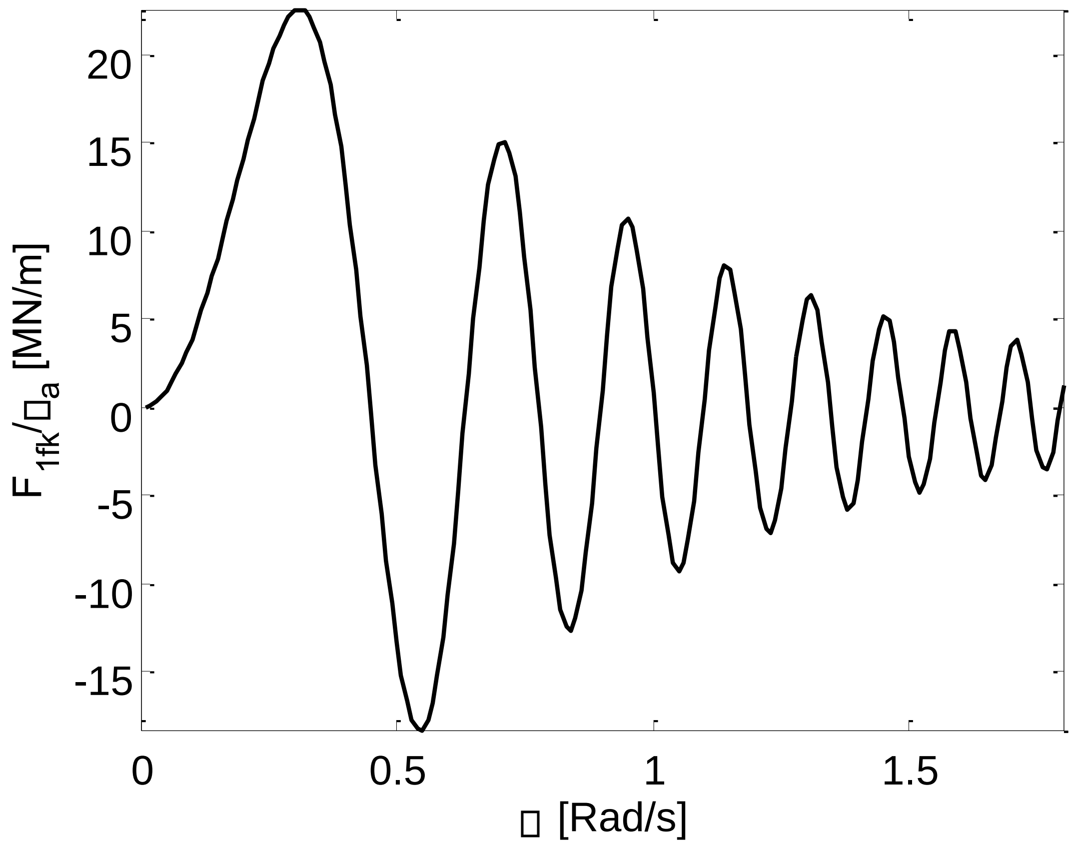


Figure 5.4: Variation of the Surge Froude-Krilov Force with Wave Frequency

Added Mass Force:

If the force acting on the elemental strip due to the acceleration of added virtual mass of water, is dF_{Ax} and its (the fluid) acceleration is given by Eqn. (5.13), then, we have:

$$dF_{Ax} = dF_{A1} + dF_{A2}$$

$$dF_{Ax} = A_{11}^{(2D)} dz \left[-\zeta_a \omega^2 e^{kz} \cos\left(-\frac{kL}{2} - \omega t \right) \right] + A_{11}^{(2D)} dz \left[\zeta_a \omega^2 e^{kz} \cos\left(\frac{kL}{2} - \omega t \right) \right]$$

$$= A_{11}^{(2D)} \zeta_a \omega^2 e^{kz} dz \left[-\cos\left(-\frac{kL}{2} - \omega t \right) + \cos\left(\frac{kL}{2} - \omega t \right) \right]$$

$$= 2A_{11}^{(2D)} \zeta_a \omega^2 sin\left(\frac{kL}{2} \right) sin(\omega t) e^{kz} dz$$

$$F_{Ax} = 2A_{11}^{(2D)} \zeta_a \omega^2 sin\left(\frac{kL}{2} \right) \sin(\omega t) \int_{-D}^{0} e^{kz} dz$$

$$F_{Ax} = 2A_{11}^{(2D)} \zeta_a \omega^2 \frac{1}{k} (1 - e^{-kD}) sin\left(\frac{kL}{2} \right) sin(\omega t) \qquad (5.26)$$

Let the amplitude of this force be F_{Ax1} so that:

$$F_{Ax} = F_{Ax1} \sin(\omega t)$$

Therefore $F_{Ax1} = 2A_{11}^{(2D)} \zeta_a \omega^2 \frac{1}{k} (1 - e^{-kD}) sin\left(\frac{kL}{2} \right)$

$$\frac{F_{Ax1}}{\zeta_a} = 2A_{11}^{(2D)} g (1 - e^{-kD}) sin\left(\frac{kL}{2} \right)$$

$$F_{Ax} = 2\zeta_a \left(A_{11}^{(2D)} g \right) (1 - e^{-kD}) sin\left(\frac{kL}{2} \right) \sin(\omega t) = F_{Ax1} \sin(\omega t) \qquad (5.27)$$

The acceleration or added mass force is out of phase with the Froude-Krilov Force. It will be wrong to add them up algebraically. Since the added mass force is very small compared to the Froude-Krilov force especially within the relevant frequency range, the surge excitation force amplitude, F_{1a}, is usually taken to be approximately equal to the amplitude of the FroudeKrilov (pressure force), F_{FK1} as given in Eqn. (5.28).

$$\left.\begin{aligned} \frac{F_{1a}}{\zeta_a} &\approx -2\left(\frac{\rho g \mathrm{B}}{\mathrm{k}}\right)\left(1-\mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right) \\ |F_{1a}| &\approx \rho g \zeta_a\left(\frac{\mathrm{B}\lambda}{\pi}\right)\left(1-\mathrm{e}^{-2\pi\mathrm{D}/\lambda}\right)\sin\left(\frac{\pi L}{\lambda}\right) \end{aligned}\right\} \tag{5.28}$$

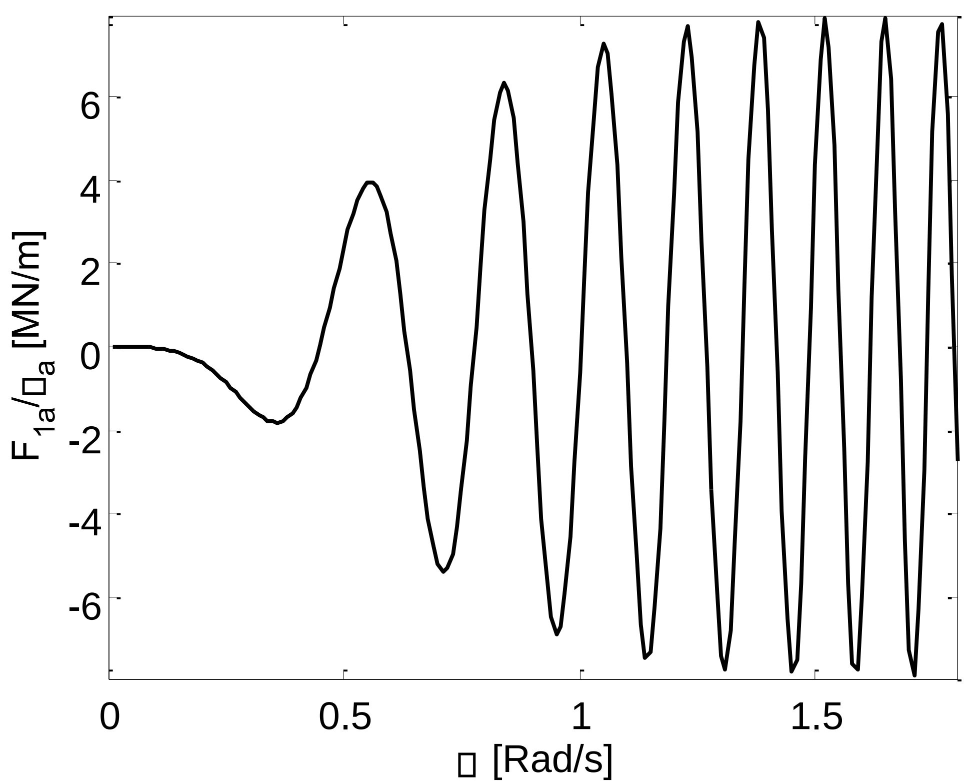


Figure 5.5: Variation of the Surge Added Mass Force with Wave Frequency

Hence, the quasi-static surge force, F_{q1}, is:

$$\left|\mathrm{F_{q1}}\right| = \left|\frac{F_{1a}}{C_{11}\zeta_a}\right| = \frac{2}{C_{11}}\left(\frac{\rho g \mathrm{B}}{\mathrm{k}}\right)\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right) = \frac{\rho g \mathrm{A_1}}{C_{11}} \qquad (5.29)$$

Where the equivalent surge area, $\mathrm{A_1} = \left(\frac{2\mathrm{B}}{\mathrm{k}}\right)\left(1 - \mathrm{e}^{-\mathrm{kD}}\right)\sin\left(\frac{kL}{2}\right)$ (5.30)

Therefore, the Surge Response Amplitude Operator, RAO_1, is:

$$RAO_1 = |\mathrm{F_{q1}}| \times Q_1 \qquad (5.31)$$

Q_1 is the surge dynamic amplification factor.

$$Q_1 = \frac{1}{\sqrt{\left(1 - {R_1}^2\right)^2 + (2d_1R_1)^2}} \qquad (5.32)$$

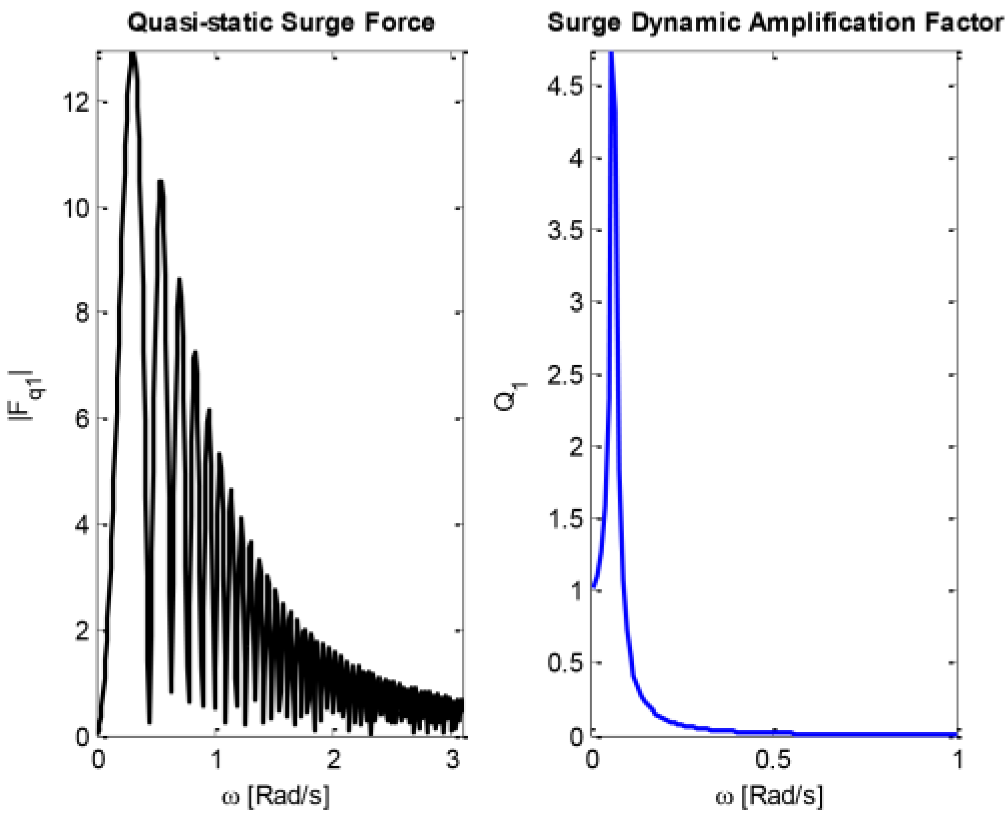
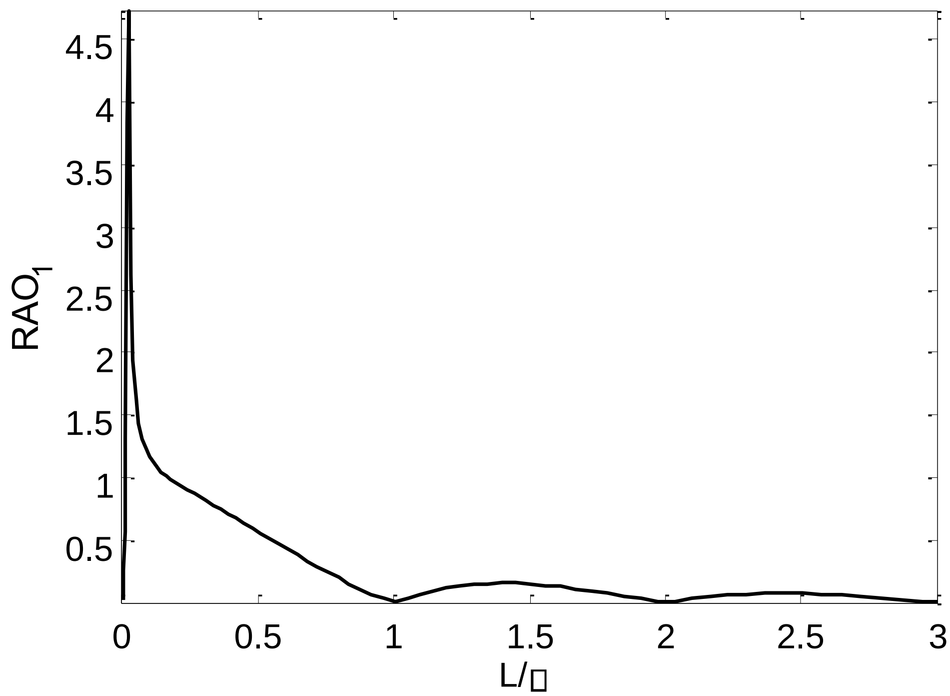


Figure 5.6: Quasi-static Surge Force and Dynamic Amplification Factor with Wave Frequency


RAO1
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
3
L/

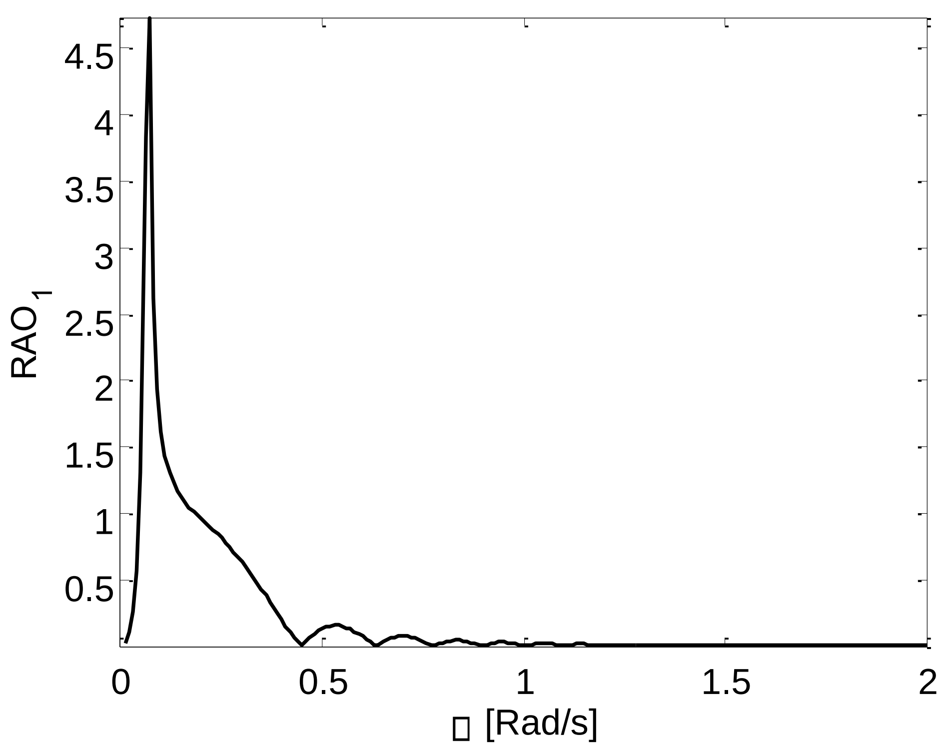

RAO1
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
[Rad/s]

Figure 5.7: Surge Response Amplitude Operator against Wave Frequency

5.4 Heave Motion

5.4.1 Added Mass in Heave

The added mass, A_{33}, of water in heave motion is

$$A_{33} = \frac{1}{2} c_{m3} \rho \pi \left(\frac{B}{2}\right)^2 L \, ; \qquad A_{33}^{(2D)} = \frac{A_{33}}{L} = \frac{1}{2} c_{m3} \rho \pi \left(\frac{B}{2}\right)^2 \qquad (5.33)$$

Where:

C_{m3} is the added mass coefficient and its value depends on the ratio, $\frac{B}{D}$.

The added mass coefficient, c_{m3}, can be evaluated using Eqn. (5.34) below:

$$\left.\begin{array}{c} c_{m3} = 0.8413 \left(\frac{B}{2D}\right)^{(-0.2692)} + 0.674 \\ OR \\ c_{m3} = 1.014 \left(\frac{B}{D}\right)^{(-0.2692)} + 0.674 \end{array}\right\} \qquad (5.34)$$

Eqn. (5.34) can be obtained by plotting the analytical added mass coefficients of a 2-D rectangular flat (thin) plate oscillating vertically in infinite fluid (from Table F. 1), and then applying power curve fit tool.

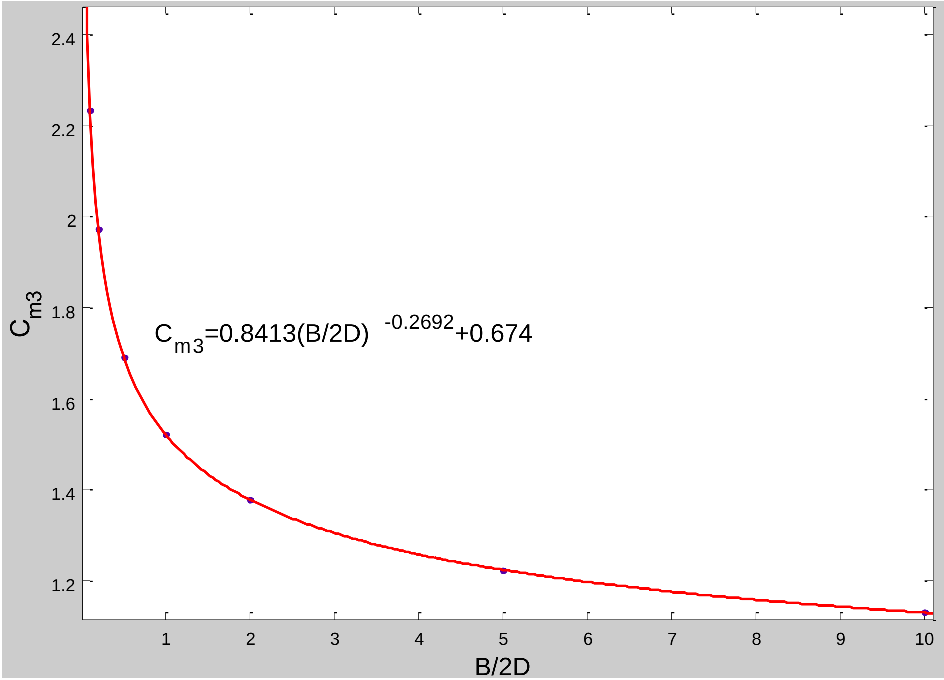


Figure 5.8: Virtual Heave Added Mass Coefficient

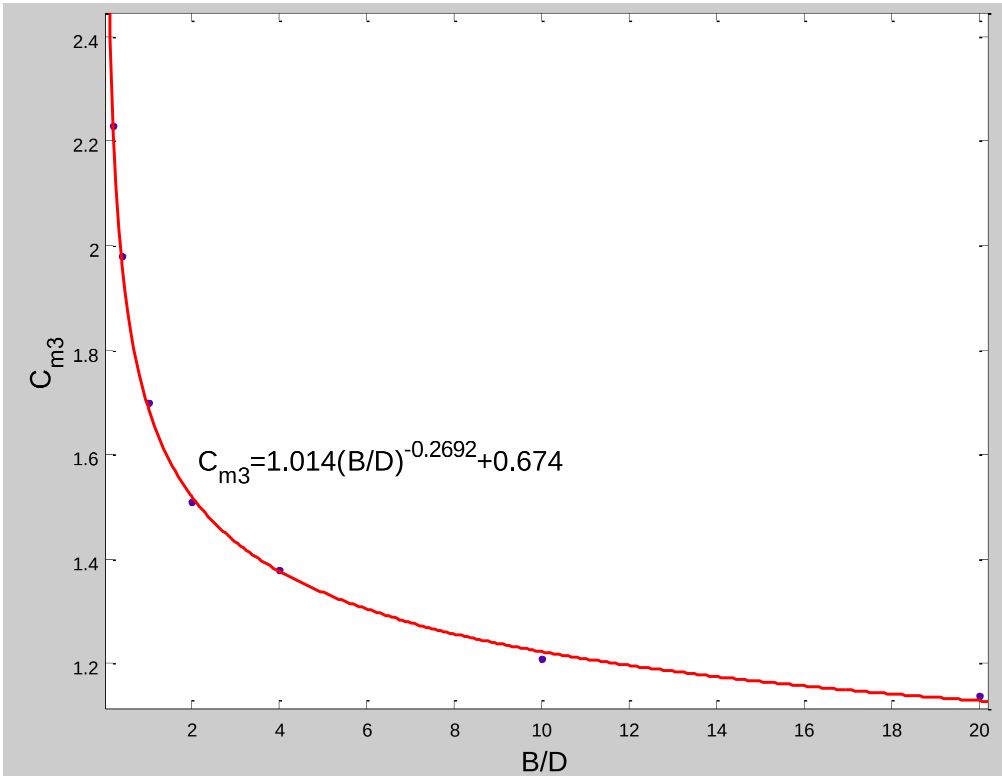


Figure 5.9: Variation of Virtual Heave Added Mass Coefficient with Breadth-draught ratio

For instance, when $\frac{B}{D} = \frac{56.7}{22.1} = 2.57, \quad c_{m3} = 1.4605$.

For a rectangular-shaped vessel, Faltinsen (Faltinsen, 1993) approximates the 2-D added mass in heave as:

$$A_{33}^{(2D)} = 0.8\rho BD$$

5.4.2 The Restoring Force in Heave Motion

The stiffness or coefficient of restoring force in heave motion can be estimated as the buoyancy due to a unit length of sinkage. This is therefore evaluated using the equation below:

$$C_{33} = \rho g B L \tag{5.35}$$

5.4.3 The Heave Natural Frequency

The natural frequency in heave motion is:

$$\omega_{n3} = \sqrt{\frac{C_{33}}{M + A_{33}}} = \sqrt{\frac{\rho g B L}{M + \frac{1}{2} c_{m3} \rho \pi \left(\frac{B}{2}\right)^2 L}} \tag{5.36}$$

C_{33} is the heave restoring coefficient or stiffness.

Therefore, the natural period in heave is:

$$T_{n3} = \frac{2\pi}{\omega_{n3}} = 2\pi \sqrt{\frac{M + \frac{1}{2} c_{m3} \rho \pi \left(\frac{B}{2}\right)^2 L}{\rho g B L}}$$

$$= 2\pi \sqrt{\frac{\rho B L D + \frac{1}{2} c_{m3} \rho \pi \left(\frac{B}{2}\right)^2 L}{\rho g B L}}$$

$$T_{n3} = \frac{2\pi}{g^{1/2}} \left(D + \frac{\pi B c_{m3}}{8}\right)^{1/2} \tag{5.37}$$

The frequency ratio is:

$$R_3 = \frac{\omega}{\omega_{n3}} \tag{5.38}$$

5.4.4 Damping

A rectangular vessel with sharp corners will have high resistance to heaving and pitching motions and this is desirable (unlike the case of round bilges). The damping is caused by wave radiation forces and viscous effects (see subsection 5.3.3). In roll, damping is largely due to viscous effects. It (damping) is a function of the square of the heaving/pitching velocity. Strictly speaking, it is non-linear and linearization has to be applied. Model experiments show that total damping factor varies from 0.06 to 0.09. Although the use of the lower factor may over-estimate the motions, it is the normal practice in design analysis. However, in this analysis, 0.08 is used. The damping coefficient may be denoted by d_{33}, while the critical damping, d_{3cr}, can be evaluated as:

$$d_{3cr} = 2(M + A_{33})\omega_{n3} = 2\sqrt{C_{33}(M + A_{33})} \tag{5.39}$$

The damping factor or ratio, d_3, is equal to:

$$\therefore \quad d_3 = \frac{d_{33}}{d_{3cr}} \tag{5.40}$$

5.4.5 The Heave Force and Response Amplitude Operator

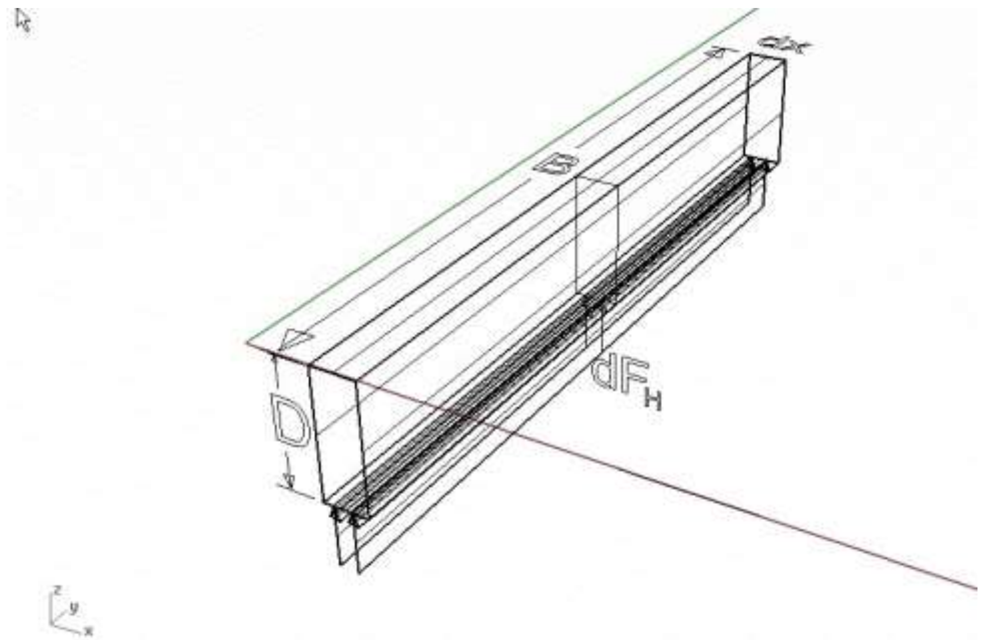


Figure 5.10: Heave Force on the Elemental Strip

Froude-Krilov and Added mass Forces causing Heave:

The dynamic pressure and acceleration of the added mass of water causing heave motion at the bottom of the vessel where $z = -D$ are given by:

$$P_{D3} = \rho g \zeta_a e^{-kD} \sin(kx - \omega t)$$

$$\dot{U}_z = -\zeta_a \omega^2 e^{-kD} \sin(kx - \omega t)$$

$$dF_H = dF_{p3} + dF_{A3} = P_{D3} B dx + A_{33}^{(2D)} \dot{U}_z dx$$

$$dF_H = \rho g \zeta_a e^{-kD} \sin(kx - \omega t) B dx - A_{33}^{(2D)} \zeta_a \omega^2 e^{-kD} \sin(kx - \omega t) dx$$

$$F_H = \left[\rho g B \zeta_a e^{-kD} - A_{33}^{(2D)} \zeta_a \omega^2 e^{-kD}\right] \int_{-L/2}^{L/2} \sin(kx - \omega t)\, dx$$

$$F_H = \left[\rho g B - A_{33}^{(2D)} \omega^2\right] \left(\zeta_a e^{-kD}\right) \left[-\frac{1}{k}\cos(kx - \omega t)\right]\Big|_{-L/2}^{L/2}$$

$$= \left[\rho g B - A_{33}^{(2D)} \omega^2\right] \left(\zeta_a e^{-kD}\right) \frac{1}{k} \left[-\cos\left(\frac{kL}{2} - \omega t\right) + \cos\left(-\frac{kL}{2} - \omega t\right)\right]$$

$$= \left[\rho g B - A_{33}^{(2D)} \omega^2\right] \left(\zeta_a e^{-kD}\right) \frac{1}{k} \left[-2 sin\left(\frac{kL}{2}\right) sin(\omega t)\right]$$

$$F_H = -2\left[\rho g B - A_{33}^{(2D)} \omega^2\right] \left(\zeta_a e^{-kD}\right) \frac{1}{k} sin\left(\frac{kL}{2}\right) sin(\omega t)$$

$$= -2\zeta_a \left[\frac{\rho g B}{k} - A_{33}^{(2D)} g\right] \left(e^{-kD}\right) sin\left(\frac{kL}{2}\right) sin(\omega t)$$

$$\therefore \quad F_H = -\rho g \zeta_a \left[\left(\frac{B\lambda}{\pi}\right) - c_{m3}\pi\left(\frac{B}{2}\right)^2\right] \left(e^{-\frac{2\pi D}{\lambda}}\right) \sin\left(\frac{\pi L}{\lambda}\right) sin(\omega t) \qquad (5.41)$$

That is:

$$F_H = F_3 = F_{3a} sin(\omega t) \qquad (5.42)$$

Therefore, the amplitude of the Heave Force, F_{3a}, is:

$$F_{3a} = -\rho g \zeta_a \left[\left(\frac{B\lambda}{\pi}\right) - c_{m3}\pi\left(\frac{B}{2}\right)^2\right] \left(e^{-\frac{2\pi D}{\lambda}}\right) \sin\left(\frac{\pi L}{\lambda}\right) = -\rho g \zeta_a A_3 \qquad (5.43)$$

$$A_3 = \left[\left(\frac{B\lambda}{\pi}\right) - c_{m3}\pi\left(\frac{B}{2}\right)^2\right] \left(e^{-\frac{2\pi D}{\lambda}}\right) \sin\left(\frac{\pi L}{\lambda}\right) \qquad (5.44)$$

$$|F_{3a}| = |\rho g \zeta_a A_3| \qquad (5.45)$$

Hence, the quasi-static heave force, F_{q3}, is:

$$|F_{q3}| = \left|\frac{F_{3a}}{C_{33}\zeta_a}\right| = \left|\frac{\rho g A_3}{C_{33}}\right| \qquad (5.46)$$

Therefore, the Heave Response Amplitude Operator, RAO_3, is:

$$RAO_3 = |F_{q3}| \times Q_3 \qquad (5.47)$$

Q_3 is the heave dynamic amplification factor.

$$Q_3 = \frac{1}{\sqrt{\left(1 - R_3{}^2\right)^2 + (2d_3R_3)^2}} \qquad (5.48)$$

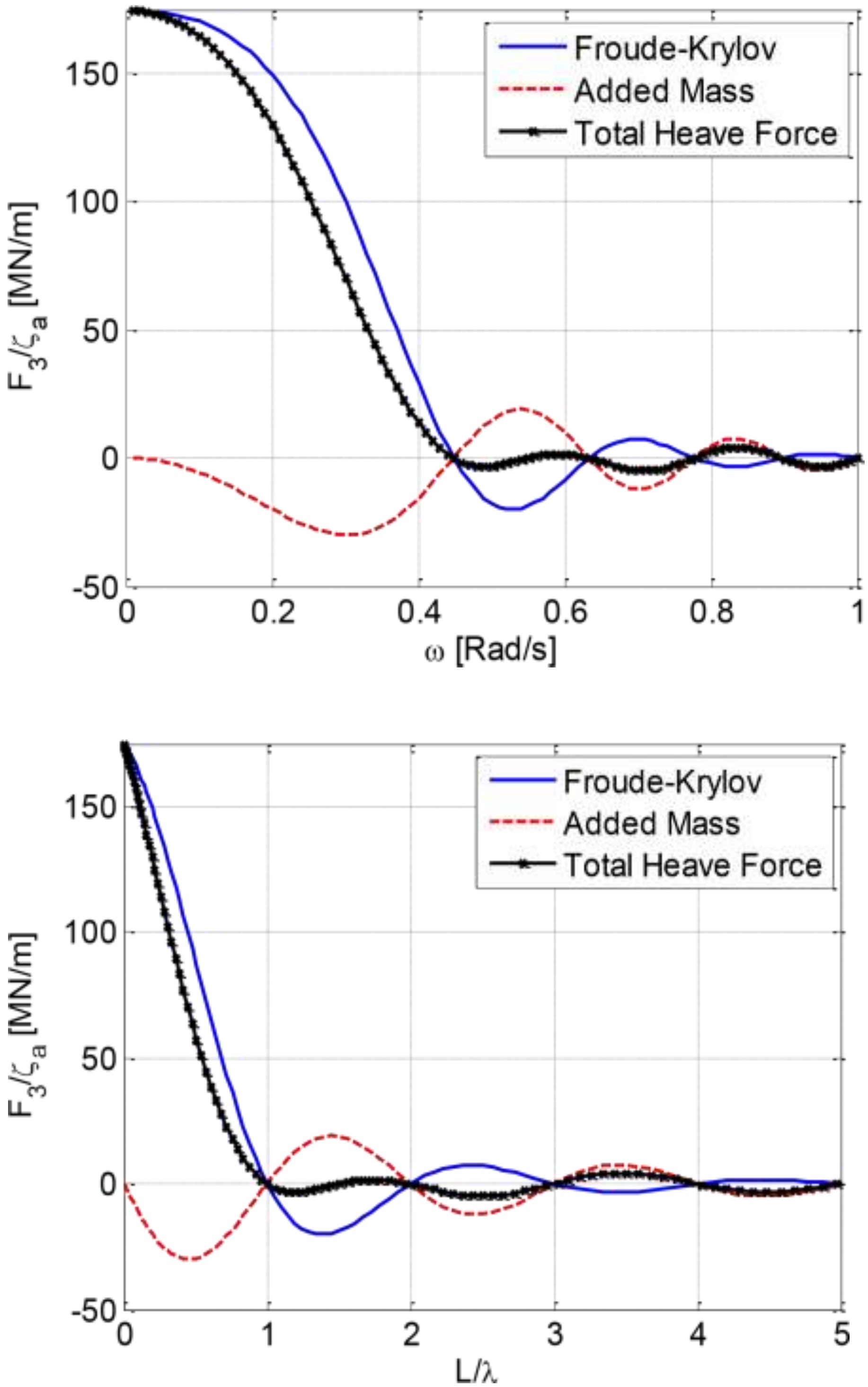


Figure 5.11: Variation of Heave Forces with Wavelength and Frequency

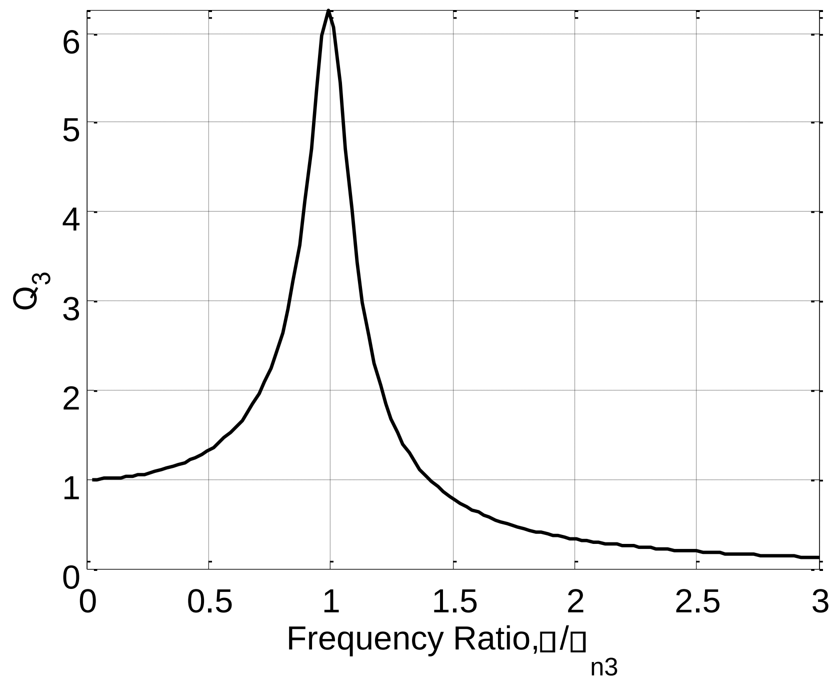


Figure 5.12: Heave Dynamic Magnification Factor versus Frequency Ratio

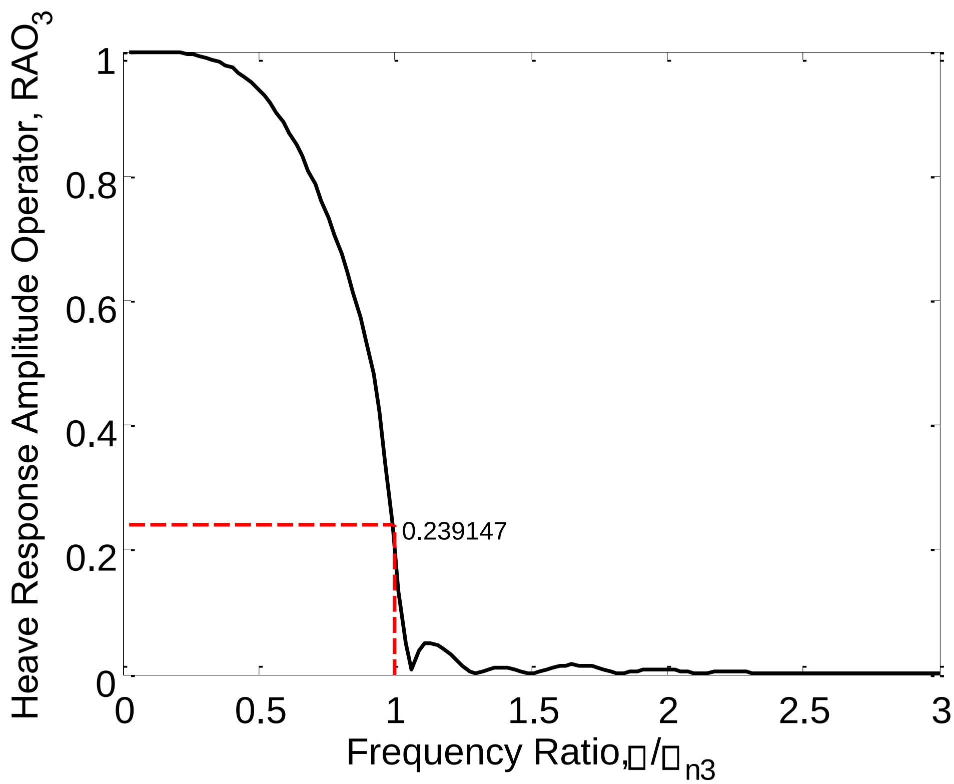


Figure 5.13: Heave Response Amplitude Operator

5.5 Pitch Motion

5.5.1 The pitch moments

The pitch moment, which is the sum of the moments of the heave forces about the y-axis, can be defined as the integral sum of the product of the heave forces and the trimming arms from the longitudinal centre of gravity over the entire length of the vessel.

$$dF_H = \rho g \zeta_a \mathrm{e}^{-\mathrm{kD}} \sin(kx - \omega t)\, B dx - A_{33}^{(2D)} \zeta_a \omega^2 \mathrm{e}^{-\mathrm{kD}} \sin(\mathrm{kx} - \omega\mathrm{t})\, dx$$

$$dM_p = dF_H \times x$$

$$M_p = [\rho g B \zeta_a \mathrm{e}^{-\mathrm{kD}} - A_{33}^{(2D)} \zeta_a \omega^2 \mathrm{e}^{-\mathrm{kD}}] \int_{-L/2}^{L/2} x \sin(\mathrm{kx} - \omega\mathrm{t})\, dx$$

If we apply method of integration by parts, $\int u dv = uv - \int v du$, in which we substitute $u = x \; and \; dv = \sin(\mathrm{kx} - \omega\mathrm{t})\, dx$, we obtain

$$M_p = \left[\rho g B - A_{33}^{(2D)} \omega^2\right] \zeta_a \left(\mathrm{e}^{-\mathrm{kD}}\right) \frac{1}{k^2} [\sin(\mathrm{kx} - \omega\mathrm{t}) - \mathrm{kx}\cos(\mathrm{kx} - \omega\mathrm{t})]\Big|_{-L/2}^{L/2}$$

$$M_p = \left[\rho g B - A_{33}^{(2D)} \omega^2\right] \zeta_a \left(\mathrm{e}^{-\mathrm{kD}}\right) \frac{1}{k^2} \left[2 sin\left(\frac{kL}{2}\right) - kL\cos\left(\frac{kL}{2}\right)\right] \cos(\omega\mathrm{t})$$

$$= -2\zeta_a \left[\frac{\rho g B}{k} - A_{33}^{(2D)} \mathrm{g}\right] \left(\mathrm{e}^{-\mathrm{kD}}\right) \frac{1}{k} \left[\left(\frac{kL}{2}\right) \cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \cos(\omega\mathrm{t})$$

$$and \qquad M_p = M_5 = M_{5a} \cos(\omega\mathrm{t}) \qquad (5.49)$$

The amplitude of Pitch Moment, M_{5a}, which is maximum when wave angle is 0° (bow) or 180° (stern) and tends to zero when angle of wave encounter tends to 90° (beam sea), is therefore given by

$$M_{5a} = -2\zeta_a \left[\frac{\rho g B}{k} - A_{33}^{(2D)} g\right] \left(e^{-kD}\right) \frac{1}{k} \left[\left(\frac{kL}{2}\right) \cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \quad (5.50)$$

Substituting eqn. (6.33) into (6.50), we obtain:

$$M_{5a} = -\rho g \zeta_a \left[\left(\frac{2B}{k}\right) - c_{m3}\pi \left(\frac{B}{2}\right)^2\right] \left(e^{-kD}\right) \frac{1}{k} \left[\frac{kL}{2} \cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right]$$

(5. 51)

$$\frac{M_{fk5}}{\zeta_a} = -2\frac{\rho g B}{k} \left(e^{-kD}\right) \frac{1}{k} \left[\frac{kL}{2} \cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \quad (5.52)$$

$$\frac{M_{A5}}{\zeta_a} = c_{m3}\rho g \pi \left(\frac{B}{2}\right)^2 \left(e^{-kD}\right) \frac{1}{k} \left[\frac{kL}{2} \cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \quad (5.53)$$

$$M_{q5} = \frac{|M_{5a}|}{C_{55}\zeta_a} \quad (5.54)$$

For simplicity, if we divide eqn. (6.51) by eqn. (6.43), we obtain:

$$M_{5a} = F_{3a} \frac{1}{k} \left[\frac{kL}{2} \cot\left(\frac{kL}{2}\right) - 1\right] = F_{3a}\, L_5 \quad (5.55)$$

Where the term, $\left\{L_5 = \left[\frac{kL}{2} \cot\left(\frac{kL}{2}\right) - 1\right]\right\}$, is called the virtual, apparent, or equivalent pitching lever.

5.5.2 The Pitch Natural Period

The pitch natural frequency is approximately equal to the heave natural period and like heave natural period, it depends purely on the draught and breadth of the vessel as shown below:

For evenly distributed mass:

$$T_{n5} = 2\pi\left(\frac{I_5 + A_{55}}{C_{55}}\right)^{1/2} = 2\pi\left(\frac{\frac{1}{12}ML^2 + \frac{1}{12}A_{33}L^2}{\rho g \nabla GM_L}\right)^{1/2}$$

For a rectangular or barge-shaped vessel, the longitudinal metacentric height, GM_L is approximately equal to the height of the longitudinal metacentre above the centre of buoyancy, BM_L.

$$GM_L \cong BM_L = \frac{\frac{1}{12}BL^3}{\nabla} = \frac{\frac{1}{12}BL^3}{\mathrm{LBD}} = \frac{L^2}{12\mathrm{D}}$$

$$C_{55} = \rho g \nabla GM_L = \rho g \mathrm{LBD}\frac{L}{12\mathrm{D}} = \rho g \mathrm{LB}\frac{L}{12} = \frac{1}{12}C_{33}L^2$$ 2 2

Therefore

$$T_{n5} \approx T_{n3} = 2\pi\left[\frac{(1/12)ML^2 + (1/12)A_{33}L^2}{(1/12)C_{33}L^2}\right]^{\frac{1}{2}} = 2\pi\left(\frac{M + A_{33}}{C_{33}}\right)^{\frac{1}{2}}$$

$$T_{n3}, T_{n5} = \frac{2\pi}{g^{\frac{1}{2}}}\left(D + \frac{\pi B c_{m3}}{8}\right)^{\frac{1}{2}} \qquad (5.56)$$

Substituting eqn. (6.34) into eqn. (6.56):

$$T_{n3}, T_{n5} \cong 2\left\{D\left[1 + 0.4\left(\frac{B}{D}\right)^{0.7} + 0.3\left(\frac{B}{D}\right)\right]\right\}^{\frac{1}{2}} \qquad (5.57)$$

B

Therefore, for a given sea state, and a given $\frac{\ }{D}$ ratio, if we must have natural heave or pitch period equal or greater than T, then the draught D must be:

$$D \geq \frac{T^2/4}{\left[1 + 0.4\left(\frac{B}{D}\right)^{0.7} + 0.3\left(\frac{B}{D}\right)\right]} \tag{5.58}$$

5.5.3 The Pitch Moment Response Amplitude Operator

Therefore, the Pitch Moment Response Amplitude Operator, RAO_5, is:

$$RAO_5 = |M_{q5}| \times Q_5 \tag{5.59}$$

Q_5 is the Pitch Moment Dynamic Amplification Factor.

$$Q_5 = \frac{1}{\sqrt{\left(1 - {R_5}^2\right)^2 + (2d_5R_5)^2}} \tag{5.60}$$

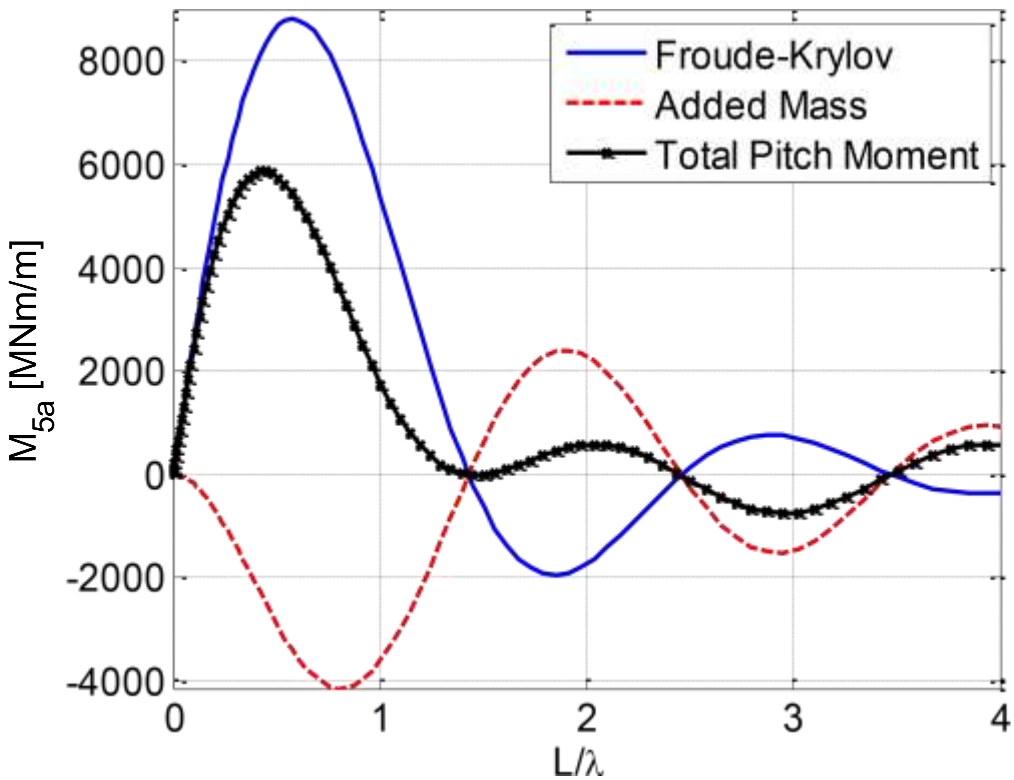


Figure 5.14: Variation of Pitch Moments with Vessel Length/Wavelength

|M /(C)| 5a
a 55

Q 5

x 10-3

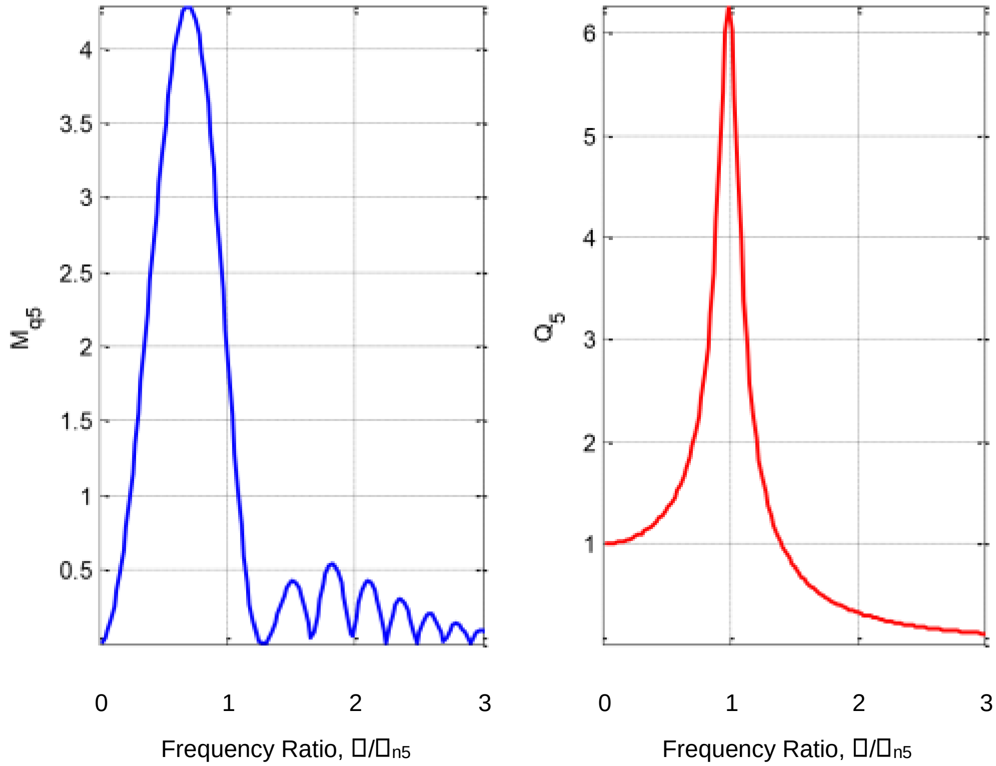


Figure 5.15: The Quasi-static Pitch Moment and Dynamic Magnification Factor versus Frequency Ratio

A good design will usually have the heave and pitch natural periods (as well as its critical wavelength: equivalent to the vessel length or its prime factors as will shown later in section 5.7) longer that peak period of wave environment in which it is to operate. The pitch RAOs at the natural and critical frequencies are respectively indicated in Figure 5.16. The vessel should operate optimally at the right hand side of these points.

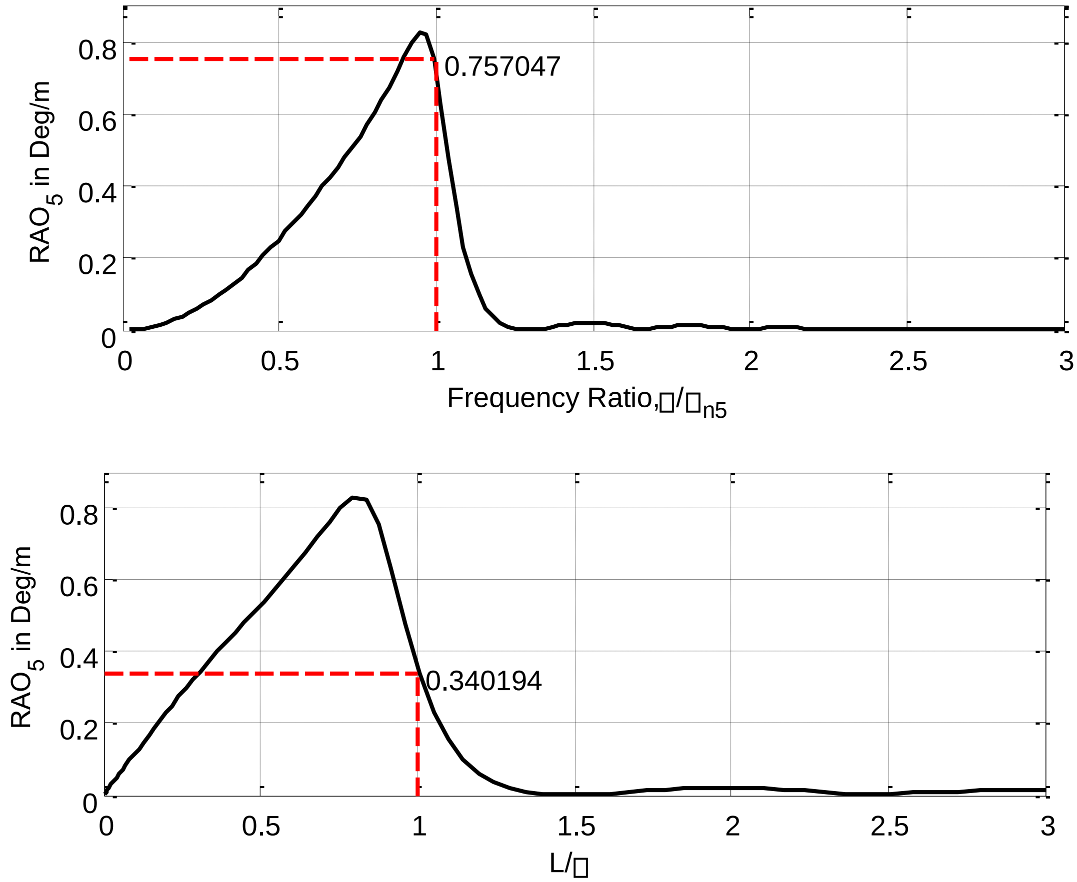


Figure 5.16: Pitch Response Amplitude Operator

5.6 Spectral Analyses

5.6.1 The Response Spectra

Having evaluated the transfer functions, RAOs, associated with the various modes of motions of the vessel, we can obtain the response spectra by computing the products of the wave spectrum and the square of RAOs. From these, the response characteristics of the floating structure for the realistic, irregular sea environments can be evaluated and statistically analized. There are several wave spectral formulations (see Chapter 3) which had already been discussed. The modified Pierson-Moskowitz or the ITTC spectrum, Eqn. (3.54), is used in the analyses.

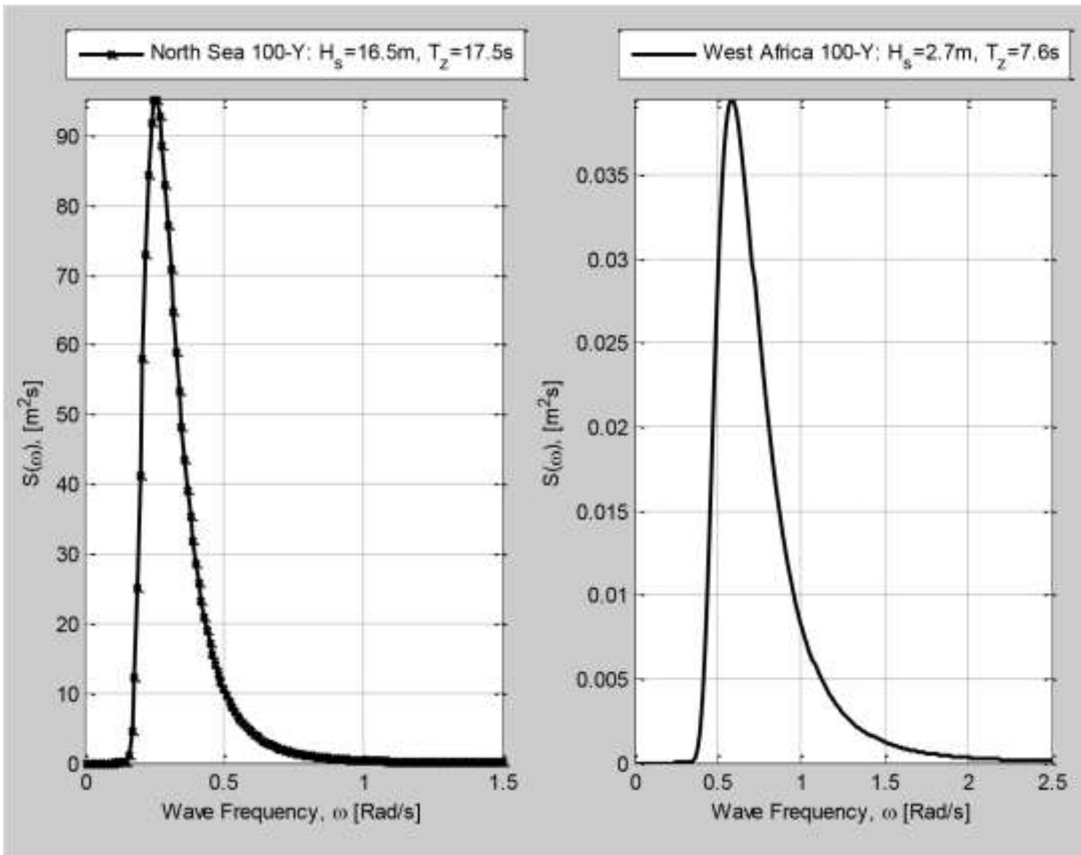


Figure 5.17: Modified Pierson-Moskowitz Spectra for 100-year Return Period Storms of the North Sea and West Africa

See 100-year return period storms in Appendix E.4 (Paik and Thayamballi, 2007).

The variance of the wave elevation (σ^2) or the zeroth moment (m_0) is equal to the area under the spectral curve measured from zero to infinite wave frequency.

$$\sigma^2 = \mathrm{m}_0 = \int_0^{\infty} S(\omega)d\,\omega \tag{5.61}$$

The square root of the variance (σ) is the root mean square water surface elevation.

Two of the root mean square water surface elevation gives us the significant wave amplitude, ζ_{asig}.

$$\zeta_{\mathrm{asig}} = 2\sqrt{\mathrm{m}_0} \tag{5.62}$$

With the significant wave height given by:

$$H_{sig} = 2\zeta_{\mathrm{asig}} = 4\sqrt{\mathrm{m}_0} \tag{5.63}$$

To evaluate the dynamic response of the vessel, first, we need to obtain the response spectrum which is the product of the wave spectrum and the square of the transfer function.

$$S_{Ri}(\omega) = S(\omega) \times [RAO_i]^2 \tag{5.64}$$

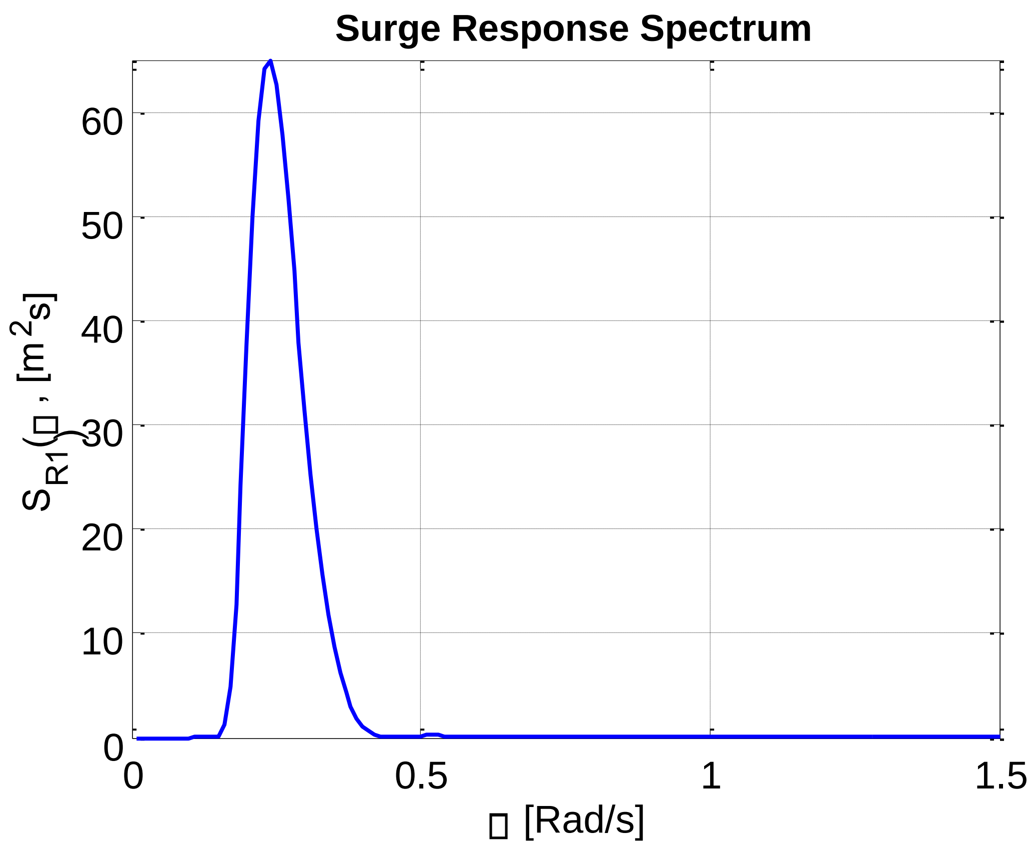


Figure 5.18: Surge Response Spectrum (plotted with the modified P-M for the North Sea 100-year Return Period Storm)

$$\mathrm{m}_{0i} = \int_0^\infty S_{Ri}(\omega)d\omega \tag{5.65}$$

Therefore, the significant motion response amplitude is:

$$\eta_{isig} = 2\sqrt{\mathrm{m}_{0i}} \tag{5.66}$$

Very importantly, the extreme or maximum response amplitude of the motion is:

$$\eta_{max} = 1.86\eta_{isig} \tag{5.67}$$

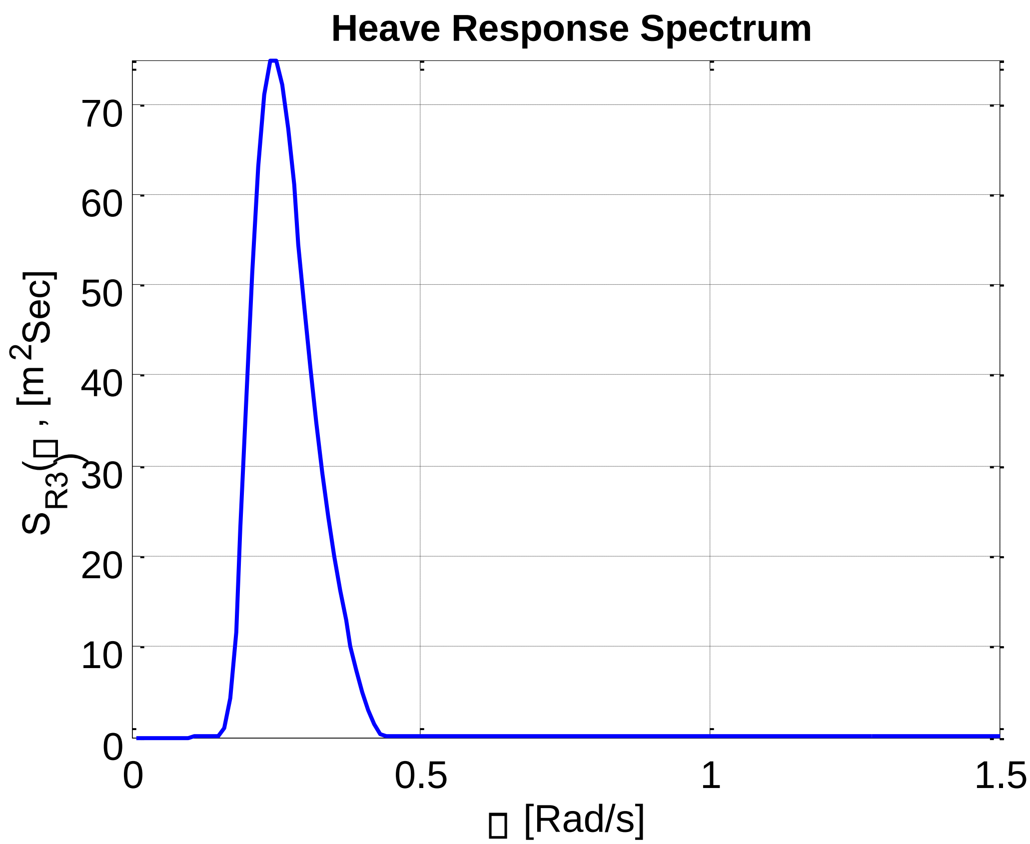


Figure 5.19: Heave Response Spectrum (plotted with the modified P-M for the North Sea 100-year Return Period Storm)

x 10^{-3} **Pitch Response Spectrum**

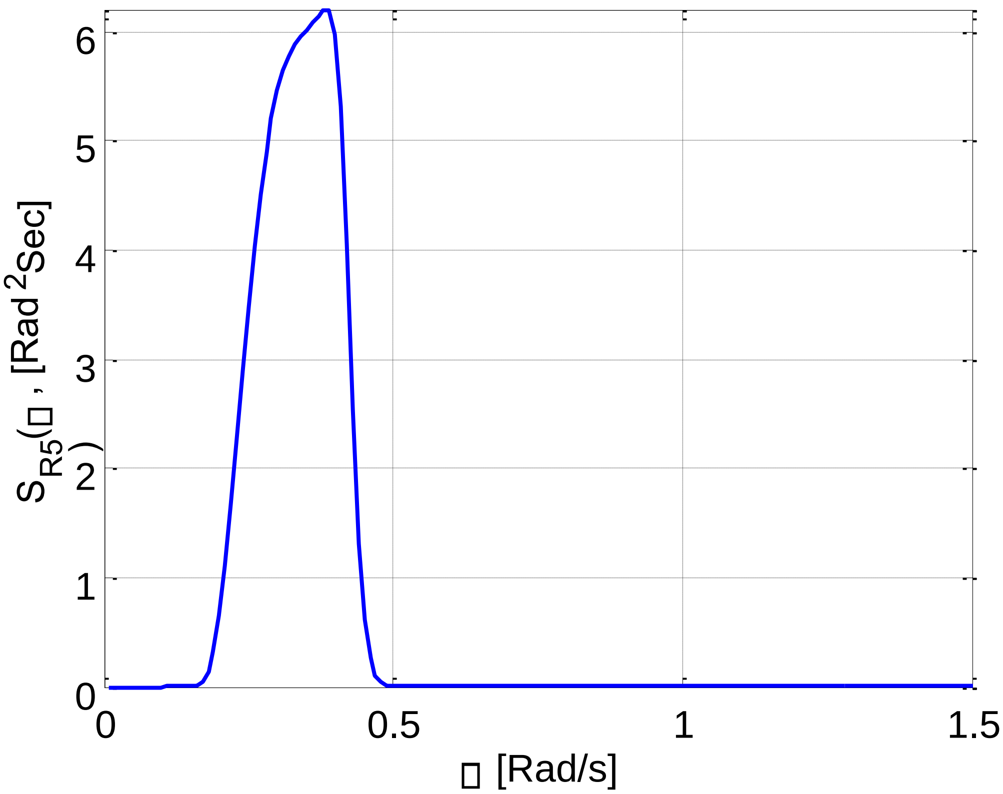


Figure 5.20: Pitch Response Spectrum (plotted with the modified P-M for the North Sea 100-year Return Period Storm)

5.7 Critical wavelength

When the wave frequency is close or equal to the natural frequency of the floating vessel, it causes resonance and high amplitude of response. This is undesirable. High amplitude of response has also been observed at frequency other than the natural frequency. In pitch motion, high response amplitude is seen at wavelength close or equal to the length of the floating structure. This is due to high wave energy induced on the structure at the critical frequency. If we consider the vessel's kinetic energy due to wave force at various wave frequencies, the energy coefficient could therefore be expressed as:

$$\in_{kj}=\frac{F_{ka}\ \times RAO_k}{F_{ja}\times RAO_j} \tag{5.68}$$

Where: The subscripts k and j indicate the motion modes being compared, while the subscript 'a' indicates the amplitude of force or moment. Although the numerator or the denominator alone is not equivalent to the kinetic energy in the respective modes of motion, the expressed quotient itself is good measure of a certain important quantity (or coefficient) relating to the work done or energy impacted on it. It can be used to identify the critical wavelength and its severity (see Figure B. 7) or other relevant phenomena. The most significant energy coefficient is $\in_{53}$ which is given by:

$$\in_{53}=\frac{F_{5a}\ \times RAO_5}{F_{3a}\times RAO_3}$$

At $\max(\in_{kj})$, $\quad \frac{k_{cr}L}{2}=\pi N, \quad \frac{L}{\lambda_{cr}}=N, \quad \omega_{cr}=\left(\frac{2\pi g N}{L}\right)^{1/2} \qquad (5.69)$ $N=1,2,3$ etc, λ_{cr} is the critical wavelength. It occurs close to the maximum amplitude of pitch moment and at zero heave force. Both heave force, F_{3a} and response, RAO_3 will be equal to zero when $sin\left(\frac{kL}{2}\right)$ or

$\left[\left(\frac{B\lambda}{\pi}\right)-c_{m3}\pi\left(\frac{B}{2}\right)^2\right]$ is equal to zero. These happen at wavelengths of $\frac{c_{m3}\pi^2 B}{4}$, L, L/2, L/3 etc. The pitch moment, F_{5a} and its corresponding response, RAO_5 will also be equal to zero at wavelengths of $\frac{c_{m3}\pi^2 B}{4}$, and L/1.43 etc.

To ensure that the vessel has a very good motion performance, these wavelengths must be well-separated from one another. Investigations have shown that the minimum separation of heave- and-pitch zeros is given by:

$$S_{min} = min\left(L - \frac{c_{m3}\pi^2 B}{4}, \quad \frac{L}{1.43} - \frac{c_{m3}\pi^2 B}{4}\right) \quad (5.70)$$

On the other hand, operation at the critical wavelength can result in high rotational motion when compared to translational motion. This, at extreme condition can cause overturning and capsize of the vessel. Furthermore, there will be high induced wave bending moment on the structure.

Therefore, checks are usually made to avoid this critical wavelength.

CHAPTER 6

6 GLOBAL STRUCTURAL RESPONSE

6.1 Introduction

The simplest level of ship structural loading and response is considered, in which the floating structure or vessel (the FPSO, in this case) is idealized as a hollow thin-wall box beam, referred to as the "hull girder." At this level of consideration we can make several simplifying approximations and assumptions, with the principal ones being:

(i) That the hull girder acts in accordance with simple beam theory.

(ii) There is only one independent variable, which is the longitudinal position, x, from one end (bow or stern)

(iii) Loads and deflections have only a single value at any cross section.

(iv) The hull girder remains elastic, its deflections are very small, and therefore, the longitudinal strain due to bending varies linearly over the cross section, about some transverse axis of zero transverse strain (neutral axis).

6.2 Still Water Loading and Wave Loading Moments

For a typical ship-shaped FPSO with varying cross-sectional area, $a(x)$, and mass distribution (mass per unit length), $m(x)$, the overall static equilibrium requires that the total upward buoyancy force equals the total weight of the vessel and that these vertical forces are collinear. So, the still water loading equations become:

$$\rho g \int_0^L a(x)dx = g \int_0^L m(x)dx = g\Delta \tag{6.1}$$

Similarly, the equilibrium of moments is also required such that:

$$\rho g \int_0^L a(x)xdx = g \int_0^L m(x)xdx = g\Delta l_G \tag{6.2}$$

Where: Δ=Mass displacement

l_G = Distance from the origin to the longitudinal centre of gravity

The elastic, small-deflection beam theory, the bending moment is related to the vertical loading on the vessel by:

$$\frac{d^2M}{dx^2} = f(x) \tag{6.3}$$

Where: $f(x)$ =Vertical load distribution

Therefore, the still-water shear force, Q, which is imposed on a section, X, is given by:

$$Q(x) = \frac{dM}{dx} = \int_0^X f(x)dx$$

$$Q(x) = \rho g \int_0^X a(x)dx - g\int_0^X m(x)dx = b(x) - w(x) \qquad (6.4)$$

Where: $Q(x)$ =Shear force distribution for still water condition

$b(x)$ =Buoyance force distribution

$w(x)$ = Weight distribution

Apart from the still water buoyancy force, there is usually additional, quite different, buoyancy force that occurs due to waves, which is both dynamic and probabilistic. Hence, in order to simplify the analysis, the buoyancy distribution due to waves is usually calculated separately and then superimposed on the static and deterministic still water buoyancy force (Hughes, 1983).

However, in this analysis, the still water net force is zero due to the assumed rectangular shape of the floating production, storage and offloading vessel being considered. This is because both the still water buoyancy force and the weight distributions are rectangular in shape, equal in magnitude, but opposite in direction, and so cancel out each other, leaving us with the dynamic wave loading to contend with.

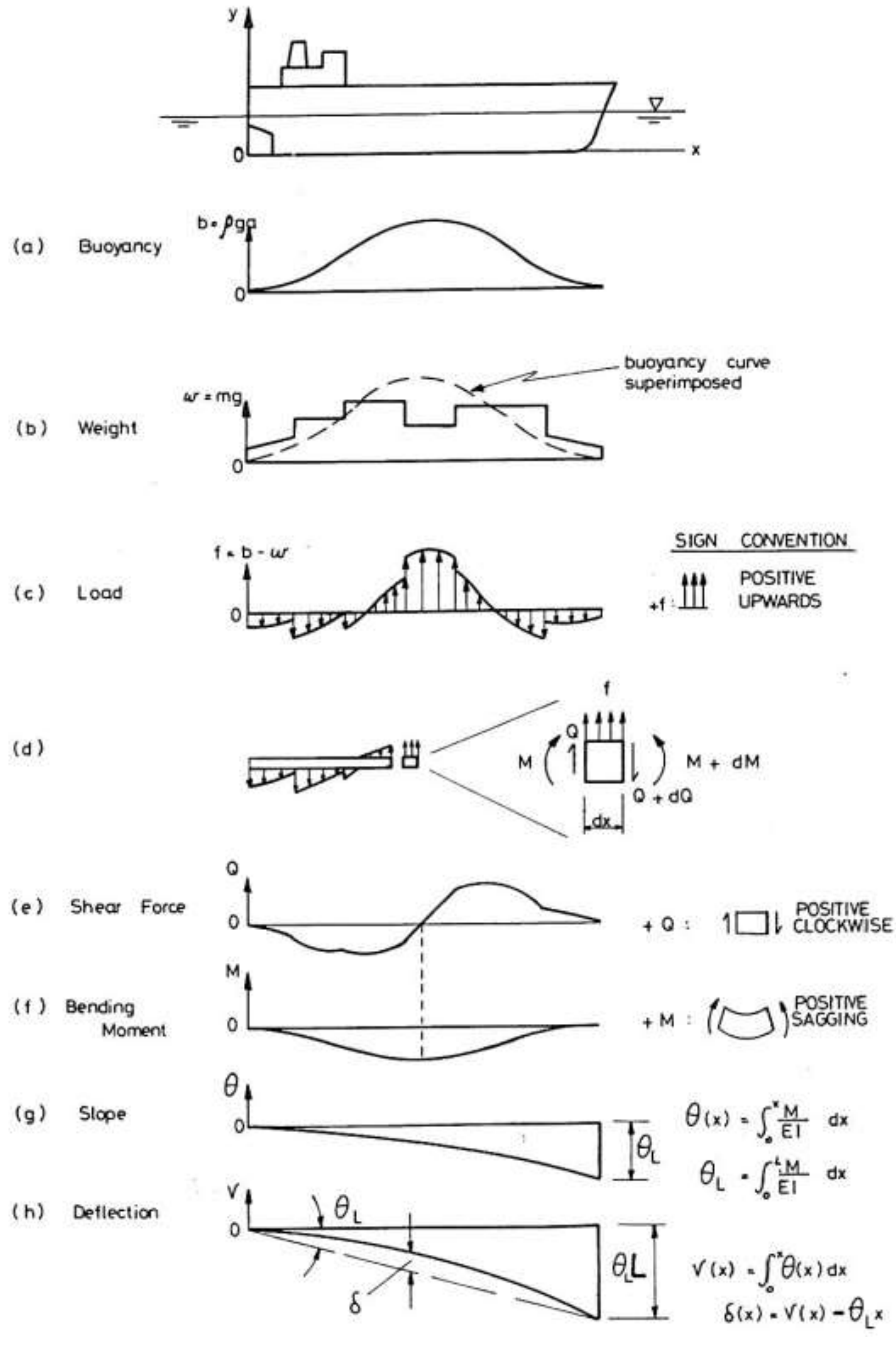


Figure 6.1: Hull Girder Bending of a Typical Ship (Hughes, 1983)

6.3 Dynamic Wave loading

Take a vessel or barge to be a box or rectangular-shaped floating body. Let the dimensions be: Length, L; Beam, B and draught, D.

Assumptions:

(1) The vessel has a constant mass density
(2) It has a zero forward speed
(3) It is moored in deep sea, with a sinusoidal wave propagating along the negative x-axis. its velocity potential is:

$$\phi = g\frac{\zeta_a}{\omega}e^{kz}\cos(\omega t + kx) \qquad (6.5)$$

We shall then derive the relevant applicable formulae required to analyse the motions and induced wave bending by taking into consideration the effect of the assumed regular wave on the floating structure. The next section takes a look at the heave and pitch responses in head sea. Thereafter, the shear force and bending moment formulations will be presented.

6.3.1 Heave Force and Pitch Moment in Head Sea

The vertical excitation force on a small body compared to the wavelength is:

On the elemental strip: $dF_3 = pdA + \left(A_{31}^{(2D)}a_1 + A_{32}^{(2D)}a_2 + A_{33}^{(2D)}a_3\right)dx$

Where: $p = -\rho\frac{\partial\phi}{\partial t} = \rho g\zeta_a e^{kz}\sin(\omega t + kx)$

$$a_2 = \frac{\partial^2\phi}{\partial y\partial t} = 0$$

$$a_3 = \frac{\partial^2 \phi}{\partial z \partial t} = -kg\zeta_a e^{kz} \sin(\omega t + kx)$$

$$A_{31}^{(2D)} = 0 \qquad and \qquad dA = Bdx$$

$$dF_3 = pBdx + A_{33}^{(2D)} a_3 dx = \zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} \sin(\omega t + kx)\, dx$$

$$F_3 = \zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} \int_{-\frac{L}{2}}^{\frac{L}{2}} \sin(\omega t + kx)\, dx$$

$$= 2\zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \sin\left(\frac{kL}{2}\right) \sin(\omega t)$$

Where the amplitude of the heave force is given by:

$$F_{3a} = 2\zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \sin\left(\frac{kL}{2}\right) \qquad (6.6)$$

If $A_{33}^{(2D)}$ is substituted in Eqn. (6.6), we obtain:

$$F_{3a} = \rho g \zeta_a \left[\frac{2B}{k} - c_{m3}\pi \left(\frac{B}{2}\right)^2\right] e^{-kD} \sin\left(\frac{kL}{2}\right) = \rho g \zeta_a A_3 \qquad (6.7)$$

Where the equivalent heaving area is:

$$A_3 = \left[\frac{2B}{k} - c_{m3}\pi \left(\frac{B}{2}\right)^2\right] e^{-kD} \sin\left(\frac{kL}{2}\right) \qquad (6.8)$$

The heave motion η_3 usually takes the form of the heave excitation force, and hence given as: $\eta_3 = \eta_{3a} \sin(\omega t)$

Therefore, the heave velocity and acceleration are respectively given by:

$$\dot{\eta}_3 = \omega \eta_{3a} \cos(\omega t); \qquad \ddot{\eta}_3 = -\omega^2 \eta_{3a} \sin(\omega t)$$

The amplitude of heave motion is: $\eta_{3a} = \frac{F_{3a}}{C_{33}} \times Q_3$

Similarly, the pitch excitation moment is:

$$dF_5 = -xdF_3 = -\zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} [x \sin(\omega t + kx)] dx$$

$$F_5 = -\zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} \int_{-L/2}^{L/2} x \sin(\omega t + kx)\, dx$$

$$F_5 = 2\zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \frac{1}{k} \left[\left(\frac{kL}{2}\right) \cos\left(\frac{kL}{2}\right) - \sin\left(\frac{kL}{2}\right)\right] cos(\omega t) \tag{6.9}$$

Where the amplitude of the pitch excitation moment is given by:

$$F_{5a} = 2\zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \frac{1}{k} \left[\left(\frac{kL}{2}\right) \cos\left(\frac{kL}{2}\right) - \sin\left(\frac{kL}{2}\right)\right]$$

The amplitude of the pitch excitation moment F_{5a} can also be obtained using:

$$\frac{F_{5a}}{F_{3a}} = \frac{1}{k} \left[\left(\frac{kL}{2}\right) \cot\left(\frac{kL}{2}\right) - 1\right] = L_5 \tag{6.10}$$

L_5 is the equivalent pitching lever. Hence, F_{5a} is the product of F_{3a} and L_5.

Also, the pitch motion η_5 usually takes the form of the pitch excitation moment and hence given as:

$$\eta_5 = \eta_{5a} \cos(\omega t)$$

$$\dot{\eta}_5 = -\omega \eta_{5a} \sin(\omega t); \quad \ddot{\eta}_5 = -\omega^2 \eta_{5a} \cos(\omega t)$$

The amplitude of pitch motion is:

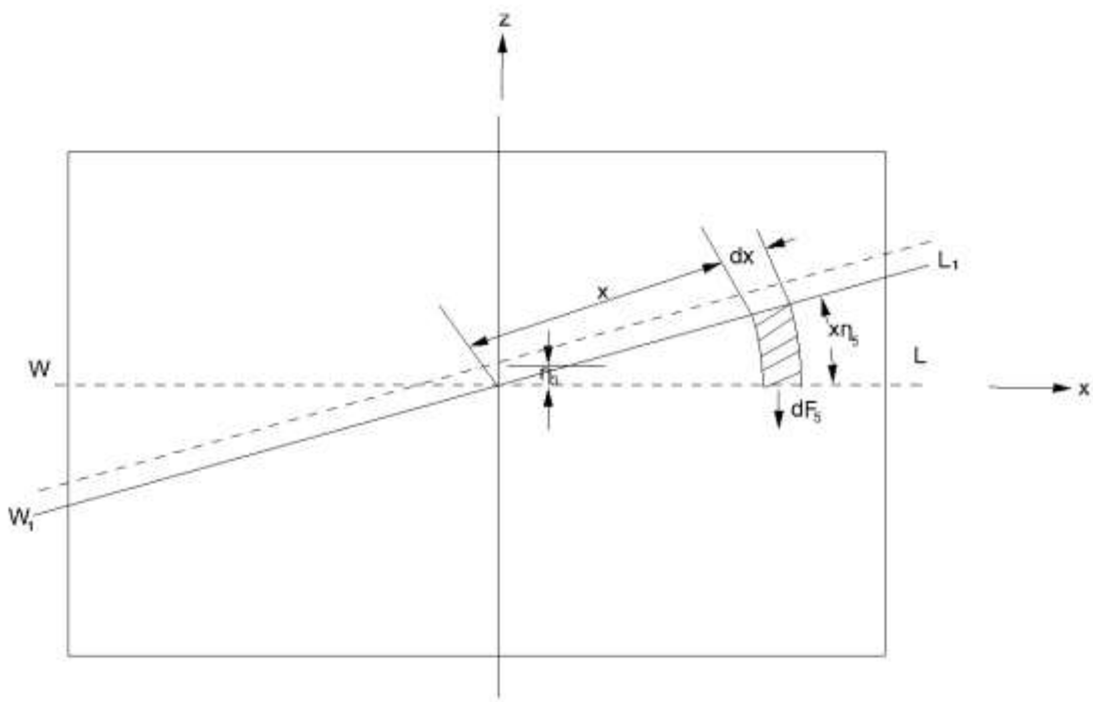
$$\eta_{5a} = \frac{F_{5a}}{C_{55}} \times Q_5$$

Where Q_3 and Q_5 are the dynamic magnification factors as defined in the previous chapter. See Eqns. (5.48) and (5.60).

The hydrostatic restoring coefficient in pitch motion C_{55} is evaluated thus:

Consider the weight dF_5 of the elemental strip:

$$dF_5 = \rho g B(x\eta_5)dx$$



$$C_{55}\eta_5 = \int_{-L/2}^{L/2} x dF_5 = \int_{-L/2}^{L/2} \rho g B \eta_5 x^2 dx = \rho g B \eta_5 \frac{x^3}{3}\bigg|_{-L/2}^{L/2}$$

$$= \frac{1}{3}\rho g B \eta_5 \left(\frac{L^3}{8} + \frac{L^3}{8}\right)$$

$$C_{55} = \rho g B \frac{L^3}{12}$$

Alternatively, we can also obtain this expression for hydrostatic restoring coefficient in pitch motion by simply multiplying the longitudinal metacentric height by the total weight of the barge as shown below.

$$GM_L \approx BM_L = \frac{(1/12)BL^3}{LBD} = \frac{L^2}{12D}; \quad M = \rho LBD$$

$$C_{55} = Mg \times GM_L = \rho g LBD \times \frac{L^2}{12D} = \rho g B \frac{L^3}{12} \tag{6.11}$$

Let us now evaluate the added moment of inertia in pitch:

$$A_{55}\ddot{\eta}_5 = \int_{-L/2}^{L/2} \left(x A_{33}^{(2D)}\right)(x\ddot{\eta}_5)dx = \ddot{\eta}_5 \left[\frac{x^3}{3} A_{33}^{(2D)}\right]_{-L/2}^{L/2} = \ddot{\eta}_5 A_{33}^{(2D)} \frac{L^3}{12}$$

$$A_{55} = A_{33}^{(2D)} \frac{L^3}{12} = A_{33} \frac{L^2}{12} \tag{6.12}$$

Similarly, the Pitching moment of inertia is:

$$I_5 = M \frac{L^2}{12}$$

Let us now prove that:

$$I_5\ddot{\eta}_5 = \int_{-L/2}^{L/2}\left(x\frac{M}{L}\right)(x\ddot{\eta}_5)dx = \ddot{\eta}_5\left[\frac{x^3}{3}\frac{M}{L}\right]_{-L/2}^{L/2} = \ddot{\eta}_5 M\frac{L^2}{12}$$

$$\therefore \qquad I_5 = M\frac{L^2}{12} = \rho BD\frac{L^3}{12} \qquad (6.13)$$

It is interesting to note that, in pitch motion, the moment of inertia, added moment of inertia, and the hydrostatic restoring coefficient (pitching stiffness) are respectively the products of the mass, added mass, stiffness in heave motion and the factor $L^2/12$.

6.3.2 Wave Induced Shear Force

The Shear Force at any point from the one end is the integral sum of the contributions from wave excitation force, restoring force and inertia force and damping force. The Shear Force, Q_X from one end of the vessel is therefore given by:

On the elemental strip:

$$dQ_X = dF_E - dF_R - dF_I - dF_D$$

$$Q_X = \int_0^X (dF_E - dF_R - dF_I - dF_D)$$

(i) Contribution from excitation force:

$$F_E = \int_0^X dF_E = \int_0^X dF_3 = \int_0^X \zeta_a\left(\rho gB - A_{33}^{(2D)}kg\right)e^{-kD}[\sin(\omega t + kx)]dx$$

$$= \zeta_a\left(\frac{\rho gB}{k} - A_{33}^{(2D)}g\right)e^{-kD}\{[\sin(kX)]\sin(\omega t) - [\cos(kX) - 1]cos(\omega t)\}$$

$$(6.14)$$

(ii) Contribution from Restoring Force:

On the elemental strip: $dF_R = (\rho g B dx)(\eta_3 - x\eta_5)$

$$F_R = \rho g B \int_0^X (\eta_3 - x\eta_5)\, dx = \rho g B X \left(\eta_3 - \frac{X}{2}\eta_5\right) \qquad (6.15)$$

(iii) Contribution from Inertia Force:

On the elemental strip: $dF_I = \left(\rho BD + A_{33}^{(2D)}\right) dx(\ddot{\eta}_3 - x\ddot{\eta}_5)$

$$F_I = \left(\rho BD + A_{33}^{(2D)}\right) \int_0^X (\ddot{\eta}_3 - x\ddot{\eta}_5) dx = \left(\rho BD + A_{33}^{(2D)}\right) X \left(\ddot{\eta}_3 - \frac{X}{2}\ddot{\eta}_5\right)$$

$$F_I = \left(\rho BD + A_{33}^{(2D)}\right) X \left(\ddot{\eta}_3 - \frac{X}{2}\ddot{\eta}_5\right) \qquad (6.16)$$

(iv) Contribution from Damping Force:

On the elemental strip: $dF_D = d_{33}^{(2D)} dx(\dot{\eta}_3 - x\dot{\eta}_5)$

In a similar way, the contribution from damping force is therefore expressed as:

$$F_D = d_{33}^{(2D)} \int_0^X (\dot{\eta}_3 - x\dot{\eta}_5) dx = d_{33}^{(2D)} X \left(\dot{\eta}_3 - \frac{X}{2}\dot{\eta}_5\right) \qquad (6.17)$$

Where: $d_{33}^{(2D)} = 2d_3 \left(\rho BD + A_{33}^{(2D)}\right) \omega_{n3} = \rho g D/\omega_{n3};\ \ d_3$ is the damping factor.

Hence, the shear force at the point X from each end is:

$$Q_X = F_E - F_R - F_I - F_D \qquad (6.18)$$

6.3.3 Wave Bending Moment

The vertical dynamic bending moment at any point from the one end is the integral sum of the contributions from wave excitation load, restoring load, and inertia moment load and damping load.

The heave motion at any point x is given by the expression, $\eta_3 - x\eta_5$ **(a)**

Contribution from excitation force:

On the elemental strip:

$$dM_E = -xdF_3 = -\zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} [x \sin(\omega t + kx)]dx$$

$$M_E == -\zeta_a \left(\rho g B - A_{33}^{(2D)} kg\right) e^{-kD} \int_0^{L/2} x \sin(\omega t + kx)\, dx$$

$$M_E = \zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \frac{1}{k} \left\{ \left[\left(\frac{kL}{2}\right) \cos\left(\frac{kL}{2}\right) - \sin\left(\frac{kL}{2}\right)\right] \cos(\omega t) + \left[1 - \left(\frac{kL}{2}\right) \sin\left(\frac{kL}{2}\right) - \cos\left(\frac{kL}{2}\right)\right] \sin(\omega t) \right\} \quad (6.19)$$

(b) Contribution from Restoring Force:

On the elemental strip: $dM_R = -xdF_R = -x[(\rho g B dx)(\eta_3 - x\eta_5)]$

$$M_R = -\int_0^{\frac{L}{2}} x dF_R = -\int_0^{\frac{L}{2}} x[(\rho gBdx)(\eta_3 - x\eta_5)]$$

$$= \rho gB \int_0^{\frac{L}{2}} (x\eta_3 - x^2\eta_5)\, dx = -\rho gB \left(\frac{x^2}{2}\eta_3 - \frac{x^3}{3}\eta_5\right)\Bigg|_0^{\frac{L}{2}}$$

$$= -\frac{1}{2}\left(\frac{L}{2}\right)^2 \rho gB\eta_3 - \frac{1}{3}\left(\frac{L}{2}\right)^3 \rho gB\eta_5$$

$$M_R = -\frac{1}{2}\left(\frac{L}{2}\right)^2 \rho gB\left(\eta_3 - \frac{L}{3}\eta_5\right) \qquad (6.20)$$

(c) Contribution from Inertia Moment Load:

On the elemental strip:

$$dM_I = -xdF_I = -x\left[\left(\rho BD + A_{33}^{(2D)}\right) dx(\ddot{\eta}_3 - x\ddot{\eta}_5)\right]$$

$$M_I = -\int_0^{\frac{L}{2}} x dF_I = -\int_0^{\frac{L}{2}} x\left[\left(\rho BD + A_{33}^{(2D)}\right) dx(\ddot{\eta}_3 - x\ddot{\eta}_5)\right]$$

$$= -\left(\rho BD + A_{33}^{(2D)}\right) \int_0^{\frac{L}{2}} (x\ddot{\eta}_3 - x^2\ddot{\eta}_5)\, dx$$

$$= -\left(\rho BD + A_{33}^{(2D)}\right)\left(\frac{x^2}{2}\ddot{\eta}_3 - \frac{x^3}{3}\ddot{\eta}_5\right)\Bigg|_0^{\frac{L}{2}}$$

$$= -\left(\rho BD + A_{33}^{(2D)}\right)\left[\frac{1}{2}\left(\frac{L}{2}\right)^2 \ddot{\eta}_3 - \frac{1}{3}\left(\frac{L}{2}\right)^3 \ddot{\eta}_5\right]$$

$$M_I = -\frac{1}{2}\left(\frac{L}{2}\right)^2 \left(\rho BD + A_{33}^{(2D)}\right)\left(\ddot{\eta}_3 - \frac{L}{3}\ddot{\eta}_5\right) \qquad (6.21)$$

(d) Contribution from Damping Force:

In a similar way, the contribution from damping force is expressed as:

$$M_D = -\frac{1}{2}\left(\frac{L}{2}\right)^2 B_{33}^{(2D)}\left(\dot{\eta}_3 - \frac{L}{3}\dot{\eta}_5\right) \tag{6.22}$$

Where: $B_{33}^{(2D)} = 2d_3\left(\rho BD + A_{33}^{(2D)}\right)\omega_{n3}$

d_3 is the damping factor.

Therefore, the wave bending moment amidships is be given by

$$M_{\otimes} = M_E - M_R - M_I - M_D \tag{6.23}$$

Hence,

$$M_{\otimes} = \zeta_a\left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD}\frac{1}{k}\left\{\left[\left(\frac{kL}{2}\right)\cos\left(\frac{kL}{2}\right) - \sin\left(\frac{kL}{2}\right)\right]\cos(\omega t) + \left[1 - \left(\frac{kL}{2}\right)\sin\left(\frac{kL}{2}\right) - \cos\left(\frac{kL}{2}\right)\right]\sin(\omega t)\right\}$$

$$+\frac{1}{2}\left(\frac{L}{2}\right)^2\left\{\begin{matrix}\left(\rho BD + A_{33}^{(2D)}\right)\left(\ddot{\eta}_3 - \frac{L}{3}\ddot{\eta}_5\right) + B_{33}^{(2D)}\left(\dot{\eta}_3 - \frac{L}{3}\dot{\eta}_5\right) \\ +\rho g B\left(\eta_3 - \frac{L}{3}\eta_5\right)\end{matrix}\right\}$$

(6.24)

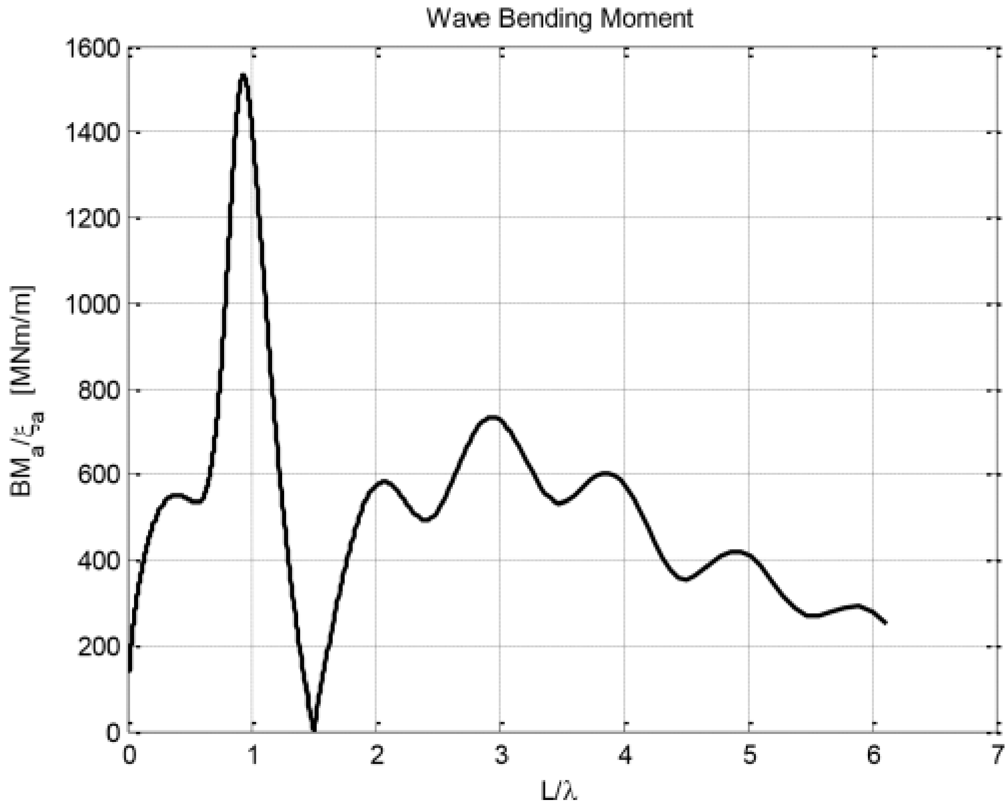


Figure 6.2: Effects of Wavelength on the Bending Moment amidships

6.4 Wave Bending Moment Distribution

The wave bending moment distribution along the hull girder from the bow to amidships may be obtained by substituting the $L/2$ in Eqn. (6.24) with the X (distance from the bow, until the amidships is reached).

$$M_X = \zeta_a \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) e^{-kD} \frac{1}{k} \{[(kX)\cos(kX) - \sin(kX)]\cos(\omega t) + [1 - (kX)\sin(kX) - \cos(kX)]\sin(\omega t)\}$$

$$+\frac{1}{2} X^2 \left\{ \begin{matrix} \left(\rho BD + A_{33}^{(2D)}\right)\left(\ddot{\eta}_3 - \frac{2}{3} X \ddot{\eta}_5\right) + d_{33}^{(2D)}\left(\dot{\eta}_3 - \frac{2}{3} X \dot{\eta}_5\right) \\ +\rho g B \left(\eta_3 - \frac{2}{3} X \eta_5\right) \end{matrix} \right\} \quad (6.25)$$

Let $\frac{M_X}{\zeta_a} = I_1 \sin(\omega t) + I_2 \cos(\omega t)$

$$\left. \begin{aligned} I_1 = \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) \frac{e^{-kD}}{k} [1 - kX \sin(kX) - \cos(kX)] \\ -\frac{X^2}{2}\left(\rho BD + A_{33}^{(2D)}\right) \omega^2 RAO_3 \\ +\frac{X^3}{3} d_{33}^{(2D)} \omega \, RAO_5 \\ +\frac{X^2}{2} \rho g B \, RAO_3 \end{aligned} \right\} \quad (6.26)$$

$$\left. \begin{aligned} I_2 = \left(\frac{\rho g B}{k} - A_{33}^{(2D)} g\right) \frac{e^{-kD}}{k} [kX \cos(kX) - \sin(kX)] \\ +\frac{X^3}{3}\left(\rho BD + A_{33}^{(2D)}\right) \omega^2 RAO_5 \\ +\frac{X^2}{2} d_{33}^{(2D)} \omega \, RAO_3 \\ -\frac{X^3}{3} \rho g B \, RAO_5 \end{aligned} \right\} \quad (6.27)$$

Where the damping factor is:

$$\xi_3 = d_3 = \frac{d_{33}^{(2D)}}{\left(\rho BD + A_{33}^{(2D)}\right) \omega_{n3}}$$

The amplitude of the bending moment distribution per unit wave amplitude is expressed as:

$$\left(\frac{M_X}{\zeta_a}\right)_{amplitude} = \left({I_1}^2 + {I_2}^2\right)^{1/2}$$

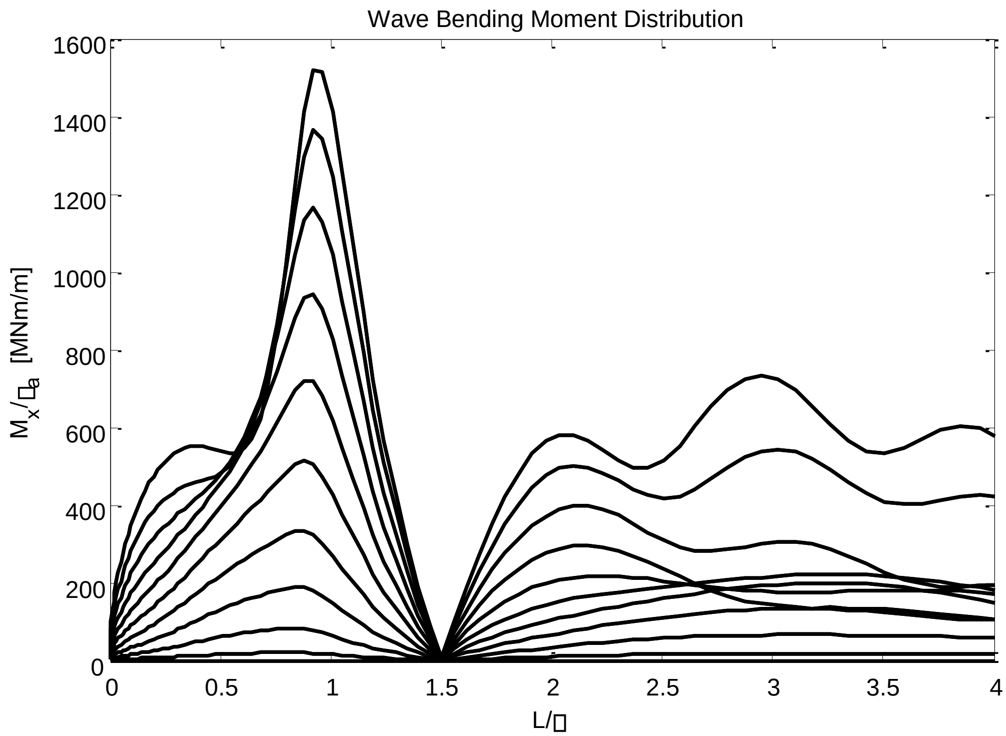


Figure 6.3: Amplitude of Wave Bending Moment per unit wave amplitude from one end up to amidships for a typical FPSO vessel

6.5 Effect of Wave Height on the Induced Bending Moment

The most probable maximum wave bending moments at different points from aft to fore perpendicular have been evaluated using the derived bending moment distribution equation and spectral analysis. At a given wave period (this is also valid at slight variation of wave period, as shown in the figure below), the induced wave bending moment is directly proportional to the significant wave height. At amidships, the slope is ¾ for this particular vessel, i.e. maximum BM (in GNm) is ¾ H_s +0.13. See Figure 6.4. The blue line indicates the BM distribution for the annual sea state of the Central North Sea (also see Table E. 3).

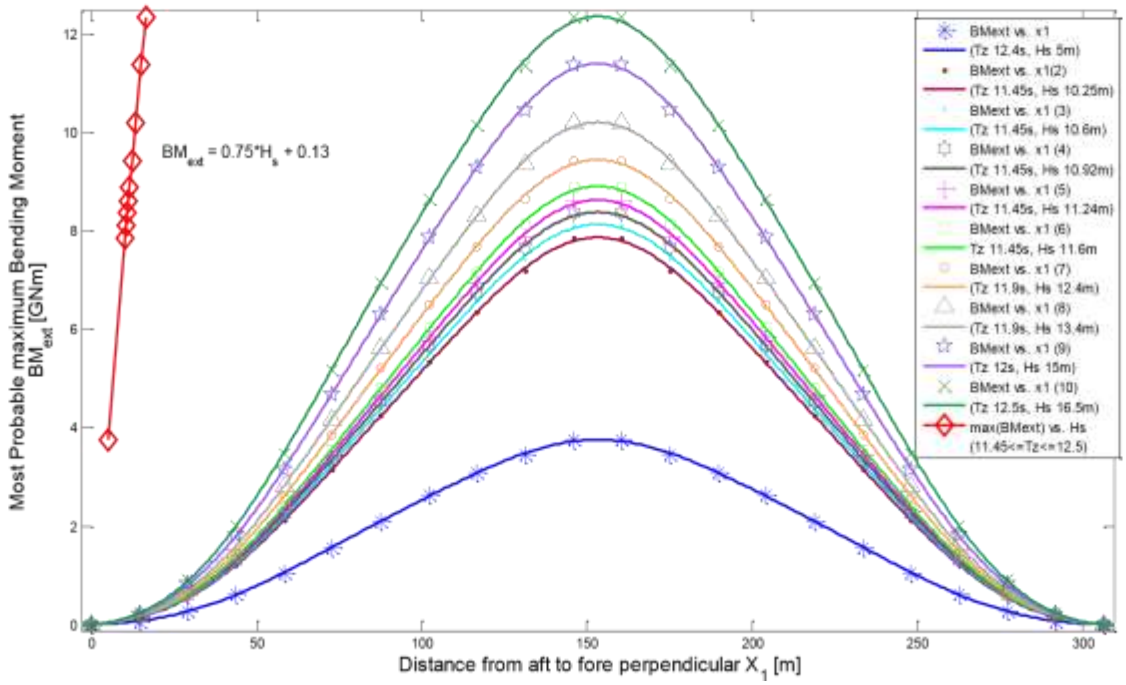


Figure 6.4: Most Probable Maximum Bending Moment Distribution for different Significant Wave Heights (or Sea States). Vessel Dimensions:
L=306.4m; B=56.7m; D_m=31.5m; D=22.1m)

Furthermore, it is interesting to note that the wave bending moment distribution follows a Fourier series (of preferably, the forth degree).

6.5.1 Prediction of Approximate Design Values of Wave Bending Moments

The prediction of the approximate design values of the wave bending moment distribution is a very important design aspect as it is considered in determining required hull girder strength. The most critical or extreme environmental condition is applied in evaluating this quantity. Here, we are considering the 100 year return period storm of the North Sea. The reason is to allow the vessel to be deployed anywhere around the globe since it has high safety factor. Classification societies such as the American Bureau of Shipping, ABS, The Lloyds Register, LR, Det Norske Veritas, DNV, among others, have suggested similar approximations which should serve as useful guides. Some important variables which influence the bending moments were not included in their approximations. These section attempts to predict the design bending moment distribution from the bow to astern using most of the relevant variables. This helps to figure out their relationship while increasing the accuracy and safety of the design.

To achieve the above goals and for simplicity, Eqn. (6.25) will be expressed as:

$$M_X = M_{X1}\sin(\omega t) + M_{X2}\cos(\omega t) \qquad (6.28)$$

$$M_X = \left({M_{X1}}^2 + {M_{X2}}^2\right)^{1/2}\sin(\beta + \omega t) \qquad (6.29)$$

$$M_X = M_{ax}\sin(\beta + \omega t) \qquad (6.30)$$

M_{ax} is the amplitude of M_X as a function of x. The distribution shows that it is maximum at amidships. Let $M_{a\otimes}$ be the amplitude of the bending moment amidships, that is, when $X = L/2$. The phase angle β is easily determined. It may also be approximately computed such that unwanted fluctuations in the dynamic distribution of the wave bending moments are eliminated.

Considering Eqns. (6.28), (6.29), and (6.30), the bending moment distribution M_X is the vector summation of the two components M_{X1} and M_{X2}. In order to curtail the unwanted fluctuations in the dynamic distribution of the wave bending moments, and to account for extreme effects of metocean conditions, the phase angle which is a function of the position X_1 from one end, is modified as shown below:

$$M_X = M_{ax} \sin(\beta + \omega t) \tag{6.31}$$

Where: $t = 0;\ \beta = k_1 X_1 = \frac{2\pi}{\lambda_1} X_1$

$$X_1: Distance\ from\ the\ bow\ to\ the\ stern$$

λ_1: *The most critical wavelength that causes maximum bending moment* λ_1 *is equal to* $2L$ (*approx.*) *such that the wave crest is located amidships.*

Hence: $\beta = \frac{\pi X_1}{L}$

Substituting these into Eqn. (6.31), the design bending moment distribution from say the bow to the stern part of the floating structure for the given sea state is obtained as:

$$M_X = f_{BM} \times M_{max} \tag{6.32}$$

Where: $M_{max} = \max(M_{ax}) = M_{a\otimes}$

Bending Moment distribution factor, $f_{BM} = sin\left(\frac{\pi X_1}{L}\right)$ (6.33)

In the same way, the shear force has been found to be:

$$Q_X = f_{SF} \times Q_{max} \qquad (6.34)$$

Where the shear force distribution factor, $f_{SF} = sin\left(\frac{2\pi X_1}{L}\right)$ (6.35)

6.5.2 Extreme Values of the Bending Moments

In order to estimate the extreme values of the wave induced bending moment, it is absolutely necessary to consider the effects of extreme wave conditions such as the North Sea, especially for FPSOs meant for global deployment. To evaluate the extreme value of BM acting at amidships, we will first and foremost obtain the variance of the bending moment response spectrum by integrating the bending moment response spectrum, that is, the product of the specified wave spectrum and square of the amplitude of bending moment at amidships (Eqn. 6.24) per unit wave amplitude from zero to infinity.

$$m_{\otimes} = \int_0^{\infty} S(\omega)\left(\frac{M_{a\otimes}}{\zeta_a}\right)^2 d\omega \qquad (6.36)$$

Therefore, the most probable extreme or maximum wave bending moment at amidships is given by:

$$BM_{ext} = 2 \times 1.86 \times \sqrt{m_{\otimes}} \qquad (6.37)$$

Figure 6.2 shows the effect of wavelength on the wave bending moment amidships per unit wave amplitude for the representative vessel (L, 306.4; B, 56.7; D_m, 31.5; and D, 22.1m). The results obtained from this analysis agree with the semi-empirical formulations of DNV and ABS for wave bending moments. See Figure D. 4.

Figure D. 5 shows the distributions of the design extreme wave bending moments for vessel designed for prevention of green water on deck and the effects of wave heights on the bending moment distribution. The results show that, for a given wave period, the induced wave bending moment is directly proportional to the wave height.

CHAPTER 7

7 SUSCEPTIBILITY OF FPSO TO GREEN WATER

7.1 Introduction

Green water is the flow of the unbroken waves which overtop the bow, side or even stern part of the deck of a ship or floating offshore structure. It depends on the relative motion between the vessel and the waves, freeboard, and the harshness or flow intensity of the wave. It occurs when the relative motion exceeds the freeboard.

Problems associated with green water which are directly related to the freeboard have remained unresolved by most of the available software, and fortunately, the method presented in this chapter will attempt to solve them. As most of the available software cannot account for the influence of freeboard which is an essential geometric characteristic responsible for deck wetness and water impact forces on deck equipment, it will be interesting to consider proffering solutions by implementing the formulae which correlate the wave loads, relative motion, size and dimensions in the coding of the programme for green water analysis (ProGreen).

Therefore, this study will analyse and discuss ways of addressing the challenges of the green water susceptibility of FPSOs and predict the required principal dimensions with respect to a given storage capacity for specified wave environment(s). One of the objectives of this research, and the primary focus in this chapter, is to determine the optimal principal dimensions of FPSO vessel necessary to prevent or mitigate these undesirable effects of green water.

The modified version of the Pierson-Moskowitz spectrum, Eqn. (3.54), remains the preferred spectrum. Also, for this green water susceptibility analysis, the vessel is assumed to be a rectangular-shaped FPSO with length L, Beam B and depth D_m, (which are evaluated based on the required storage capacity as given in chapter 5) and it is to be operated in the North Sea of 100-year Return Period storm; the zero up-crossing period and significant wave height are 17.5s and 16.5m respectively.

7.2 Preliminary Design Objectives or Constraints

The specification of the maximum permissible freeboard exceedance (denoted as e) is taken as the major design constraint in green water analyses. In addition to this, the preliminary design objectives given in section 1.4 are also considered and adopted for both the green water analysis and the determination of the optimal design of vessels which are to be operated in the harsh wave environment such as the North Sea.

7.3 Relative Motion

The wave profile and heave motion at any point, x are respectively given by expressions:

$$\zeta_a \sin(\omega t + kx) \text{ and } \eta_3 - x\eta_5$$

Therefore, the relative motion between wave and vessel at the bow is:

$$\eta_{3R} = \eta_3 - \frac{L}{2}\eta_5 - \zeta_a \sin\left(\omega t + \frac{kL}{2}\right)$$

$$= \eta_{3a}\sin(\omega t) - \frac{L\eta_{5a}}{2}\cos(\omega t) - \zeta_a \sin\left(\omega t + \frac{kL}{2}\right)$$

$$= \eta_{3a}\sin(\omega t) - \frac{L\eta_{5a}}{2}\cos(\omega t)$$

$$- \zeta_a\left[\sin(\omega t)\cos\left(\frac{kL}{2}\right) + \cos(\omega t)\sin\left(\frac{kL}{2}\right)\right]$$

$$= \left[\eta_{3a} - \zeta_a cos\left(\frac{kL}{2}\right)\right]\sin(\omega t) - \left[\frac{L\eta_{5a}}{2} + \zeta_a \sin\left(\frac{kL}{2}\right)\right]\cos(\omega t)$$

So, the amplitude of the relative motion between the bow and the wave is:

$$\eta_{3Ra} = \left\{ \left[\eta_{3a} - \zeta_a cos\left(\frac{kL}{2}\right) \right]^2 + \left[\frac{L\eta_{5a}}{2} + \zeta_a \sin\left(\frac{kL}{2}\right) \right]^2 \right\}^{1/2}$$

$$\frac{\eta_{3Ra}}{\zeta_a} = \left\{ \left[\frac{\eta_{3a}}{\zeta_a} - cos\left(\frac{kL}{2}\right) \right]^2 + \left[\frac{\eta_{5a}L}{2\zeta_a} + \sin\left(\frac{kL}{2}\right) \right]^2 \right\}^{1/2}$$

$$RAO_R = \left\{ \left[RA\acute{O}_3 - cos\left(\frac{kL}{2}\right) \right]^2 + \left[\frac{RA\acute{O}_5 L}{2} + \sin\left(\frac{kL}{2}\right) \right]^2 \right\}^{1/2} \qquad (7.1)$$

Where $RA\acute{O}_3 = \eta_{3a}/\zeta_a$ and $RA\acute{O}_5 = \eta_{5a}/\zeta_a$

The responses in regular waves are modified to account for the irregularities. Hence, for more realistic irregular waves, spectral analyses are adopted to obtain the most probable maximum responses. Let the most probable maximum amplitude of the relative motion be R. Consequently, the maximum allowable draught is required to be greater than this maximum relative motion ($D > R$) in order to prevent the bow from exiting the water (bow slamming). Furthermore, a minimum freeboard, equivalent to R is needed to avoid green water on the deck.

Since the maximum value is 1.86 times the significant value, therefore, the most probable maximum amplitude of the relative motion between the wave and the vessel at the bow is:

$$R = 1.86 \times 2\sqrt{\int_0^\infty (RAO_R)^2 S(\omega) d\omega} \qquad (7.2)$$

(Assuming about 1000 cycles of waves in 3 hours).

7.4 Freeboard Exceedance

Consider length-breadth ratios ranging from 4.5 to 5.8 and breadth-depth ratios ranging from 1.4 to 2.4, both with incremental steps of 0.1. This yields one hundred and fifty four (154) different designs of FPSO of a given storage capacity and efficiency, say 2 million barrels of oil and 58% respectively. Then, the most probable maximum heave, pitch, relative motions as well as the freeboard exceedance are computed using a very robust and efficient programme (ProGreen) written for this research. The freeboard exceedance is the difference between the most probable relative motion and the freeboard. For each of the vessels being analysed (for $i = 1\ to\ n$, where i represents each of the n, i.e. 154, vessels), it is given by:

$$E_i = R_i - (D_{mi} - D_i) = R_i - (1 - z_m)(\mathrm{a}_i \mathrm{b}_i)^{-1} \left(\frac{S_c}{C_f \times E_s} \right)^{\frac{1}{3}} \qquad (7.3)$$

Where the factors are: $\mathrm{a} = [x_b{}^2 \times y_d]^{1/3}$; $b = [y_d/x_b]^{1/3}$; $z_m = \nabla / C_n$.

These analyses are integrated in one computer program called the ProGreen. The ProGreen is a program which utilizes this method to effectively determine the susceptibility of various designs of FPSOs to green water. All the designs and analyses of the various FPSOs for a specified storage capacity are carried out and the freeboard exceedances are computed. The optimal design is then selected. Optimal design here implies the best principal dimensions of the vessel with the lowest responses as well as satisfying the imposed constraints. The main constraint for the green water analysis is the predetermined maximum allowable freeboard exceedance, e and it is given by:

$$e \leq E \tag{7.4}$$

Where E is the most probable maximum freeboard exceedance for each vessel.

The green water loads (with the inherent nonlinearity) on the superstructures are not considered in this Chapter. Only its freeboard exceedance is evaluated from the relative motion RAO based on linear assumption and spectral analysis. The most probable maximum freeboard exceedance depends on the relative motion and freeboard only.

7.5 Optimal Design using ProGreen

To determine the optimal design point, the programme allows us to efficiently compute all the required response characteristics and parameters, compare their corresponding freeboard exceedances with the maximum permissible and the display the best (optimal dimensions). The optimal design is obtained when the maximum green water permissible criterion (eqn. 8.4) is met with minimum heave and pitch motions.

$$L_o, B_o, D_{mo}, D_o = L_a, B_a, D_{ma}, D_a(\eta_{3max} \equiv \min(\eta_{3max})) \tag{7.5}$$

Where the subscript, 'o' represents "optimal design" of the ProGreen.

Figure 7.1 and Figure 7.2 show the heave and pitch response amplitudes per unit wave amplitudes, and relative motions response amplitude operators with increasing B/D_m and L/B respectively. As the B/D_m and L/B ratios increase, the peaks of the pitching and relative motions shift rightwards (on the graph of RAOs) approaching the critical wavelength (i.e. when $\frac{L}{\lambda}$ tends to unity). At the critical wavelength, the pitch motion is high compared to the heave motion, and the vessel is likely going to experience high wave bending moment.

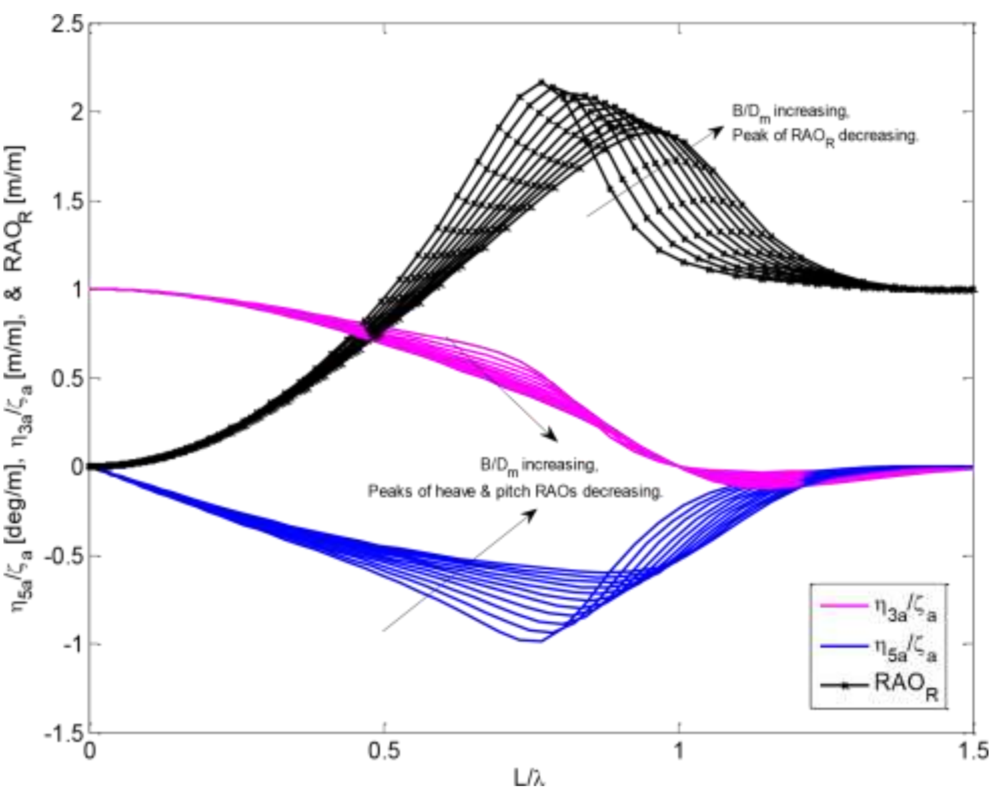


Figure 7.1: The Relative Motion Response Amplitude Operators, Heave and Pitch amplitudes per unit wave amplitudes for various B/D_m Ratios and constant L/B ratio (L/B=5.4 was used in this case)

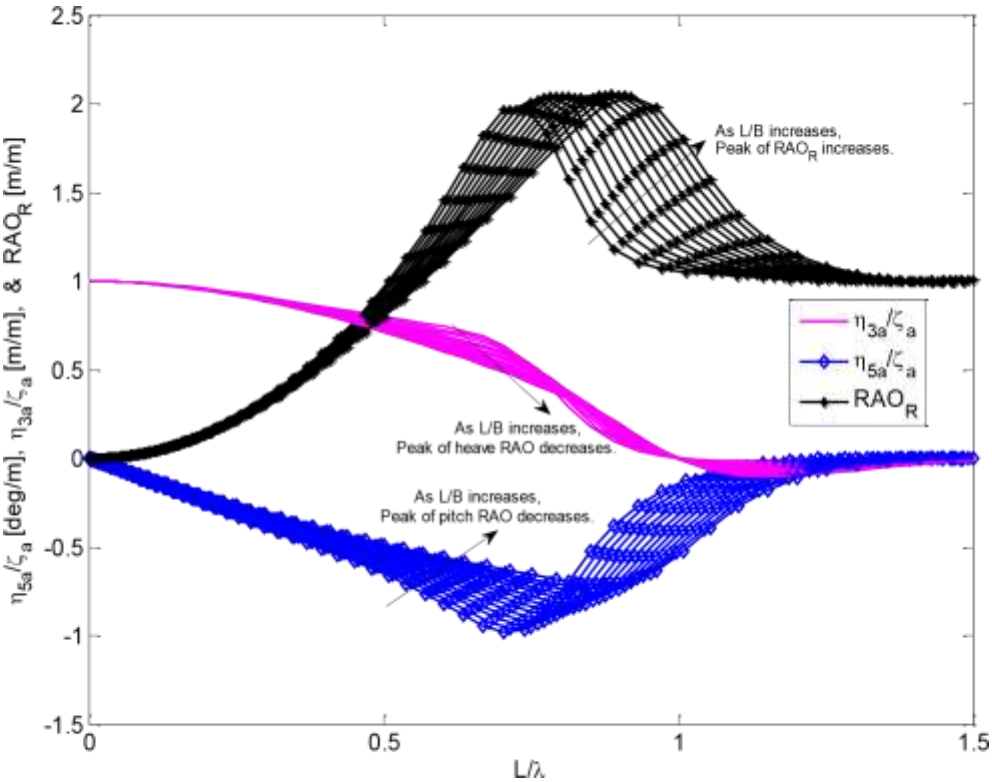


Figure 7.2: The Relative Motion Response Amplitude Operators, Heave and Pitch amplitudes per unit wave amplitudes for various L/B Ratios and constant B/D_m ratio (B/D_m =1.8 was used in this case)

As the B/D_m (and hence the "b" of Eqn. (7.3) increases, the peak of the RAO_R decreases (Figure 7.1). Conversely, as L/B (and hence the "a" of Eqn. (7.3) increases, the peak of the RAO_R also increases. In both cases, the freeboard exceedances increase (see Figure 7.4 and Figure 7.6).

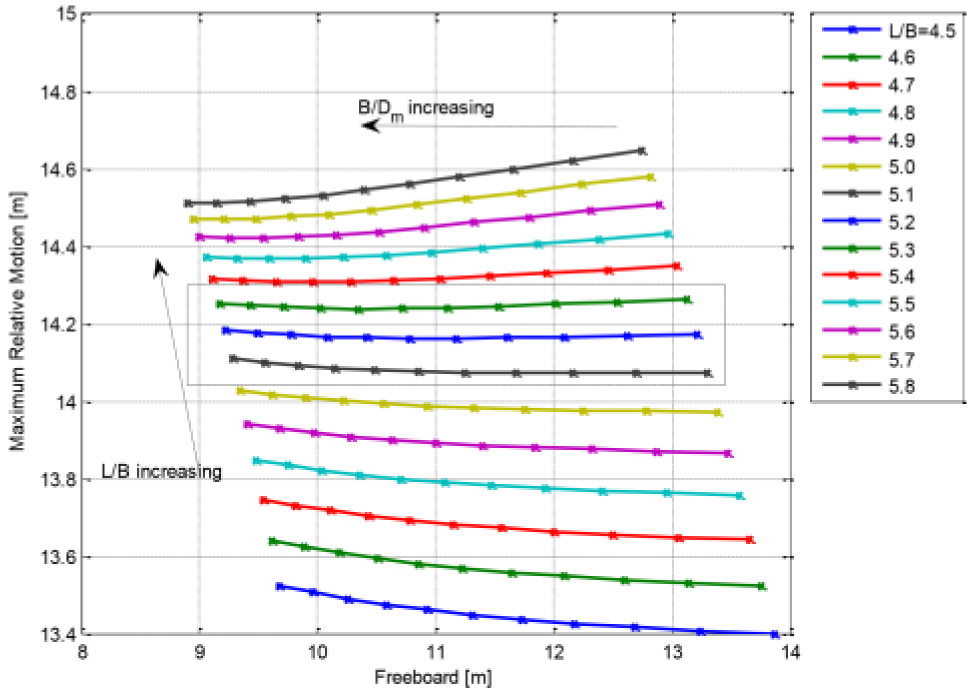


Figure 7.3: Effects of Freeboard on the Most Probable Maximum Relative Motion for given L/B

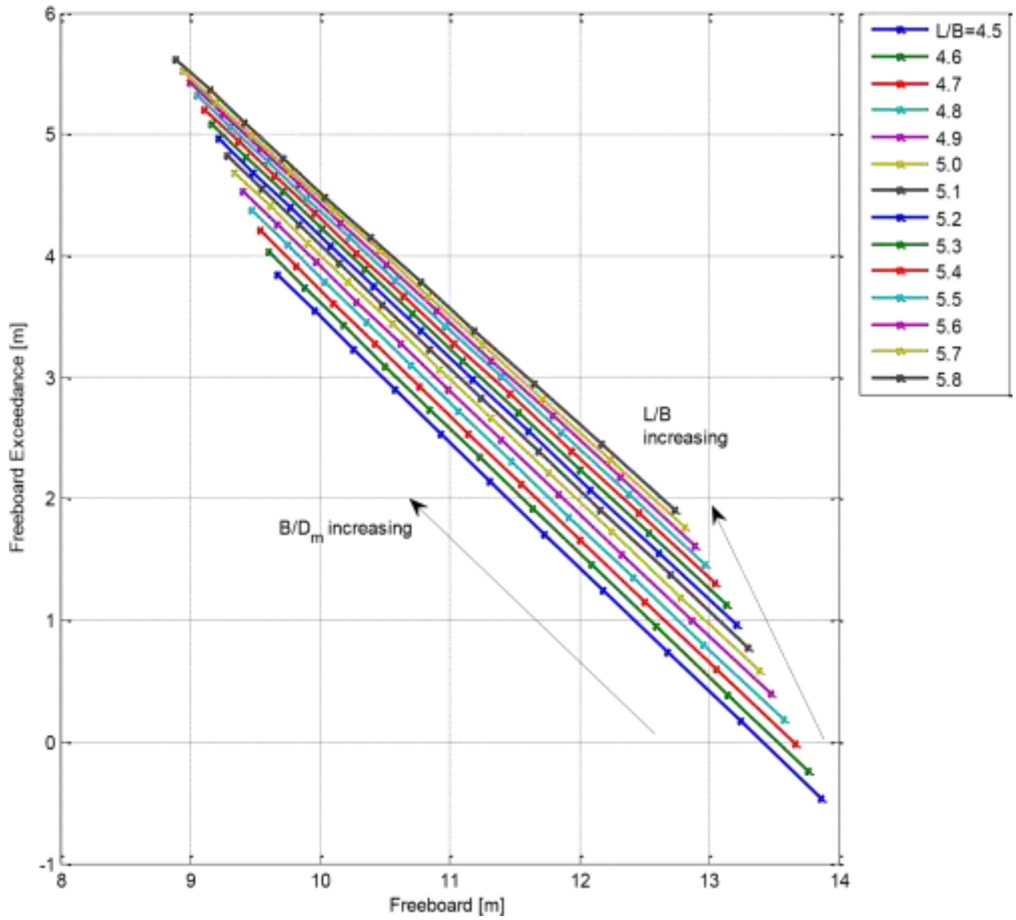


Figure 7.4: Effects of Freeboard on the Exceedance for given L/B

Figure 7.3 and Figure 7.4 show the variations of the most probable maximum relative motion R, (between the bow and the wave) and the exceedance with freeboard for given L/B ratios (ranging from 4.5 to 5.8). For L/B ratios of 5.1, 5.2 and 5.3, R flattens out and nearly remains
constant for all values of B/D_m.

The B/D_m has greater influence on the freeboard. The freeboard decreases more rapidly with increase in B/D_m (See Figure 7.3 and Figure 7.4), and slowly with increase in L/B (See Figures Figure 7.4 and Figure 7.5).

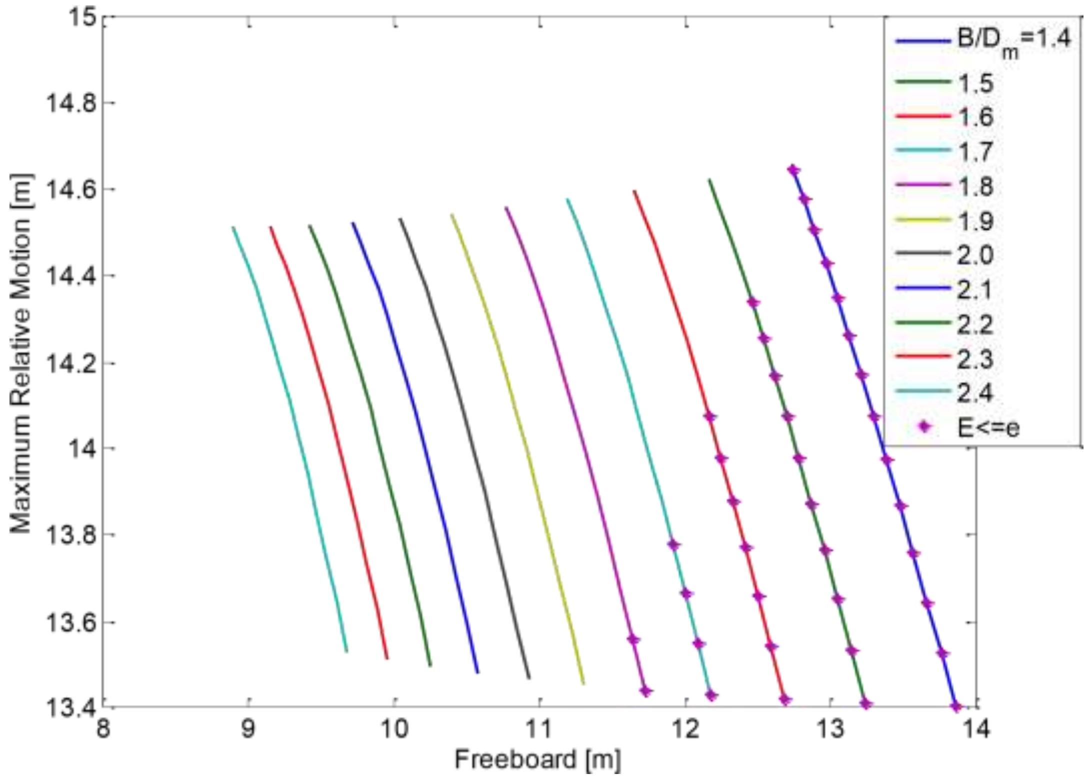


Figure 7.5: Effects of Freeboard on the Most Probable Maximum Relative Motion for given B/D_m ratios. The vessels that satisfy the maximum permissible green water exceedance, e = 2m are shown (with the magenta asterisk)

Generally, the exceedance is directly proportional to the pitch, heave and relative motions but inversely proportional to the freeboard. So, in order to minimize the vulnerability of the vessel to green water, the exceedance must be low enough, and to avoid it, the exceedance must be less or equal to zero, i.e. the maximum permissible should be set at zero.

$L_a, B_a, D_{ma}, D_a = L, B, D_m, D(E_i \leq e) \qquad i.e. \quad e = 0$ (7.6) Where the subscript, 'a' represents "avoidance of green water".

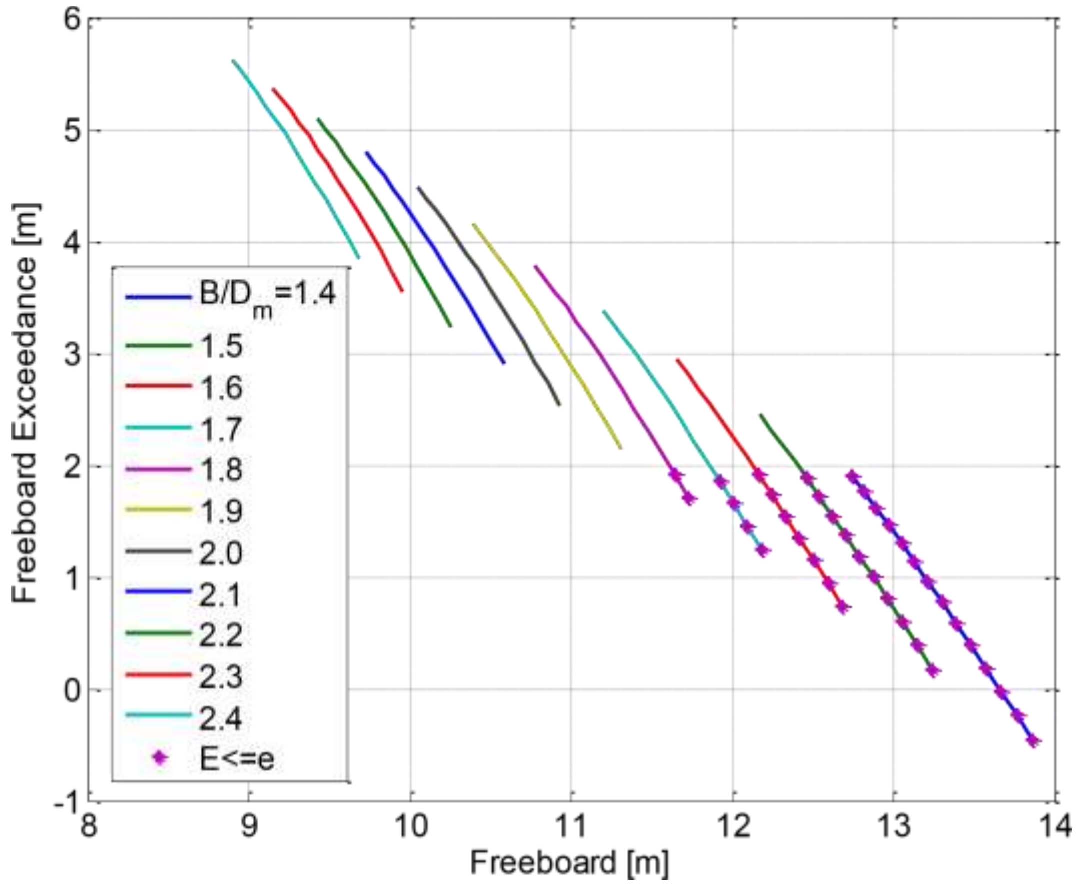


Figure 7.6: Effects of Freeboard on the Exceedance for given B/D_m

In this study, 154 vessels have been analysed as described above (using the ProGreen). The optimal design of FPSO of 2Mbbls of storage capacity for the North Sea has been determined as shown in Table 7.1 and Table 7.2. However, if a different design is preferably selected due to other factors, then the process deck should be raised to account for the estimated freeboard exceedance. In Figure 7.4 for instance, the FPSO with L/B of 5.4, and B/D_m of 1.6 has a freeboard of 11.5m and exceedance of 2.4m. Therefore, the topside/process deck is required to be raised 2.4m above the main deck.

Table 7.1: Green Water Susceptibility of 2Mbbl oil storage capacity FPSOs in 100 Return Period Storm of the North Sea

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [deg]	η_5 [m]	R >0	$D-R$ [s]	T$_{n3,5}$ [m]	E
1	4.5	1.4	249.6	55.5	39.6	25.7	13.9	13.1	8.6	13.4	12.3	15.3	-0.5
2	4.5	1.5	255.4	56.7	37.8	24.6	13.2	12.9	8.3	13.4	11.2	15.2	0.2
3	4.5	1.6	260.9	58.0	36.2	23.6	12.7	12.6	8.1	13.4	10.1	15.1	0.7
4	4.5	1.7	266.2	59.2	34.8	22.6	12.2	12.4	8.0	13.4	9.2	15.1	1.2
5	4.5	1.8	271.4	60.3	33.5	21.8	11.7	12.2	7.8	13.4	8.3	15.0	1.7
6	4.5	1.9	276.3	61.4	32.3	21.0	11.3	12.0	7.6	13.5	7.6	15.0	2.1
7	4.5	2	281.1	62.5	31.2	20.3	10.9	11.9	7.5	13.5	6.8	14.9	2.5
8	4.5	2.1	285.7	63.5	30.2	19.6	10.6	11.7	7.3	13.5	6.2	14.9	2.9
9	4.5	2.2	290.1	64.5	29.3	19.0	10.3	11.6	7.2	13.5	5.6	14.8	3.2
10	4.5	2.3	294.5	65.4	28.5	18.5	10.0	11.4	7.0	13.5	5.0	14.8	3.6
11	4.5	2.4	298.7	66.4	27.7	18.0	9.7	11.3	6.9	13.5	4.4	14.8	3.8
12	4.6	1.4	253.2	55.1	39.3	25.6	13.8	13.0	8.5	13.5	12.0	15.3	-0.2
13	4.6	1.5	259.1	56.3	37.6	24.4	13.1	12.7	8.3	13.5	10.9	15.2	0.4
14	4.61.6	264.8	57.6	36.0	23.4	12.6	12.5	8.1	13.5	9.8	15.1	1.0	
15	4.61.7	270.2	58.7	34.5	22.5	12.1	12.3	7.9	13.6	8.9	15.0	1.5	
16	4.61.8	275.4	59.9	33.3	21.6	11.6	12.1	7.7	13.6	8.1	15.0	1.9	
17	4.61.9	280.4	61.0	32.1	20.9	11.2	11.9	7.5	13.6	7.3	14.9	2.3	

18	4.62	285.2	62.0	31.0	20.2	10.9	11.7	7.4	13.6	6.6	14.9	2.7	
19	4.62.1	289.9	63.0	30.0	19.5	10.5	11.6	7.2	13.6	5.9	14.8	3.1	
20	4.62.2	294.4	64.0	29.1	18.9	10.2	11.4	7.1	13.6	5.3	14.8	3.4	
21	4.62.3	298.8	65.0	28.2	18.4	9.9	11.3	7.0	13.6	4.7	14.7	3.7	
22	4.6	2.4	303.1	65.9	27.5	17.8	9.6	11.2	6.8	13.6	4.2	14.7	4.0
23	4.7	1.4	256.9	54.7	39.0	25.4	13.7	12.9	8.4	13.6	11.7	15.2	0.0
24	4.7	1.5	262.9	55.9	37.3	24.2	13.1	12.6	8.2	13.7	10.6	15.1	0.6
25	4.7	1.6	268.6	57.1	35.7	23.2	12.5	12.4	8.0	13.7	9.6	15.0	1.2
26	4.7	1.7	274.1	58.3	34.3	22.3	12.0	12.2	7.8	13.7	8.6	15.0	1.7
27	4.7	1.8	279.3	59.4	33.0	21.5	11.6	12.0	7.6	13.7	7.8	14.9	2.1
28	4.7	1.9	284.4	60.5	31.9	20.7	11.1	11.8	7.4	13.7	7.0	14.8	2.5
29	4.7	2	289.3	61.6	30.8	20.0	10.8	11.6	7.3	13.7	6.3	14.8	2.9
30	4.7	2.1	294.1	62.6	29.8	19.4	10.4	11.5	7.1	13.7	5.7	14.8	3.3
31	4.7	2.2	298.7	63.5	28.9	18.8	10.1	11.3	7.0	13.7	5.1	14.7	3.6
32	4.7	2.3	303.1	64.5	28.0	18.2	9.8	11.2	6.9	13.7	4.5	14.7	3.9
33	4.7	2.4	307.5	65.4	27.3	17.7	9.5	11.1	6.7	13.8	4.0	14.7	4.2
34	4.8	1.4	260.5	54.3	38.8	25.2	13.6	12.7	8.3	13.8	11.4	15.2	0.2
35	4.8	1.5	266.6	55.5	37.0	24.1	13.0	12.5	8.1	13.8	10.3	15.1	0.8
36	4.8	1.6	272.4	56.7	35.5	23.1	12.4	12.2	7.9	13.8	9.3	15.0	1.4
37	4.8	1.7	277.9	57.9	34.1	22.1	11.9	12.0	7.7	13.8	8.4	14.9	1.9
38	4.8	1.8	283.3	59.0	32.8	21.3	11.5	11.8	7.5	13.8	7.5	14.9	2.3
39	4.8	1.9	288.4	60.1	31.6	20.6	11.1	11.7	7.3	13.8	6.8	14.8	2.7
40	4.8	2	293.4	61.1	30.6	19.9	10.7	11.5	7.2	13.8	6.1	14.7	3.1
41	4.8	2.1	298.2	62.1	29.6	19.2	10.4	11.3	7.0	13.8	5.4	14.7	3.5
42	4.8	2.2	302.9	63.1	28.7	18.6	10.0	11.2	6.9	13.8	4.8	14.7	3.8
43	4.8	2.3	307.4	64.0	27.8	18.1	9.7	11.1	6.8	13.8	4.3	14.6	4.1
44	4.8	2.4	311.8	65.0	27.1	17.6	9.5	10.9	6.6	13.9	3.7	14.6	4.4
45	4.9	1.4	264.1	53.9	38.5	25.0	13.5	12.6	8.2	13.9	11.2	15.1	0.4
46	4.9	1.5	270.3	55.2	36.8	23.9	12.9	12.3	8.0	13.9	10.0	15.0	1.0
47	4.9	1.6	276.2	56.4	35.2	22.9	12.3	12.1	7.8	13.9	9.0	14.9	1.5
48	4.9	1.7	281.8	57.5	33.8	22.0	11.8	11.9	7.6	13.9	8.1	14.9	2.0
49	4.9	1.8	287.2	58.6	32.6	21.2	11.4	11.7	7.4	13.9	7.3	14.8	2.5
50	4.9	1.9	292.4	59.7	31.4	20.4	11.0	11.5	7.3	13.9	6.5	14.7	2.9
51	4.9	2	297.5	60.7	30.4	19.7	10.6	11.4	7.1	13.9	5.8	14.7	3.3
52	4.9	2.1	302.4	61.7	29.4	19.1	10.3	11.2	6.9	13.9	5.2	14.7	3.6
53	4.9	2.2	307.1	62.7	28.5	18.5	10.0	11.1	6.8	13.9	4.6	14.6	4.0
54	4.9	2.3	311.7	63.6	27.7	18.0	9.7	11.0	6.7	13.9	4.0	14.6	4.3
55	4.92.4	316.1	64.5	26.9	17.5	9.4	10.8	6.6	13.9	3.5	14.6	4.5	
56	5 1.4	267.7	53.5	38.2	24.9	13.4	12.5	8.1	14.0	10.9	15.1	0.6 57	5
	1.5	273.9	54.8	36.5	23.7	12.8	12.2	7.9	14.0	9.8	15.0	1.2	
58	5 1.6	279.9	56.0	35.0	22.7	12.2	12.0	7.7	14.0	8.8	14.9	1.7	

59	5 1.7	285.6	57.1	33.6	21.8	11.8	11.8	7.5	14.0	7.9	14.8	2.2	
60	5 1.8	291.1	58.2	32.3	21.0	11.3	11.6	7.3	14.0	7.0	14.7	2.7	
61	5 1.9	296.4	59.3	31.2	20.3	10.9	11.4	7.2	14.0	6.3	14.7	3.1	
62	5 2	301.5	60.3	30.2	19.6	10.6	11.3	7.0	14.0	5.6	14.6	3.4	
63	5 2.1	306.5	61.3	29.2	19.0	10.2	11.1	6.9	14.0	5.0	14.6	3.8	
64	5 2.2	311.2	62.2	28.3	18.4	9.9	11.0	6.7	14.0	4.4	14.6	4.1	
65	5 2.3	315.9	63.2	27.5	17.9	9.6	10.9	6.6	14.0	3.8	14.5	4.4	
66	5 2.4	320.4	64.1	26.7	17.4	9.3	10.7	6.5	14.0	3.3	14.5	4.7	
67	5.1	1.4	271.3	53.2	38.0	24.7	13.3	12.4	8.1	14.1	10.6	15.0	0.8
68	5.1	1.5	277.6	54.4	36.3	23.6	12.7	12.1	7.8	14.1	9.5	14.9	1.4
69	5.1	1.6	283.6	55.6	34.8	22.6	12.2	11.9	7.6	14.1	8.5	14.8	1.9
70	5.1	1.7	289.4	56.7	33.4	21.7	11.7	11.7	7.4	14.1	7.6	14.8	2.4
71	5.1	1.8	295.0	57.8	32.1	20.9	11.2	11.5	7.2	14.1	6.8	14.7	2.8
72	5.1	1.9	300.3	58.9	31.0	20.1	10.8	11.3	7.1	14.1	6.1	14.6	3.2
73	5.1	2	305.5	59.9	30.0	19.5	10.5	11.2	6.9	14.1	5.4	14.6	3.6
74	5.1	2.1	310.5	60.9	29.0	18.8	10.1	11.0	6.8	14.1	4.8	14.6	3.9
75	5.1	2.2	315.4	61.8	28.1	18.3	9.8	10.9	6.6	14.1	4.2	14.5	4.3
76	5.1	2.3	320.1	62.8	27.3	17.7	9.6	10.7	6.5	14.1	3.6	14.5	4.6
77	5.1	2.4	324.7	63.7	26.5	17.2	9.3	10.6	6.4	14.1	3.1	14.5	4.8
78	5.2	1.4	274.8	52.8	37.7	24.5	13.2	12.2	8.0	14.2	10.4	15.0	1.0
79	5.2	1.5	281.2	54.1	36.1	23.4	12.6	12.0	7.7	14.2	9.3	14.9	1.6
80	5.2	1.6	287.3	55.3	34.5	22.4	12.1	11.8	7.5	14.2	8.3	14.8	2.1
81	5.2	1.7	293.2	56.4	33.2	21.6	11.6	11.6	7.3	14.2	7.4	14.7	2.6
82	5.2	1.8	298.8	57.5	31.9	20.8	11.2	11.4	7.2	14.2	6.6	14.7	3.0
83	5.2	1.9	304.3	58.5	30.8	20.0	10.8	11.2	7.0	14.2	5.9	14.6	3.4
84	5.2	2	309.5	59.5	29.8	19.3	10.4	11.1	6.8	14.2	5.2	14.6	3.7
85	5.2	2.1	314.6	60.5	28.8	18.7	10.1	10.9	6.7	14.2	4.6	14.5	4.1
86	5.2	2.2	319.5	61.4	27.9	18.2	9.8	10.8	6.5	14.2	4.0	14.5	4.4
87	5.2	2.3	324.3	62.4	27.1	17.6	9.5	10.6	6.4	14.2	3.4	14.4	4.7
88	5.2	2.4	328.9	63.2	26.4	17.1	9.2	10.5	6.3	14.2	2.9	14.4	5.0
89	5.3	1.4	278.3	52.5	37.5	24.4	13.1	12.1	7.9	14.3	10.1	14.9	1.1
90	5.3	1.5	284.8	53.7	35.8	23.3	12.5	11.9	7.7	14.3	9.0	14.8	1.7
91	5.3	1.6	291.0	54.9	34.3	22.3	12.0	11.7	7.4	14.3	8.1	14.7	2.2
92	5.3	1.7	296.9	56.0	33.0	21.4	11.5	11.5	7.2	14.2	7.2	14.7	2.7
93	5.3	1.8	302.6	57.1	31.7	20.6	11.1	11.3	7.1	14.2	6.4	14.6	3.1
94	5.3	1.9	308.1	58.1	30.6	19.9	10.7	11.1	6.9	14.2	5.6	14.6	3.5
95	5.3	2	313.5	59.1	29.6	19.2	10.4	10.9	6.7	14.2	5.0	14.5	3.9
96	5.3	2.1	318.6	60.1	28.6	18.6	10.0	10.8	6.6	14.2	4.4	14.5	4.2
97	5.3	2.2	323.6	61.1	27.8	18.0	9.7	10.7	6.5	14.2	3.8	14.4	4.5 98
	5.3	2.3	328.4	62.0	26.9	17.5	9.4	10.5	6.3	14.2	3.3	14.4	4.8

99	5.32.4	333.1	62.8	26.2	17.0	9.2	10.4	6.2	14.3	2.8	14.4	5.1	
100	5.41.4	281.8	52.2	37.3	24.2	13.0	12.0	7.8	14.4	9.9	14.9	1.3	
101	5.41.5	288.4	53.4	35.6	23.1	12.5	11.8	7.6	14.3	8.8	14.8	1.9	
102	5.41.6	294.6	54.6	34.1	22.2	11.9	11.5	7.4	14.3	7.8	14.7	2.4	
103	5.41.7	300.7	55.7	32.8	21.3	11.5	11.3	7.2	14.3	7.0	14.6	2.9	
104	5.4	1.8	306.4	56.7	31.5	20.5	11.0	11.2	7.0	14.3	6.2	14.6	3.3
105	5.4	1.9	312.0	57.8	30.4	19.8	10.6	11.0	6.8	14.3	5.5	14.5	3.7
106	5.4	2	317.4	58.8	29.4	19.1	10.3	10.8	6.6	14.3	4.8	14.5	4.0
107	5.4	2.1	322.6	59.7	28.4	18.5	10.0	10.7	6.5	14.3	4.2	14.4	4.4
108	5.4	2.2	327.6	60.7	27.6	17.9	9.7	10.6	6.4	14.3	3.6	14.4	4.7
109	5.4	2.3	332.5	61.6	26.8	17.4	9.4	10.4	6.2	14.3	3.1	14.3	4.9
110	5.4	2.4	337.3	62.5	26.0	16.9	9.1	10.3	6.1	14.3	2.6	14.3	5.2
111	5.5	1.4	285.3	51.9	37.0	24.1	13.0	11.9	7.7	14.4	9.7	14.8	1.5
112	5.5	1.5	291.9	53.1	35.4	23.0	12.4	11.7	7.5	14.4	8.6	14.7	2.0
113	5.5	1.6	298.3	54.2	33.9	22.0	11.9	11.4	7.3	14.4	7.6	14.6	2.5
114	5.5	1.7	304.4	55.3	32.6	21.2	11.4	11.2	7.1	14.4	6.8	14.6	3.0
115	5.5	1.8	310.2	56.4	31.3	20.4	11.0	11.1	6.9	14.4	6.0	14.5	3.4
116	5.5	1.9	315.9	57.4	30.2	19.6	10.6	10.9	6.7	14.4	5.3	14.5	3.8
117	5.5	2	321.3	58.4	29.2	19.0	10.2	10.7	6.6	14.4	4.6	14.4	4.1
118	5.5	2.1	326.6	59.4	28.3	18.4	9.9	10.6	6.4	14.4	4.0	14.4	4.5
119	5.5	2.2	331.7	60.3	27.4	17.8	9.6	10.5	6.3	14.4	3.4	14.3	4.8
120	5.5	2.3	336.6	61.2	26.6	17.3	9.3	10.4	6.2	14.4	2.9	14.3	5.1
121	5.5	2.4	341.4	62.1	25.9	16.8	9.1	10.2	6.0	14.4	2.4	14.3	5.3
122	5.6	1.4	288.7	51.6	36.8	23.9	12.9	11.8	7.6	14.5	9.4	14.8	1.6
123	5.6	1.5	295.4	52.8	35.2	22.9	12.3	11.5	7.4	14.5	8.4	14.7	2.2
124	5.6	1.6	301.9	53.9	33.7	21.9	11.8	11.3	7.2	14.5	7.4	14.6	2.7
125	5.6	1.7	308.0	55.0	32.4	21.0	11.3	11.1	7.0	14.5	6.6	14.5	3.1
126	5.6	1.8	314.0	56.1	31.1	20.2	10.9	11.0	6.8	14.4	5.8	14.5	3.5
127	5.6	1.9	319.7	57.1	30.0	19.5	10.5	10.8	6.6	14.4	5.1	14.4	3.9
128	5.6	2	325.2	58.1	29.0	18.9	10.2	10.7	6.5	14.4	4.4	14.4	4.3
129	5.6	2.1	330.5	59.0	28.1	18.3	9.8	10.5	6.3	14.4	3.8	14.3	4.6
130	5.6	2.2	335.7	59.9	27.2	17.7	9.5	10.4	6.2	14.4	3.3	14.3	4.9
131	5.6	2.3	340.7	60.8	26.5	17.2	9.3	10.3	6.1	14.4	2.8	14.3	5.2
132	5.6	2.4	345.6	61.7	25.7	16.7	9.0	10.1	6.0	14.4	2.3	14.2	5.4
133	5.7	1.4	292.2	51.3	36.6	23.8	12.8	11.7	7.5	14.6	9.2	14.7	1.8
134	5.7	1.5	299.0	52.4	35.0	22.7	12.2	11.4	7.3	14.6	8.2	14.6	2.3
135	5.7	1.6	305.5	53.6	33.5	21.8	11.7	11.2	7.1	14.5	7.2	14.6	2.8
136	5.7	1.7	311.7	54.7	32.2	20.9	11.3	11.0	6.9	14.5	6.4	14.5	3.3
137	5.71.8	317.7	55.7	31.0	20.1	10.8	10.9	6.7	14.5	5.6	14.4	3.7	

138	5.71.9	323.5	56.7	29.9	19.4	10.5	10.7	6.5	14.5	4.9	14.4	4.0 139	5.7
	2	329.0	57.7	28.9	18.8	10.1	10.6	6.4	14.5	4.3	14.3	4.4	
140	5.72.1	334.4	58.7	27.9	18.2	9.8	10.4	6.2	14.5	3.7	14.3	4.7	
141	5.72.2	339.7	59.6	27.1	17.6	9.5	10.3	6.1	14.5	3.1	14.3	5.0	
142	5.72.3	344.7	60.5	26.3	17.1	9.2	10.2	6.0	14.5	2.6	14.2	5.3	
143	5.72.4	349.7	61.3	25.6	16.6	8.9	10.1	5.9	14.5	2.1	14.2	5.5	
144	5.81.4	295.6	51.0	36.4	23.7	12.7	11.6	7.4	14.6	9.0	14.7	1.9	
145	5.8	1.5	302.4	52.1	34.8	22.6	12.2	11.3	7.2	14.6	8.0	14.6	2.5
146	5.8	1.6	309.0	53.3	33.3	21.6	11.7	11.1	7.0	14.6	7.0	14.5	2.9
147	5.8	1.7	315.3	54.4	32.0	20.8	11.2	10.9	6.8	14.6	6.2	14.5	3.4
148	5.8	1.8	321.4	55.4	30.8	20.0	10.8	10.8	6.6	14.6	5.4	14.4	3.8
149	5.8	1.9	327.2	56.4	29.7	19.3	10.4	10.6	6.5	14.5	4.8	14.3	4.2
150	5.8	2	332.9	57.4	28.7	18.7	10.0	10.5	6.3	14.5	4.1	14.3	4.5
151	5.8	2.1	338.3	58.3	27.8	18.1	9.7	10.3	6.2	14.5	3.5	14.2	4.8
152	5.8	2.2	343.6	59.2	26.9	17.5	9.4	10.2	6.0	14.5	3.0	14.2	5.1
153	5.8	2.3	348.8	60.1	26.1	17.0	9.2	10.1	5.9	14.5	2.5	14.2	5.4
154	5.8	2.4	353.7	61.0	25.4	16.5	8.9	10.0	5.8	14.5	2.0	14.1	5.6

Where: The green water constraint is $F_B - R \geq 0$

Slamming constraint is D-R>0

F_B: Freeboard

Table 7.2: Optimal Design for 365.3kton FPSO for 100 year return period storm of the North Sea using ProGreen (given a maximum permissible freeboard exceedance of zero)

L_o [m]	B_o [m]	D_{mo} [m]	D_o [m]
256.9	54.7	39.0	25.4

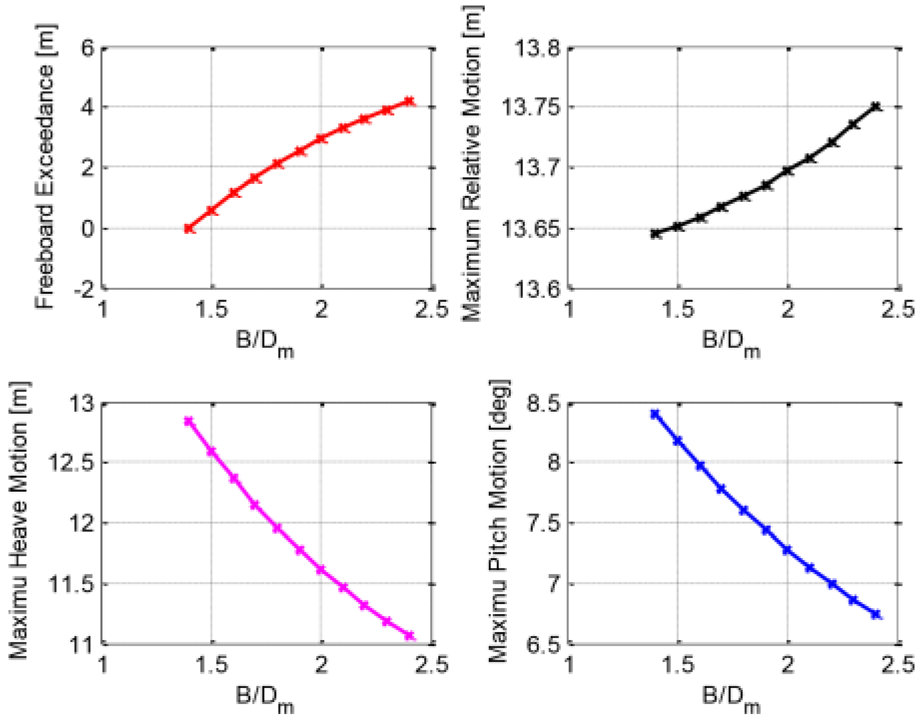


Figure 7.7: The most probable maximum Freeboard Exceedance, Relative Motion, Heave and Pitch Amplitudes for various breadth-depth Ratios and constant L/B ratio of 4.7.

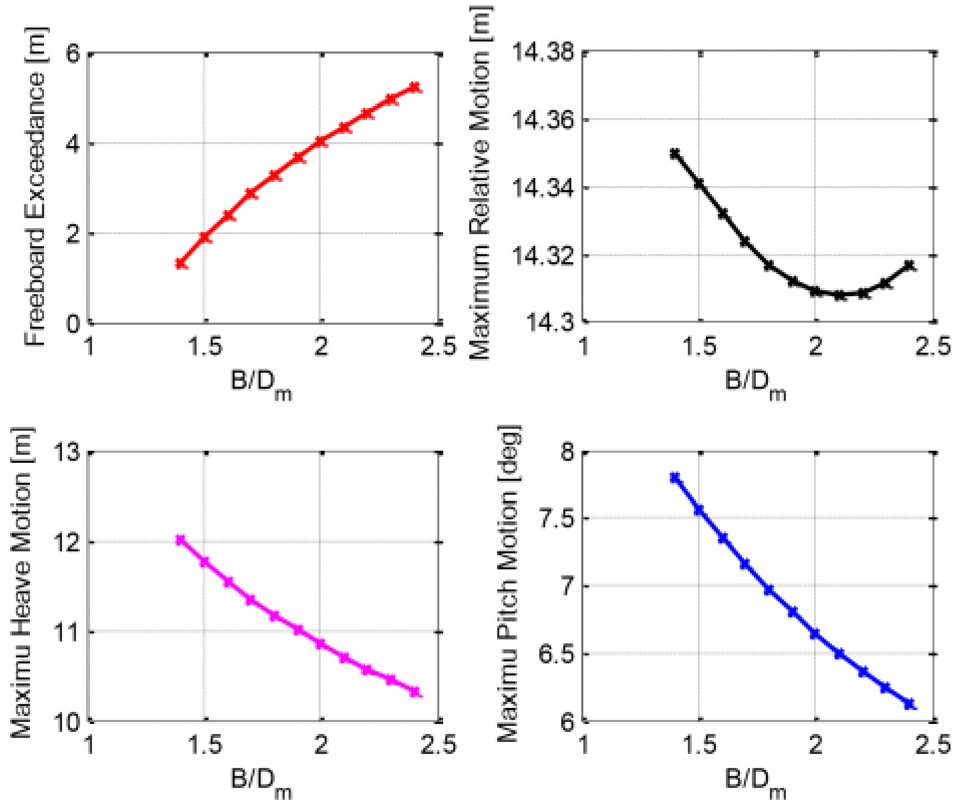


Figure 7.8: The most probable maximum Freeboard Exceedance, Relative Motion, Heave and Pitch Amplitudes for various breadth-depth Ratios, (at constant L/B ratio of 5.4)

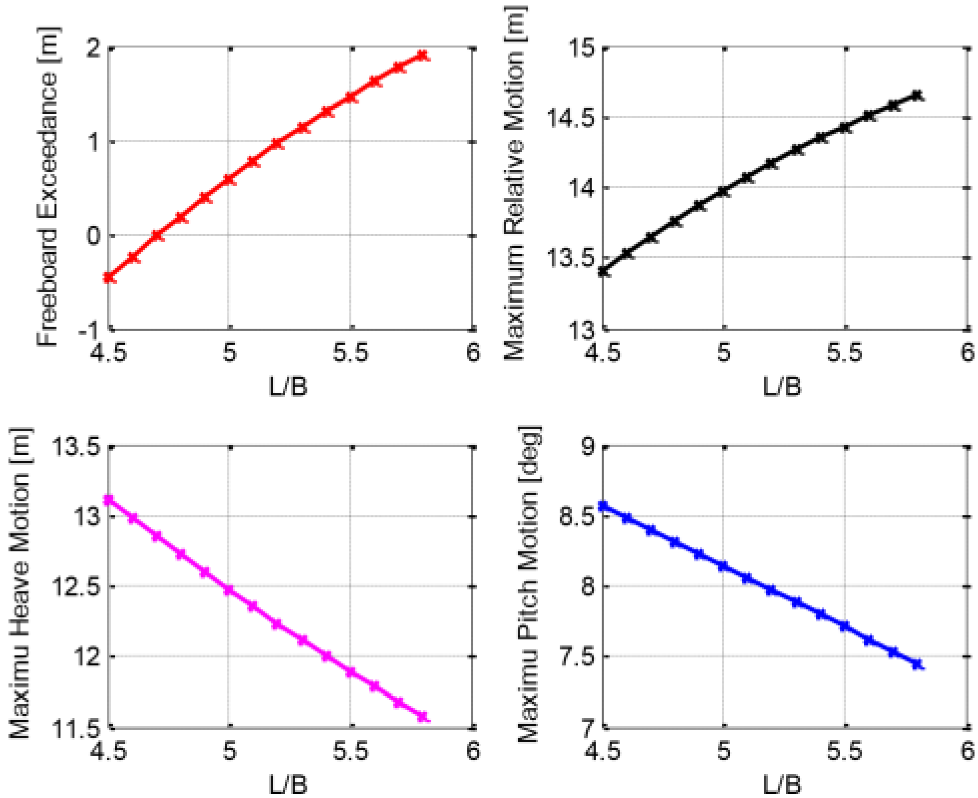


Figure 7.9: The most probable maximum Freeboard Exceedance, Relative Motion, Heave and Pitch Amplitudes for various L/B Ratios and constant breadth-depth ratio of 1.4.

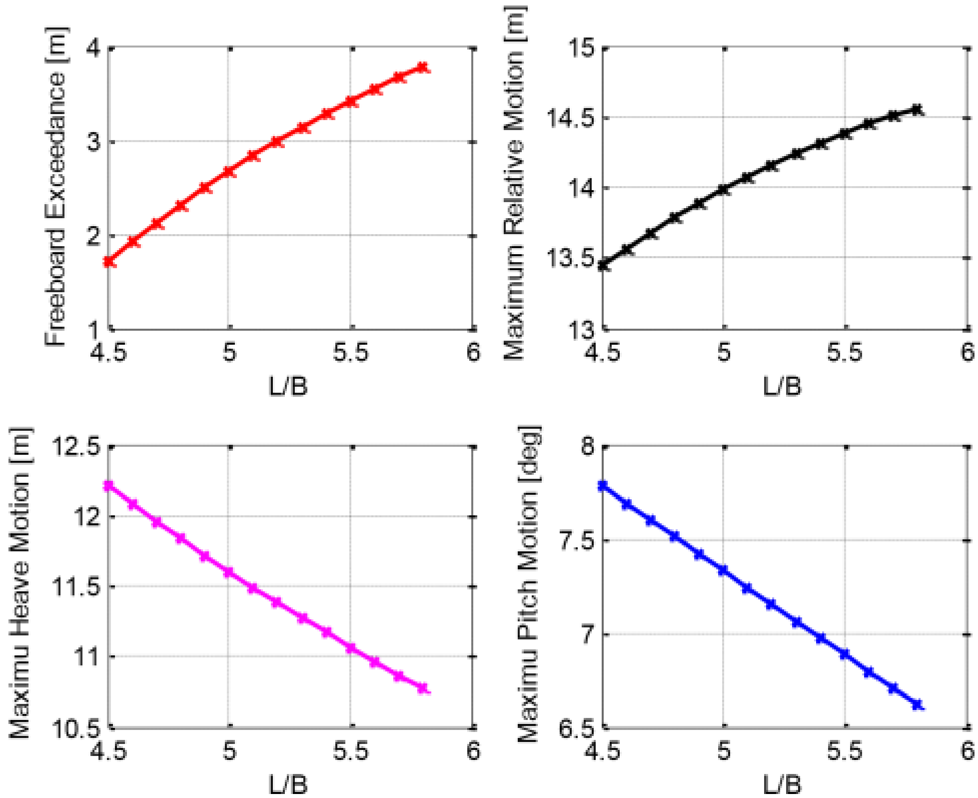


Figure 7.10: The most probable maximum Freeboard Exceedance, Relative Motion, Heave and Pitch Amplitudes against L/B Ratios, at constant Breadth-depth ratio of 1.8

7.6 Concluding Remarks

This analysis illustrated in this chapter and its programme (the ProGreen for evaluating the green water susceptibility) efficiently and swiftly predict the vessel dimensions which would be suitable for a specified storage capacity (and hence, displacement), geometric constraints and maximum permissible freeboard exceedance level, and a given wave condition.

This is based on the most probable maximum amplitudes of heave, pitch, relative motions and exceedances computed which are also displayed for inspection in case of any further desired change of specifications.

The results show that, for a given breadth-depth ratio, increase in lengthbreadth ratio leads to reduction in heave and pitch motions while the relative motion and freeboard exceedance increase.

Similarly, for a given length-breadth ratio, increase in breadth-depth ratio leads to reduction in heave and pitch motions whereas the relative motion and freeboard exceedance increase. There are few exceptions which are definitely of high relevance (depending on the wave condition and size of vessel). For instance, with L/B of 5.4, relative motion tends to decrease instead, as breadth-depth ratio increases up to about 2.1 as shown in Figure 7.8.

Interestingly, the programme helps to eliminate the hurdle of manually selecting the expected optimal design with respect to any specified design constraints.

As length-breadth and breadth-depth ratios increase, although heave and pitch motions become better, other response characteristics/effects such as bending moment (as well as green water susceptibility as already demonstrated) may rise and could lead to higher cost of construction. To strike a more suitable balance, the effects of other response characteristics (including bending moment) has been considered and incorporated in the overall optimal design in the next chapter.

CHAPTER 8

8 OVERALL OPTIMAL DESIGN

8.1 Introduction

The evaluation of principal dimensions of a Floating Production, Storage and Offloading (FPSO) system is one of the most critical tasks at the initial design stage of the FPSO vessel. It is therefore important to get this right from the onset. This chapter presents a simple method of determining the optimal principal dimensions of FPSO vessels of any specified oil storage capacity. An Optimal Design Programme (OPTIMAP) has therefore been developed to analyse and compare the various responses of floating production vessels with the aim of selecting the best possible design to ensure not only a reduction in cost of construction, but also to maintain a safe operation and overall optimal performance of the vessel with regards to her dynamic responses in deep sea waves.

The problem of optimization can be described as the process of minimizing the objective response function(s), in order to have the best performance, with respect to some predetermined geometric and functional constraints. The objective function is the user-defined sea-keeping related response characteristics such as the RAOs (the maxima of RAOs may be used), the root-mean-square values, or the most probable maximum values (in situation where extreme value determination may be of paramount importance). These response characteristics have been found to be a function of the principal dimensions and/or the underwater form of the vessel.

Various choices of optimization variables in a number of approaches and their related problems have been discussed by Hearn et al. (1991). Furthermore, Hooke and Jeeves' (1961) direct search method has been found to work well in solving optimization problems with solutions evaluated by nonlinear programming techniques.

Generally, these methods have several limitations when they are applied to sea-keeping problems partly due to the challenges of obtaining suitable objective function(s) for such analyses. In view of these challenges, Bales (1980) proposed a different objective function for minimization. It is known as the Bales sea-keeping Rank which is given by:

$$R = \sum_{j=1}^{m} w_j r_j \qquad (8.1)$$

In this case, the designer determines a set of responses r_i and their various weighting factors, w_j, where $j = 1\ to\ m$ responses included in the objective functions. The response weighting factors are values of judgement which the designer must make on the basis of the mission requirements which he is attempting to satisfy (Bales, 1980). They represent the relative importance of the various response characteristics being analysed.

8.2 Optimal Design Using Proposed Relative Goodness Method

Since there are indeed multiple response characteristics that may be required to be minimized, the objective functions have to be expressed in terms of their overall measure of their goodness (or acceptance) and the geometric constraints for a required constant storage capacity (which is directly related to the vessel's cubic number). It is possible to quantify the relative goodness (a measure of its desirable dynamic performance). It is defined as the sum of the weighted ratios of reciprocals of the dynamic response characteristics of the FPSO vessel compared to those of their respective minima. In other words, for a vessel to remain safe and efficiently productive in challenging, extreme meteorological and oceanic conditions, it is desirable to minimize its responses especially the heave and pitch motions. It may be desirable to include other wave effects that influence the cost of construction and maintenance at the initial design stage. The wave bending moment and the effects of green water for instance may be considered and minimized as well, at the design stage. A vessel with lower wave bending moment, for instance, will require a smaller amount of steel and hence lower cost to construct. Therefore, in this analysis, the effects of wave bending moment will be included as a form of response characteristic in the objective function that requires minimization.

The structure of the optimization problem comprises the following descriptors:

(i) Design geometric variables

(ii) Geometric and functional constraints

(iii) Objective functions (as a function of (i) and (ii))

(iv) Relative goodness (as a function of (i), (ii) and (iii)).

8.2.1 Geometric Variables and Constraints

Since the size and arrangement influence the cost of construction of the vessel, it is important to consider the factors affecting them (Paik, 2007). These include provision of sufficient: (i) Oil storage capacity, (ii) Deck area, and (iii) Displacement and ballast capacity.

The required oil storage capacity, S_c, which is the required maximum volume of crude oil to be safely stored in the storage tanks of the vessel, must be known and made compatible with the production rate and offloading arrangements. It is ideal to relate this to a constant overall volume known as the cubic number of the vessel using a desirable oil storage efficiency. The Oil Storage Efficiency, E_s , is the ratio of the required oil storage capacity to the overall cubic volume provided by the hull. The required storage capacity, in barrels of oil, is given by:

$$S_c = C_f \times E_s \times C_n \tag{8.2}$$

$C_n = L \times B \times D_m = Cubic\ number$

$L = Length\ between\ perpendiculars$

$B = Breadth$

$D_m = Depth\ moulded$

$C_f =$ Conversion factor

($C_f = 6.28981077$; That is: $1m^3 = 6.28981077bbl$).

Having found the cubic number in terms of the oil storage capacity and the storage efficiency, it becomes relatively easier and rational to express the two remaining factors (provision of sufficient deck area, displacement and ballast capacity) which also influence the size as a function of the design geometric variables, length-breadth (x_b), and breadth-depth (y_d) ratios. With this in mind, the geometric constraints are therefore given by:

$$x_{bmin} \leq x_b \leq x_{bmax} \tag{8.3}$$

$$y_{dmin} \leq y_d \leq y_{dmax} \tag{8.4}$$

These geometric constraints can be transformed in terms of the vessel lengths as given below:

$$L_{min} \leq L \leq L_{max} \tag{8.5}$$

Where:

$$L_{min} = \left({x_b}_{min}^{\ 2} \times {y_d}_{min} \times \frac{S_c}{C_f \times E_s} \right)^{1/3}$$

$$L_{max} = \left({x_b}_{max}^{\ 2} \times {y_d}_{max} \times \frac{S_c}{C_f \times E_s} \right)^{1/3}$$

Consider length-breadth ratio ranging from 4.5 to 5.8 and breadth-depth ratios ranging from 1.4 to 2.4, both with incremental steps of 0.1. This yields one hundred and fifty four (154) different designs of FPSO with minimum and maximum length of about 250 and 354m for 2 million barrels oil storage capacity FPSOs.

The major task here is to select the vessel (from say, the total of 154 FPSO vessels in the above-mentioned case) which will have the best performance in terms of various relevant dynamic responses such as the heave, pitch, bending moment and/or the effects of green water due to operation in extreme wave condition. It may not be enough to select a vessel with only just the minimum heave, pitch, bending moment, or the green water exceedance level as there may not be such vessel with all the responses minimized at the same time. The proposed relative goodness method (RGM) is a reliable way of analysing the performances of these vessels and then selecting the overall best based on the general design requirements and functional constraints. The general preliminary design constraints are as follow (Miller, 1992):

(i) The storage capacity must be capable of taking the output during the average interval of shuttle tanker calls.

(ii) The transverse metacentric height, GM_T, must be around 3m or more, in the fully-loaded condition.

(iii) The natural rolling period must be greater than 12 seconds. A good design usually has the natural motion periods longer than the peak period of the spectrum which is exceeded for less than 2% of the time and low heave forces and pitch moments at all shorter periods.

(iv) In order to ensure that a better motion response is achieved, the zero force frequencies for heave and pitch must be spread out as much as possible.

(v) The ratio L/D_m must be less than 13 (from structural point of view).

(vi) The underdeck volume should not exceed 1.8 times the displacement.

This implies that:

$D_m/D \leq 1.8$, i.e. $D \geq 0.56D_m$.

This enables the vessel to accommodate the segregated ballast and the produced water storage capacity.

(vii) The required external surface areas should be as small as possible, which implies low values L/B and L/D_m ratios.

(viii) In extreme wave condition, effects of green water should be reduced by ensuring that there is sufficient depth necessary to minimize freeboard exceedance while maintaining enough length (or its disparity with wavelength) required for good motion (Akandu et al., 2014b; Akandu et al., 2014a). The induced motions should not exceed the levels within which the separators have been designed to operate. Some conventional separators have been designed to cope with the following levels of motion: Angular motions, 0 to 7.5^o; linear motions, 0 to 0.25g.

8.2.2 Relative Goodness Evaluation

Let $i = 1$ to n different FPSO vessels to be analysed, $j = 1$ to m response characteristics, $\zeta_i^{(j)}$ being considered with weighting factors, w_j. Then, the relative goodness, Ω_i, of each of the vessels, which is a very good measure of the sea-keeping rank is given by:

$$\Omega_i = \sum_{j=1}^{m} \left[\frac{w_j \ \zeta_{min}^{(j)}}{\zeta_i^{(j)}} \right] \qquad (8.6)$$

The first vessel for instance will have a relative goodness as (the sum of the weighted reciprocities of the dynamic response characteristics of the FPSO vessel compared to that of the minimum):

$$\Omega_1 = \frac{1/\zeta_1^{(1)}}{1/\zeta_{min}^{(1)}} w_1 + \frac{1/\zeta_1^{(2)}}{1/\zeta_{min}^{(2)}} w_2 + \frac{1/\zeta_1^{(3)}}{1/\zeta_{min}^{(3)}} w_3 + \cdots + \frac{1/\zeta_1^{(m)}}{1/\zeta_{min}^{(m)}} w_m$$

$$= \sum_{j=1}^{m} \left[\frac{1/\zeta_1^{(j)}}{1/\zeta_{min}^{(j)}} w_j \right] = \sum_{j=1}^{m} \left[\frac{w_j \ \zeta_{min}^{(j)}}{\zeta_1^{(j)}} \right]$$

The second vessel will have a relative goodness of:

$$\Omega_2 = \frac{1/\zeta_2^{(1)}}{1/\zeta_{min}^{(1)}} w_1 + \frac{1/\zeta_2^{(2)}}{1/\zeta_{min}^{(2)}} w_2 + \frac{1/\zeta_2^{(3)}}{1/\zeta_{min}^{(3)}} w_3 + \cdots + \frac{1/\zeta_2^{(m)}}{1/\zeta_{min}^{(m)}} w_m$$

$$= \sum_{j=1}^{m} \left[\frac{1/\zeta_2^{(j)}}{1/\zeta_{min}^{(j)}} w_j \right] = \sum_{j=1}^{m} \left[\frac{w_j \ \zeta_{min}^{(j)}}{\zeta_2^{(j)}} \right]$$

Therefore, the i^{th} vessel will have a relative goodness of:

$$\Omega_i = \frac{1/\zeta_i^{(1)}}{1/\zeta_{min}^{(1)}} w_1 + \frac{1/\zeta_i^{(2)}}{1/\zeta_{min}^{(2)}} w_2 + \frac{1/\zeta_i^{(3)}}{1/\zeta_{min}^{(3)}} w_3 + \cdots + \frac{1/\zeta_i^{(m)}}{1/\zeta_{min}^{(m)}} w_m$$

$$= \sum_{j=1}^{m} \left[\frac{1/\zeta_i^{(j)}}{1/\zeta_{min}^{(j)}} w_j \right] = \sum_{j=1}^{m} \left[\frac{w_j \ \zeta_{min}^{(j)}}{\zeta_i^{(j)}} \right] \qquad (Q.E.D)$$

The overall best of all the vessels under investigation is the vessel with the maximum value of the relative goodness, Ω_i which satisfies all the given constraints such as the green water constraint, $E_i \leq e$. That is, the most probable maximum green water exceedance, E_i, is less or equal to the maximum allowable level, e, above the top of the main deck.

The green water exceedance levels have been evaluated by Akandu et al. (2014a):

$$E_i = R_i - (1 - z_m)(x_{bi} \times y_{di}{}^2)^{-1/3} \left(\frac{S_c}{C_f \times E_s} \right)^{\frac{1}{3}}$$

Where $z_m = \nabla / C_n \approx 0.65$, and R_i is the most probable relative motion in m for each of the vessels.

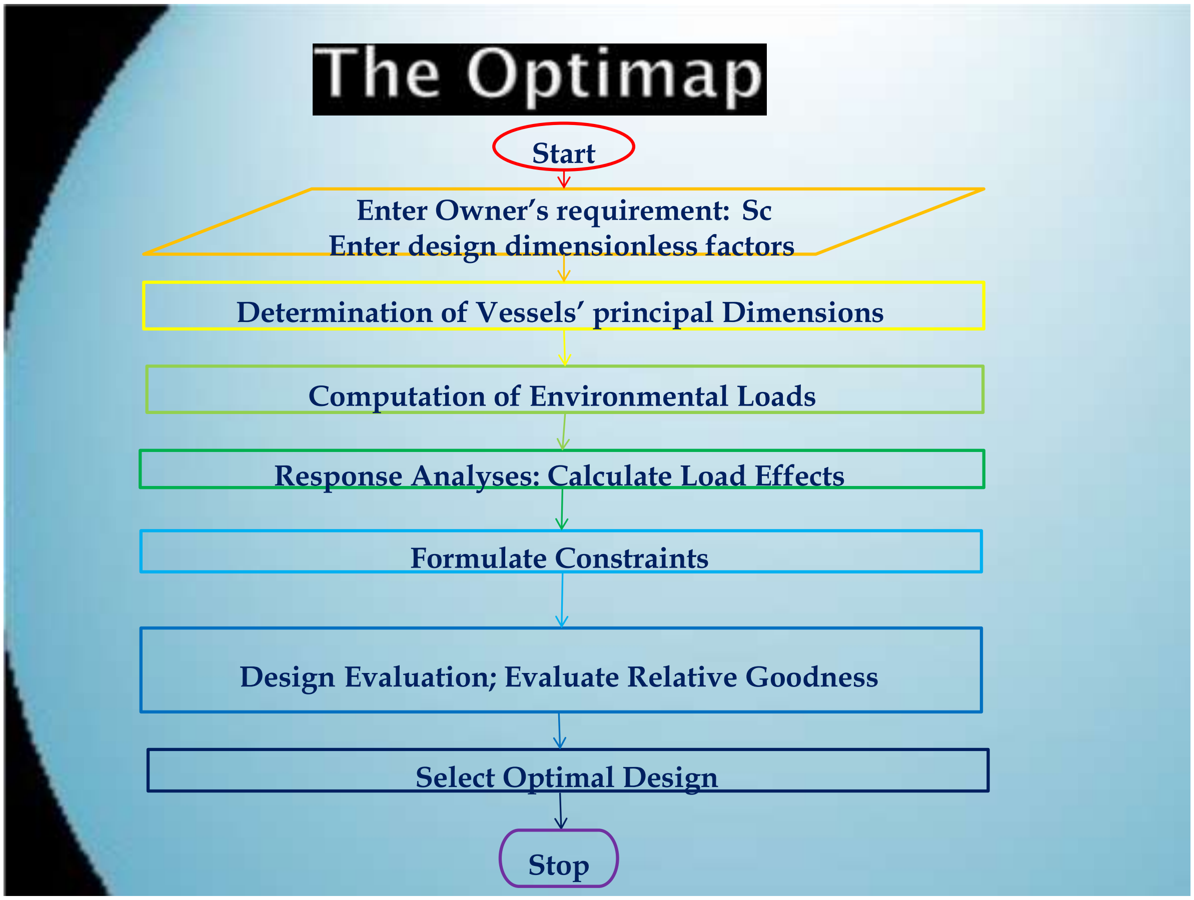


Figure 8.1: Optimal Design Programme Flowchart

8.3 Design of a 2-million barrels oil storage capacity FPSO using OPTIMAP

154 FPSO vessels (with 2-million barrels oil storage capacity each) have been analysed with the most probable maximum responses evaluated. The analysis is aimed at not only predicting these responses but also selecting best which has the overall optimum dynamic response. Some vessel operators may require the one with the optimal heave, others might be delighted to have vessel that will have the problem of green water on-board solved. Also, lower bending moment at amidships will mean lesser steel material and therefore,

lower cost of construction. All these factors have been considered with special emphasis on the green water constraint which requires that the maximum green water exceedance level should not exceed 2m. This programme which is called OPTIMAP allows users to input the allowable green water exceedance. It also allows users to choose the sea state in terms of significate wave height and zero up-crossing period. In this case, 16.5m and 17.5s respectively have been used. The overall optimal designs for up to [1], 1, 2, and 2.5m permissible green water exceedance levels have been obtained as:

Table 8.[2]: The overall optimal principal dimensions for 0, 1, [34] and 2.5m maximum permissible green water exceedance levels

e	**L**	**B**	**D_m**	**D**

See Table 8.2 and Table 8.3 for more details.

Most of the vessels with lower breadth-depth ratios (1.4 to 1.8) have sufficiently high freeboard necessary to overcome green water issues as also indicated by their high relative goodness values. For any given breadthdepth or length-breadth ratios, the maximum relative goodness value or the Optimap number which satisfies all the given constraints gives the optimal point. See Figures 8.2-8.7.

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[1]	256.9	54.7	39.0	25.4
[2]	274.8	52.8	37.7	24.5
[3]	295.6	51.0	36.4	23.7
[4] 2.5	302.4	52.1	34.8	22.6

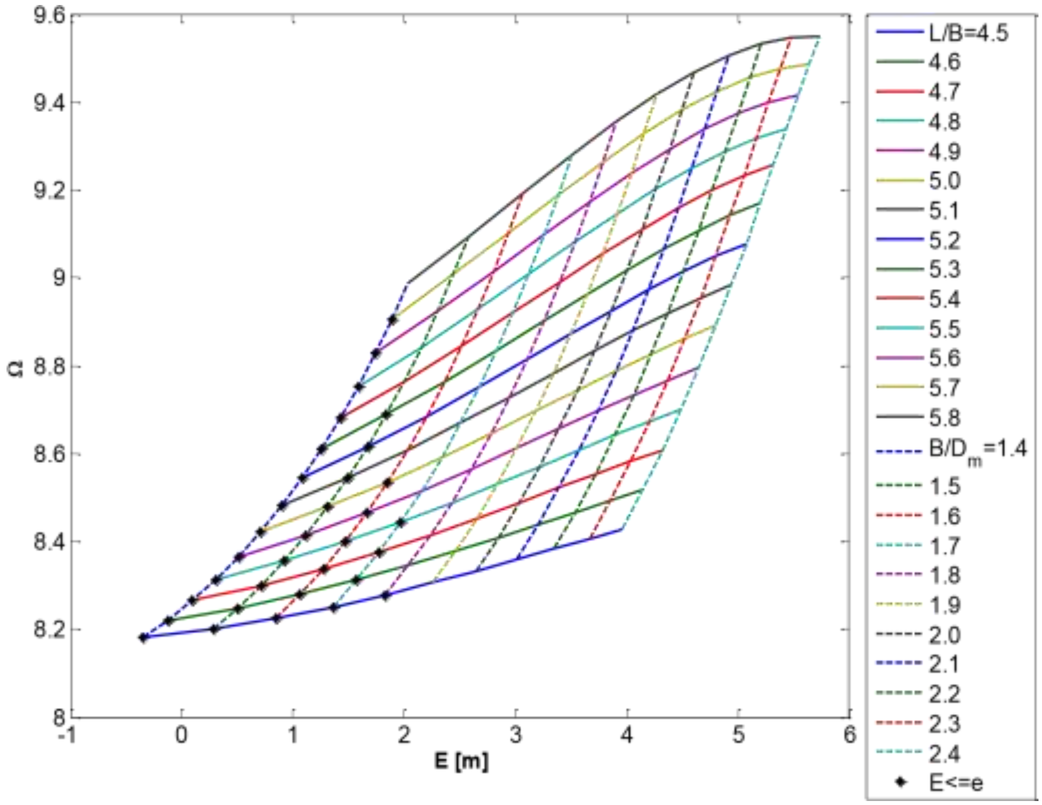


Figure 8.2: The variation of relative goodness with the most probable maximum green water exceedance

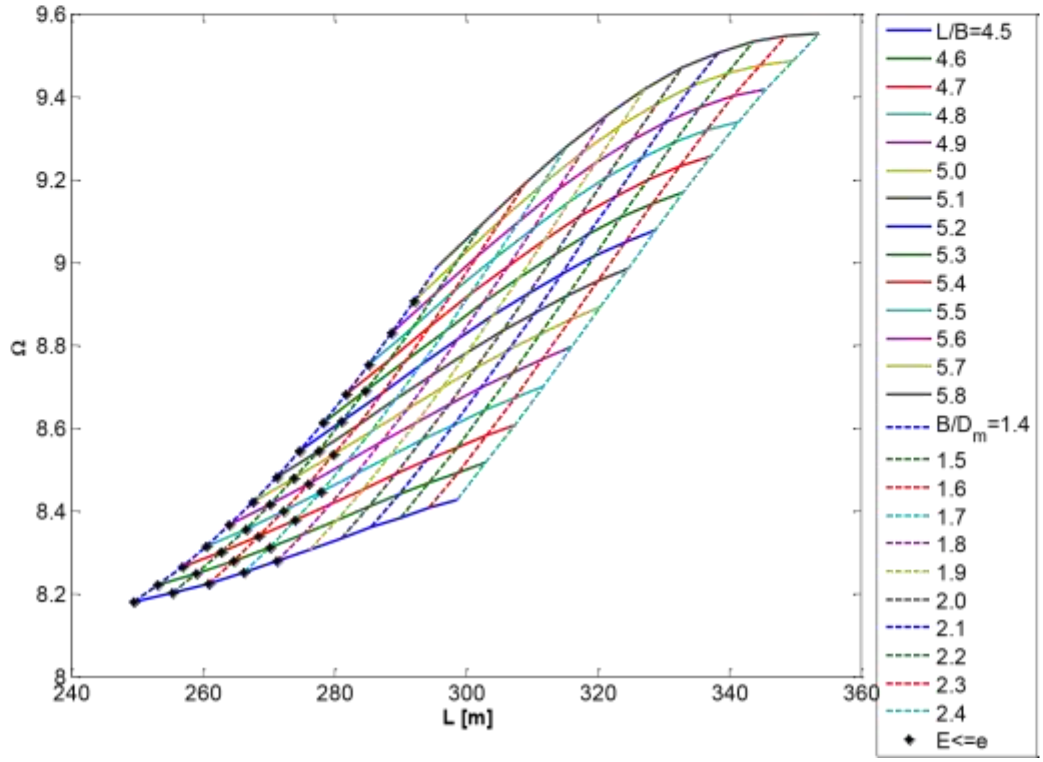


Figure 8.3: The relative goodness versus the Length of FPSOs

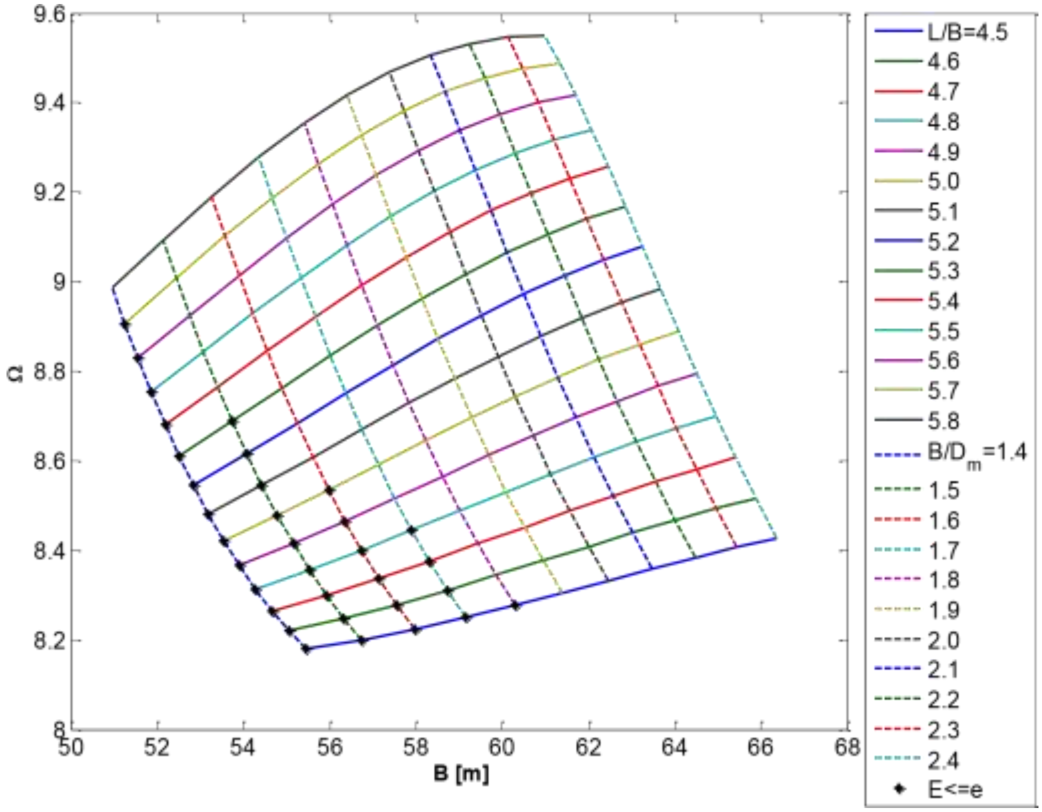


Figure 8.4: The graphs of relative goodness versus the Beam

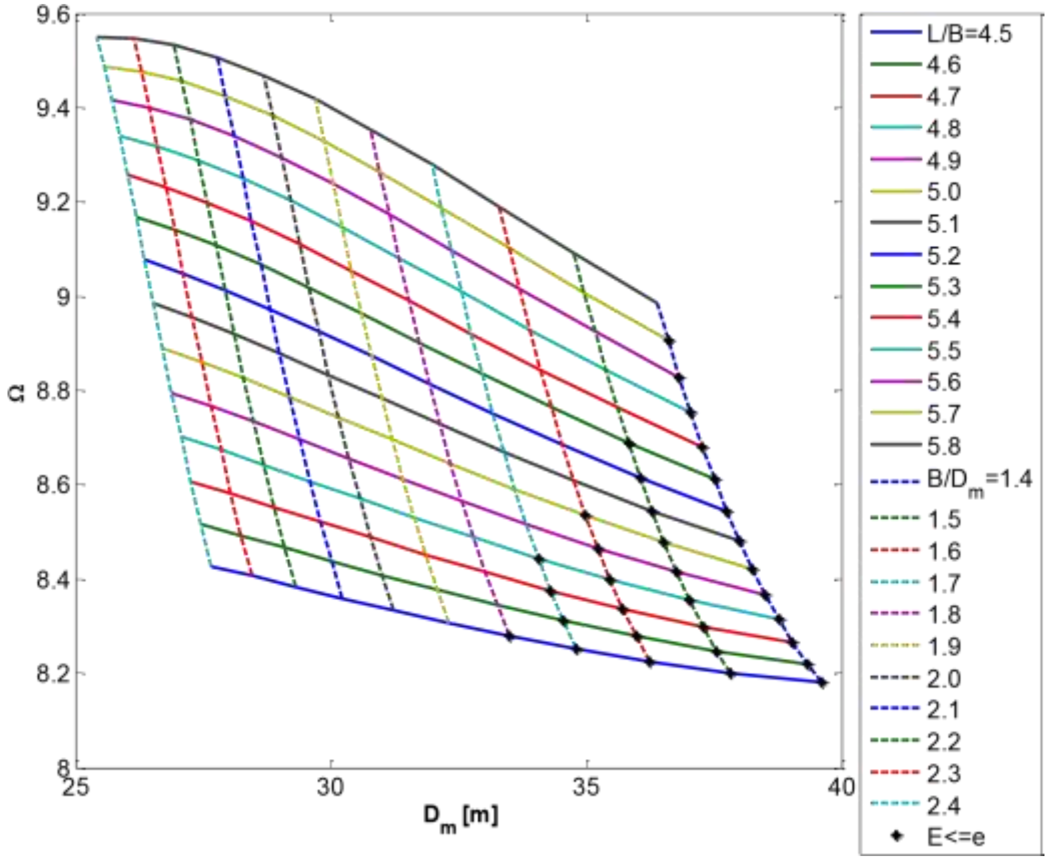


Figure 8.5: The relative goodness versus the Depth

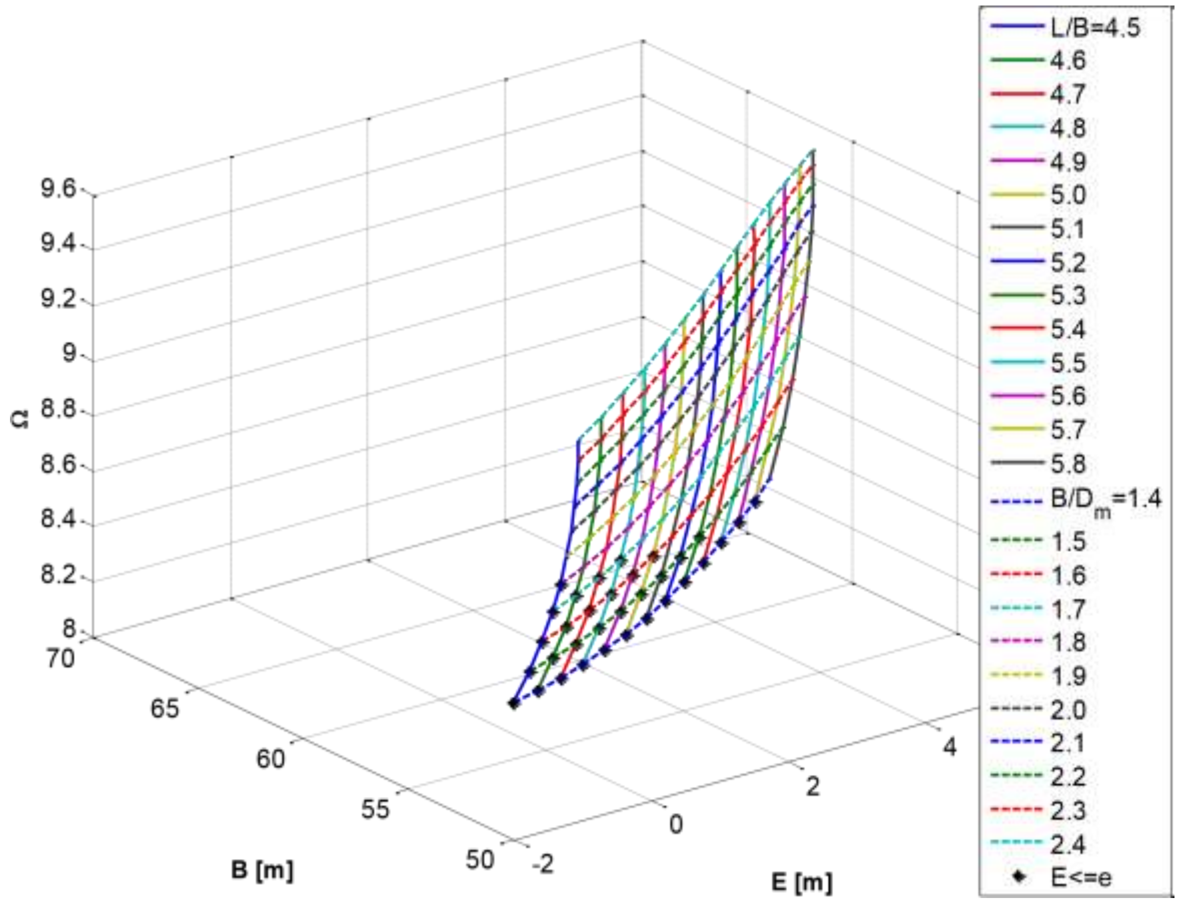


Figure 8.6: The Variation of the Optimap Number with beam and exceedance

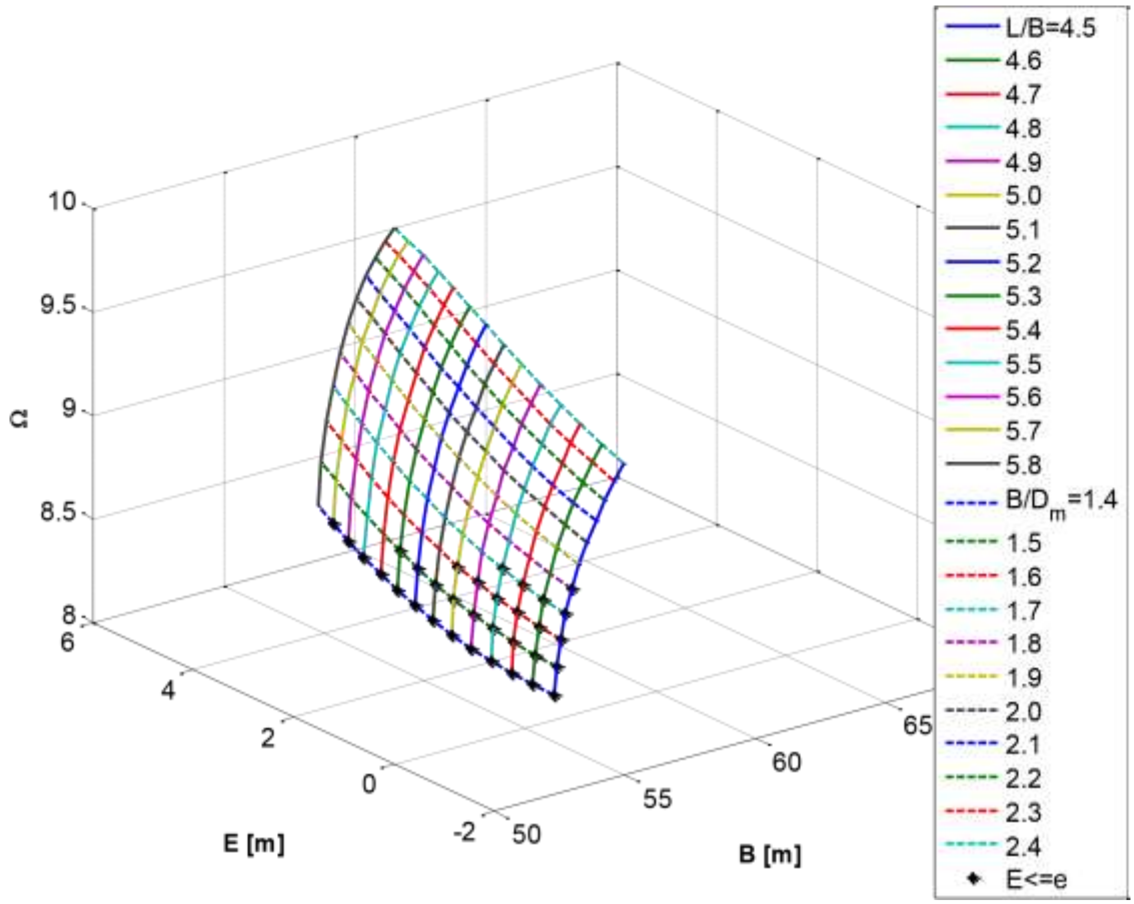


Figure 8.7: The Variation of the Optimap Number with beam and exceedance (B and E axes interchanged)

Table 8.2: The Responses and the Relative Goodness Values of 2-Million Barrel Storage Capacity FPSO Vessels that satisfied the specified allowable

Green Water exceedance of 2m (above the main deck)

L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	ζ_3 [m]	ζ_5 [deg]	BM [GNm]	Ω
4.5	1.4	249.5586	55.4575	39.6125	25.7481	13.1114	8.5615	9.3011	8.2021
4.5	1.5	255.3643	56.7476	37.8318	24.5906	12.8534	8.3465	9.4938	8.2207
4.5	1.6	260.9175	57.9817	36.2385	23.555	12.6191	8.1452	9.6736	8.2432
4.5	1.7	266.2438	59.1653	34.8031	22.622	12.4052	7.9567	9.8438	8.268
4.5	1.8	271.3651	60.3034	33.5019	21.7762	12.209	7.78	10.0072	8.2939
4.6	1.4	253.2422	55.0526	39.3233	25.5602	12.9801	8.4801	9.3109	8.2419
4.6	1.5	259.1336	56.3334	37.5556	24.4111	12.7232	8.2627	9.4909	8.2676
4.6	1.6	264.7687	57.5584	35.974	23.3831	12.4901	8.0595	9.6582	8.2968
4.6	1.7	270.1737	58.7334	34.5491	22.4569	12.2775	7.8694	9.8163	8.3277
4.6	1.8	275.3706	59.8632	33.2573	21.6173	12.0826	7.6915	9.9681	8.3591
4.7	1.4	256.8992	54.6594	39.0424	25.3776	12.8509	8.3975	9.312	8.2858
4.7	1.5	262.8757	55.931	37.2873	24.2368	12.5951	8.1779	9.479	8.3187
4.7	1.6	268.5922	57.1473	35.717	23.2161	12.3634	7.9729	9.6337	8.3544
4.7	1.7	274.0752	58.3139	34.3023	22.2965	12.1523	7.7814	9.7797	8.3913
4.8	1.4	260.5303	54.2772	38.7694	25.2001	12.7237	8.3139	9.3047	8.3336
4.8	1.5	266.5913	55.5399	37.0266	24.0673	12.4694	8.0922	9.4586	8.3737
4.8	1.6	272.3886	56.7476	35.4673	23.0537	12.2392	7.8855	9.6007	8.4159
4.8	1.7	277.9491	57.9061	34.0624	22.1406	12.0296	7.6927	9.7348	8.4586
4.9	1.4	264.1364	53.9054	38.5038	25.0275	12.5987	8.2294	9.2894	8.3853

4.9	1.5	270.2813	55.1594	36.773	23.9024	12.3459	8.0057	9.4301	8.4324
4.9	1.6	276.1588	56.3589	35.2243	22.8958	12.1174	7.7975	9.5596	8.4811
5	1.4	267.7179	53.5436	38.2454	24.8595	12.4758	8.1442	9.2664	8.4406
5	1.5	273.9462	54.7892	36.5262	23.742	12.2248	7.9186	9.3939	8.4948
5	1.6	279.9034	55.9807	34.9879	22.7421	11.9981	7.709	9.5111	8.5497
5.1	1.4	271.2757	53.1913	37.9938	24.696	12.3553	8.0583	9.236	8.4995
5.1	1.5	277.5867	54.4288	36.2858	23.5858	12.1062	7.831	9.3504	8.5607
5.1	1.6	283.6231	55.6124	34.7577	22.5925	11.8813	7.6201	9.4557	8.6217
5.2	1.4	274.8103	52.8481	37.7487	24.5366	12.2371	7.9718	9.1986	8.5619
5.2	1.5	281.2035	54.0776	36.0517	23.4336	11.99	7.743	9.3004	8.6298
5.3	1.4	278.3223	52.5136	37.5097	24.3813	12.1212	7.885	9.1548	8.6274
5.3	1.5	284.7973	53.7353	35.8236	23.2853	11.8762	7.6548	9.2442	8.702
5.4	1.4	281.8123	52.1875	37.2768	24.2299	12.0077	7.7978	9.105	8.6961
5.4	1.5	288.3684	53.4016	35.601	23.1407	11.765	7.5664	9.1827	8.7771
5.5	1.4	285.2808	51.8692	37.0495	24.0821	11.8966	7.7105	9.0498	8.7677
5.6	1.4	288.7284	51.5586	36.8276	23.9379	11.7879	7.6231	8.9898	8.8419
5.7	1.4	292.1555	51.2553	36.611	23.7971	11.6816	7.5357	8.9255	8.9187
5.8	1.4	295.5626	50.9591	36.3993	23.6596	11.5777	7.4485	8.8577	8.9977

Table 8.3: The Responses and the Relative Goodness Values of 2-Million

Barrel Storage Capacity FPSO Vessels that satisfied the specified allowable Green Water exceedance of 0m (above the main deck)

L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	ζ_3 [m]	ζ_5 [deg]	BM [GNm]	Ω
4.5	1.4	249.5586	55.4575	39.6125	25.7481	13.1114	8.5615	9.3011	8.2021
4.6	1.4	253.2422	55.0526	39.3233	25.5602	12.9801	8.4801	9.3109	8.2419
4.7	1.4	256.8992	54.6594	39.0424	25.3776	12.8509	8.3975	9.312	8.2858

It is convenient to express the heave or pitch natural periods as a function of the breadth and draught by substituting Eqn. (5.34) into Eqn. (5.37).

$$T_{n3}, T_{n5} \cong 2\left\{D\left[1 + 0.4\left(\frac{B}{D}\right)^{0.7} + 0.3\left(\frac{B}{D}\right)\right]\right\}^{\frac{1}{2}} \qquad (8.7)$$

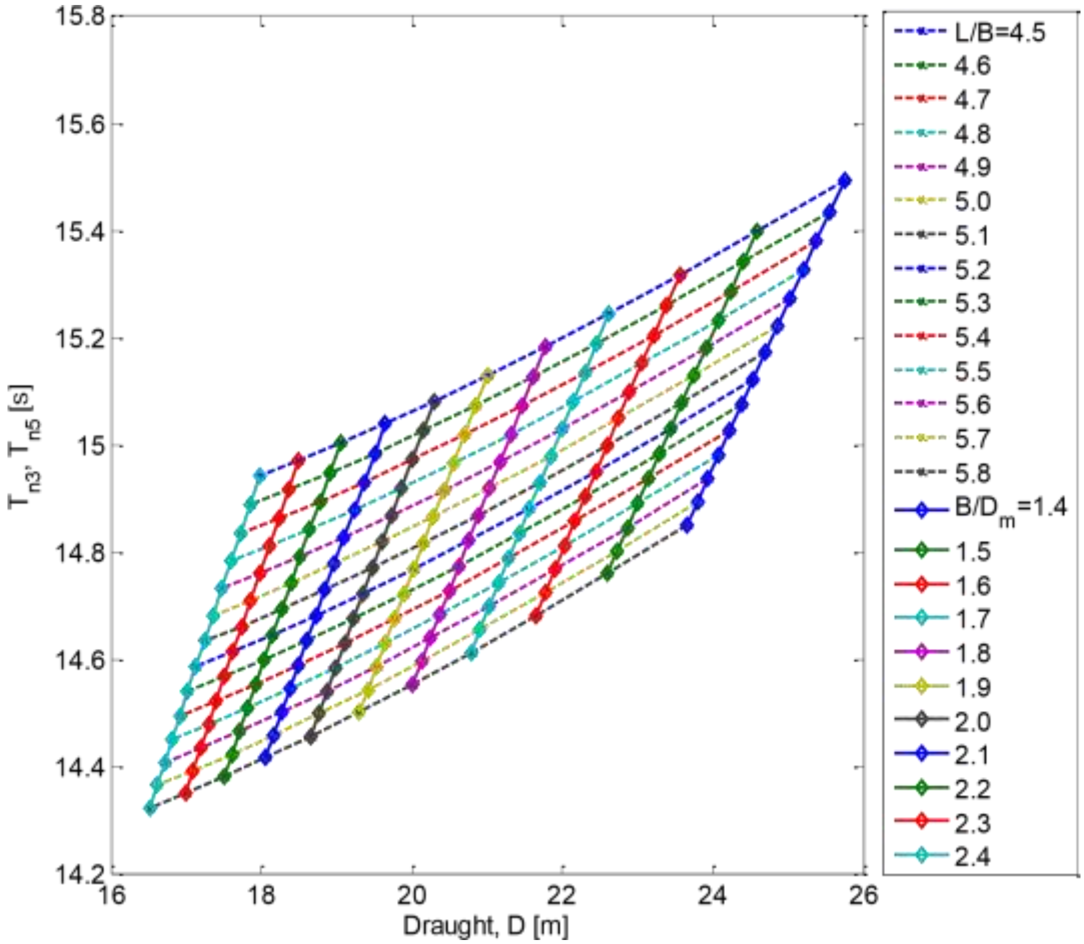


Figure 8.8: Variations of Natural Heave or Pitch Period with Draught

8.4 Application to Various Ocean Regions

Interestingly, the optimal design program (Optimap) does not only make predictions of the best principal dimensions of new FPSO vessels and generate required relevant design data, it can also be applied to investigate or evaluate the performance of existing vessels which are being used in exploration operations in various ocean regions of the world, and it is particularly useful in optimising vessels deployed where the effects of wave impact is high (say, from very rough to phenomenal/huge waves).

In this section, the performance of some selected FPSOs used in various regions of the world, from the rough ocean waves of West Africa to the huge sea waves of the North Sea, will be evaluated and possible comparisons made. Table 8.4 shows some selected FPSOs used in different regions, and which have been used for demonstration.

Table 8.4: Selected FPSOs from Various Ocean Regions

Name of Vessel	Location	Storage Capacity [kbbl]	Storage Eff. [%]	Length L [m]	Breadth B [m]	Depth D_m [m]	Draught D [m]	L/B	B/D_m
Aoka Mizu	Ettrick Field, North Sea, UK	600	43.6	248	42	21	15	5.9	2.0
Asgard A	Asgard, Norway	920	43.3	278	45	27	19	6.2	1.7
Yuum Ka'Ak Naab	KuMaZu, Mexico	2200	51.4	327	65	32	23	5.0	2.0
Aker Smart 2	Indonesia	1300	58.2	290	51	24	18	5.7	2.1
Frade	Frade, Brazil	1500	47.7	337	55	27	21	6.1	2.0
Abo	Abo, Nigeria	932	51.0	269	54	20	15	5.0	2.7
Agbami	Agbami, OPL Nigeria	1800	48.3	319	58	32	23	5.5	1.8

The analyses can be run separately for each vessel. However, it is better and more efficient to run the analyses collectively, in which case, the optimal design programme (Optimap) is slightly modified to handle all the selected vessels with their respective 100 year return period storms (See Table E. 4) in an iterative manner.

Since the programme requires the maximum permissible green water exceedance of freeboard, and at this point, they are unknown for these vessels, it is recommended to run the progammes first with a uniform, high exceedance (infinity can be used). This allows the computations of the actual most probable responses and freeboard exceedances which are instantly exported to excel format for inspection.

The next step is to apply the computed exceedances (of the vessels under investigation from the generated data) as the maximum permissible. Then, vary them slightly within tight ranges in order to make the best choice. With these, the programme is rerun to obtain new optimal design (the vessel which satisfies the given constraint(s) with the highest Optimap number).

Considering the range of breadth-depth (1.7 to 2.7) and the breadth-depth ratios of the selected FPSOs as shown in Table 8.4, the following geometric constraints are used for the analysis:

$$4.9 \leq x_b \leq 6.2 \tag{8.8}$$

$$1.7 \leq y_d \leq 2.7 \tag{8.9}$$

The weighting factors used are 4, 3.5, and 2.5 on a ten-point ranking scale (i.e. 40, 35 and 25%) for heave, pitch and bending moment respectively.

Table 8.5 summarises the selections made using the Optimal Design Programme in comparison with the rectangular equivalents of the parent vessels under investigation. The green colour represents the optimised vessels while the blue colour represents the parent vessels.

The proposed relative goodness method demonstrated here shows how a more balanced performance improvement (when handling multiple response characteristics) can be achieved. For Aker Smart 2, for instance, heave, pitch and bending moments amidships were reduced by 3, 2, and 6 percent, while for Agbami, they were improved by 4, 3 and 5 percent respectively.

Table 8.5: Comparison of optimised designs with FPSOs in different parts of the globe

Name of Vessel	Location	Length L [m]	Breadth B [m]	Depth D_m [m]	Draught D [m]	Free-board FB [m]	Max. Freeboard Exceedance E [m]	Max. Heave η_3 [m]	Max. Pitch η_5 [deg]	Max. Wave Bending Moment BM [GNm]
Aoka Mizu	Ettrick Field, North Sea, UK	248	42	21	15	6				
		247.89	42.01	21.01	15.00	6.01	5.95	11.95	7.67	3.76
		249.16	40.85	21.50	15.35	6.15	5.89	11.93	7.66	3.67
					Changes:	2%	-1%	0%	0%	-2%
Asgard A	Asgard, Norway	278	45	27	19	8				
		280.52	45.25	26.61	18.73	7.89	5.56	11.48	7.29	5.57
		280.52	45.25	26.61	18.73	7.89	5.56	11.48	7.29	5.57
					Changes:	0%	0%	0%	0%	0%

Yuum Ka'Ak Naab	KuMaZu, Mexico	327	65	32	23	9				
		324.04	64.81	32.4	23.29	9.11	4.79	6.25	5.47	11.85
		331.04	59.11	34.77	24.99	9.78	4.61	6.12	5.47	11.03
					Changes:	7%	-1%	-2%	0%	-7%
Aker Smart 2	Indonesia	290	51	24	18	6				
		289.37	50.77	24.17	18.13	6.04	5.57	4.20	4.75	4.71
		296.01	47.74	25.13	18.85	6.28	5.51	4.07	4.64	4.41
					Changes:	4%	-1%	-3%	-2%	-6%
Frade	Frade, Brazil	337	55	27	21	6				
		333.84	54.73	27.36	21.28	6.08	2.54	3.71	3.22	4.86
		337.48	54.43	27.22	21.17	6.05	2.59	3.65	3.16	4.79
					Changes:	-1%	2%	-1%	-2%	-1%
Abo	Abo, Nigeria	269	54	20	15	5				
		269.67	53.93	19.98	14.98	4.99	-1.24	2.03	1.85	1.53
		281.63	45.42	22.71	17.03	5.68	-1.74	1.96	1.81	1.29
					Changes:	14%	-40%	-4%	-2%	-15%
Agbami	Agbami, OPL Nigeria	319	58	32	23	9				
		318.34	57.88	32.16	23.11	9.04	-4.76	1.88	1.71	2.91
		319.86	56.12	33.01	23.73	9.28	-4.95	1.87	1.71	2.85
					Changes:	3%	-4%	0%	0%	-2%
		327.3	55.47	32.63	23.45	9.18	-4.82	1.81	1.66	2.77
					Changes:	1%	-1%	-4%	-3%	-5%

Details of the results are presented in Table 8.6 to Table 8 12. .

Table 8.6: Optimap results for FPSOs of 160.12kton displacement, 600kbbl Oil storage capacity being compared with Aoka Mizu

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]

1 4.9 1.7 207.47 42.34 24.91 17.78 7.12 13.15 9.08 4.14 3.70 13.05 16.63 2 4.9 1.8 211.46 43.16 23.98 17.12 6.86 13.00 8.90 4.41 3.76 12.99 15.37 3 4.9 1.9 215.31 43.94 23.13 16.51 6.61 12.86 8.72 4.67 3.83 12.94 14.43 4 4.9 2.0 219.02 44.70 22.35 15.96 6.39 12.74 8.56 4.90 3.90 12.89 13.69 5 4.9 2.1 222.61 45.43 21.63 15.45 6.19 12.62 8.41 5.12 3.97 12.85 13.10 6 4.9 2.2 226.09 46.14

20.97 14.97 6.00 12.51 8.27 5.33 4.03 12.81 12.62 7 4.9 2.3 229.46 46.83 20.36 14.54 5.82 12.41 8.13 5.52 4.10 12.77 12.22 8 4.9 2.4 232.74 47.50 19.79 14.13 5.66 12.31 8.01 5.70 4.17 12.74 11.88

9 4.9 2.5 235.93 48.15 19.26 13.75 5.51 12.22 7.89 5.87 4.25 12.72 11.59

10 4.9 2.6 239.04 48.78 18.76 13.40 5.37 12.13 7.78 6.04 4.32 12.69 11.34 11 4.9 2.7 242.06 49.40 18.30 13.06 5.23 12.05 7.67 6.19 4.40 12.67 11.12 12 5.0 1.7 210.28 42.06 24.74 17.66 7.08 13.06 8.99 4.27 3.69 13.01 16.59 13 5.0 1.8 214.33 42.87 23.81 17.00 6.81 12.91 8.81 4.54 3.76 12.95 15.33 14 5.0 1.9 218.23 43.65 22.97 16.40 6.57 12.78 8.63 4.80 3.82 12.89 14.39 15 5.0 2.0 221.99 44.40 22.20 15.85 6.35 12.65 8.47 5.03 3.89 12.84 13.65 16 5.0 2.1 225.63 45.13 21.49 15.34 6.15 12.53 8.32 5.25 3.95 12.80 13.06 17 5.0 2.2 229.16 45.83 20.83 14.87 5.96 12.42 8.18 5.45 4.02 12.76 12.58 18 5.0 2.3 232.58 46.52 20.22 14.44 5.78 12.32 8.04 5.64 4.09 12.73 12.18 19 5.0 2.4 235.90 47.18 19.66 14.04 5.62 12.22 7.92 5.82 4.16 12.70 11.85 20 5.0 2.5 239.13 47.83 19.13 13.66 5.47 12.13 7.80 5.99 4.23 12.67 11.55 21 5.0 2.6 242.28 48.46 18.64 13.31 5.33 12.05 7.69 6.15 4.30 12.65 11.30 22 5.0 2.7 245.34 49.07 18.17 12.98 5.20 11.96 7.58 6.31 4.38 12.63 11.08 23 5.1 1.7 213.08 41.78 24.58 17.55 7.03 12.97 8.90 4.40 3.68 12.97 16.55

24 5.1 1.8 217.18 42.58 23.66 16.89 6.77 12.82 8.72 4.67 3.75 12.90 15.29

25 5.1 1.9 221.13 43.36 22.82 16.29 6.53 12.69 8.54 4.92 3.81 12.85 14.35 26 5.1 2.0 224.94 44.11 22.05 15.75 6.31 12.57 8.38 5.15 3.87 12.80 13.61 27 5.1 2.1 228.63 44.83 21.35 15.24 6.11 12.45 8.23 5.37 3.94 12.76 13.03

28 5.1 2.2 232.20 45.53 20.70 14.78 5.92 12.34 8.09 5.57 4.00 12.72 12.55 29 5.1 2.3 235.67 46.21 20.09 14.34 5.75 12.24 7.95 5.76 4.07 12.69 12.15 30 5.1 2.4 239.03 46.87 19.53 13.94 5.59 12.14 7.83 5.94 4.14 12.66 11.81 31 5.1 2.5 242.31 47.51 19.00 13.57 5.44 12.05 7.71 6.10 4.21 12.63 11.52 32 5.1 2.6 245.50 48.14 18.51 13.22 5.30 11.97 7.60 6.26 4.29 12.61 11.27

33 5.1 2.7 248.61 48.75 18.05 12.89 5.16 11.88 7.49 6.42 4.37 12.59 11.05

34 5.2 1.7 215.85 41.51 24.42 17.43 6.98 12.89 8.81 4.52 3.67 12.92 16.51 35 5.2 1.8 220.01 42.31 23.50 16.78 6.72 12.74 8.63 4.79 3.74 12.86 15.25 36 5.2 1.9 224.01 43.08 22.67 16.19 6.48 12.61 8.45 5.04 3.80 12.81 14.31 37 5.2 2.0 227.87 43.82 21.91 15.64 6.27 12.48 8.29 5.27 3.86 12.76 13.58 38 5.2 2.1 231.61 44.54 21.21 15.14 6.07 12.37 8.14 5.48 3.92 12.72 12.99 39 5.2 2.2 235.23 45.24 20.56 14.68 5.88 12.26 8.00 5.68 3.99 12.68 12.51 40 5.2 2.3 238.74 45.91 19.96 14.25 5.71 12.16 7.86 5.87 4.05 12.65 12.11 41 5.2 2.4 242.15 46.57 19.40 13.85 5.55 12.06 7.74 6.04 4.13 12.62 11.78

42 5.2 2.5 245.47 47.20 18.88 13.48 5.40 11.97 7.62 6.21 4.20 12.59 11.49 43 5.2 2.6 248.70 47.83 18.39 13.13 5.26 11.89 7.51 6.37 4.28 12.57 11.24 44 5.2 2.7 251.84 48.43 17.94 12.81 5.13 11.80 7.41 6.52 4.36 12.55 11.02 45 5.3 1.7 218.61 41.25 24.26 17.32 6.94 12.80 8.72 4.64 3.66 12.88 16.47 46 5.3 1.8 222.82 42.04 23.36 16.68 6.68 12.66 8.54 4.91 3.72 12.82 15.21 47 5.3 1.9 226.87 42.81 22.53 16.09 6.44 12.53 8.36 5.15 3.78 12.77 14.27 48 5.3 2.0 230.78 43.54 21.77 15.55 6.23 12.40 8.20 5.38 3.84 12.72 13.54 49 5.3 2.1 234.57 44.26 21.08 15.05 6.03 12.29 8.05 5.59 3.91 12.68 12.96

50 5.3 2.2 238.23 44.95 20.43 14.59 5.84 12.18 7.91 5.79 3.97 12.64 12.48 51 5.3 2.3 241.79 45.62 19.83 14.16 5.67 12.08 7.77 5.97 4.04 12.61 12.08 52 5.3 2.4 245.24 46.27 19.28 13.77 5.51 11.99 7.65 6.15 4.11 12.58 11.74 53 5.3 2.5 248.60 46.91 18.76 13.40 5.37 11.90 7.53 6.31 4.19 12.55 11.45 54 5.3 2.6 251.87 47.52 18.28 13.05 5.23 11.81 7.42 6.47 4.27 12.53 11.20 55 5.3 2.7 255.06 48.13 17.82 12.73 5.10 11.73 7.32 6.62 4.35 12.51 10.99 56 5.4 1.7 221.35 40.99 24.11 17.22 6.90 12.72 8.63 4.76 3.65 12.84 16.44 57 5.4 1.8 225.61 41.78 23.21 16.57 6.64 12.58 8.45 5.02 3.71 12.78 15.18 58 5.4 1.9 229.72 42.54 22.39 15.99 6.40 12.45 8.27 5.26 3.77 12.73 14.24 59 5.4 2.0 233.68 43.27 21.64 15.45 6.19 12.32 8.11 5.49 3.83 12.68 13.51 60 5.4 2.1 237.51 43.98 20.94 14.95 5.99 12.21 7.96 5.69 3.89 12.64 12.92 61 5.4 2.2 241.22 44.67 20.30 14.50 5.81 12.10 7.82 5.89 3.96 12.60 12.44 62 5.4 2.3 244.82 45.34 19.71 14.07 5.64 12.00 7.69 6.07 4.02 12.57 12.05 63 5.4 2.4 248.32 45.98 19.16 13.68 5.48 11.91 7.56 6.25 4.10 12.54 11.71 64 5.4 2.5 251.72 46.61 18.65 13.31 5.33 11.82 7.45 6.41 4.18 12.51 11.42

65 5.4 2.6 255.03 47.23 18.16 12.97 5.20 11.73 7.34 6.56 4.26 12.49 11.17 66 5.4 2.7 258.26 47.83 17.71 12.65 5.07 11.65 7.23 6.71 4.35 12.47 10.96 67 5.5 1.7 224.08 40.74 23.97 17.11 6.85 12.64 8.54 4.87 3.64 12.80 16.40 68 5.5 1.8 228.39 41.53 23.07 16.47 6.60 12.50 8.36 5.13 3.69 12.74 15.14 69 5.5 1.9 232.54 42.28 22.25 15.89 6.36 12.37 8.18 5.37 3.75 12.69 14.20

70 5.5 2.0 236.55 43.01 21.50 15.35 6.15 12.25 8.02 5.59 3.81 12.64 13.47 71 5.5 2.1 240.43 43.71 20.82 14.86 5.95 12.13 7.87 5.79 3.87 12.60 12.89 72 5.5 2.2 244.19 44.40 20.18 14.41 5.77 12.03 7.73 5.99 3.94 12.56 12.41 73 5.5 2.3 247.83 45.06 19.59 13.99 5.60 11.93 7.60 6.17 4.01 12.53 12.01 74 5.5 2.4 251.37 45.70 19.04 13.60 5.45 11.83 7.48 6.34 4.09 12.50 11.68

75 5.5 2.5 254.82 46.33 18.53 13.23 5.30 11.75 7.36 6.50 4.17 12.47 11.39 76 5.5 2.6 258.17 46.94 18.05 12.89 5.16 11.66 7.25 6.65 4.26 12.45 11.14 77 5.5 2.7 261.44 47.53 17.61 12.57 5.04 11.58 7.15 6.80 4.35 12.43 10.93 78 5.6 1.7 226.79 40.50 23.82 17.01 6.81 12.56 8.45 4.97 3.62 12.77 16.36 79 5.6 1.8 231.15 41.28 22.93 16.37 6.56 12.42 8.27 5.23 3.68 12.71 15.11 80 5.6 1.9 235.35 42.03 22.12 15.79 6.33 12.29 8.09 5.47 3.73 12.65 14.17 81 5.6 2.0 239.41 42.75 21.38 15.26 6.11 12.17 7.93 5.68 3.80 12.60 13.44 82 5.6 2.1 243.34 43.45 20.69 14.77 5.92 12.06 7.78 5.89 3.86 12.56 12.86

83 5.6 2.2 247.14 44.13 20.06 14.32 5.74 11.95 7.64 6.08 3.93 12.53 12.38 84 5.6 2.3 250.83 44.79 19.47 13.90 5.57 11.85 7.51 6.26 4.00 12.49 11.98 85 5.6 2.4 254.41 45.43 18.93 13.52 5.41 11.76 7.39 6.43 4.08 12.46 11.65 86 5.6 2.5 257.90 46.05 18.42 13.15 5.27 11.67 7.28 6.59 4.17 12.44 11.36 87 5.6 2.6 261.29 46.66 17.95 12.81 5.13 11.59 7.17 6.74 4.26 12.41 11.11 88 5.6 2.7 264.60 47.25 17.50 12.49 5.00 11.51 7.07 6.89 4.35 12.39 10.90 89 5.7 1.7 229.48 40.26 23.68 16.91 6.77 12.48 8.37 5.07 3.61 12.73 16.33 90 5.7 1.8 233.89 41.03 22.80 16.28 6.52 12.34 8.18 5.33 3.66 12.67 15.07

91 5.7 1.9 238.15 41.78 21.99 15.70 6.29 12.22 8.00 5.56 3.72 12.61 14.13 92 5.7 2.0 242.25 42.50 21.25 15.17 6.08 12.10 7.84 5.78 3.78 12.57 13.41 93 5.7 2.1 246.22 43.20 20.57 14.69 5.88 11.99 7.69 5.98 3.85 12.53 12.82 94 5.7 2.2 250.07 43.87 19.94 14.24 5.70 11.88 7.56 6.17 3.92 12.49 12.35 95 5.7 2.3 253.81 44.53 19.36 13.82 5.54 11.78 7.43 6.34 4.00 12.46 11.95 96 5.7 2.4 257.43 45.16 18.82 13.44 5.38 11.69 7.31 6.51 4.08 12.43 11.62

97 5.7 2.5 260.96 45.78 18.31 13.08 5.24 11.60 7.19 6.67 4.17 12.40 11.33 98 5.7 2.6 264.39 46.38 17.84 12.74 5.10 11.52 7.09 6.82 4.26 12.38 11.08 99 5.7 2.7 267.74 46.97 17.40 12.42 4.98 11.44 6.99 6.97 4.37 12.35 10.87

100 5.8 1.7 232.15 40.03 23.55 16.81 6.73 12.41 8.28 5.17 3.59 12.69 16.30 101 5.8 1.8 236.62 40.80 22.66 16.18 6.48 12.27 8.09 5.42 3.65 12.63 15.04 102 5.8 1.9 240.92 41.54 21.86 15.61 6.25 12.14 7.92 5.65 3.70 12.58 14.10 103 5.8 2.0 245.08 42.25 21.13 15.08 6.04 12.02 7.76 5.86 3.77 12.53 13.37 104 5.8 2.1 249.10 42.95 20.45 14.60 5.85 11.91 7.61 6.06 3.84 12.49 12.79 105 5.8 2.2 252.99 43.62 19.83 14.16 5.67 11.81 7.47 6.25 3.91 12.45 12.32

106 5.8 2.3 256.77 44.27 19.25 13.74 5.50 11.71 7.34 6.42 3.99 12.42 11.92 107 5.8 2.4 260.43 44.90 18.71 13.36 5.35 11.62 7.22 6.59 4.08 12.39 11.59 108 5.8 2.5 264.00 45.52 18.21 13.00 5.21 11.53 7.11 6.75 4.18 12.36 11.30 109 5.8 2.6 267.48 46.12 17.74 12.66 5.07 11.45 7.01 6.90 4.28 12.34 11.05

110 5.8 2.7 270.86 46.70 17.30 12.35 4.95 11.37 6.91 7.04 4.39 12.32 10.84 111 5.9 1.7 234.82 39.80 23.41 16.72 6.70 12.33 8.19 5.26 3.58 12.66 16.26 112 5.9 1.8 239.33 40.56 22.54 16.09 6.45 12.20 8.00 5.51 3.63 12.60 15.00

113	5.9	1.9	243.68	41.30	21.74	15.52	6.22	12.07	7.83	5.74	3.69	12.54	14.07
114	5.9	2.0	247.89	42.01	21.01	15.00	6.01	11.95	7.67	5.95	3.76	12.50	13.34
115	5.9	2.1	251.95	42.70	20.34	14.52	5.82	11.84	7.52	6.14	3.83	12.45	12.76

116 5.9 2.2 255.89 43.37 19.71 14.08 5.64 11.74 7.39 6.33 3.91 12.42 12.29 117 5.9 2.3 259.71 44.02 19.14 13.66 5.47 11.64 7.26 6.50 3.99 12.38 11.89 118 5.9 2.4 263.42 44.65 18.60 13.28 5.32 11.55 7.14 6.67 4.09 12.35 11.56 119 5.9 2.5 267.03 45.26 18.10 12.93 5.18 11.46 7.03 6.82 4.19 12.33 11.27 120 5.9 2.6 270.54 45.85 17.64 12.59 5.04 11.38 6.93 6.97 4.30 12.30 11.02 121 5.9 2.7 273.97 46.44 17.20 12.28 4.92 11.30 6.83 7.12 4.41 12.28 10.81 122 6.0 1.7 237.46 39.58 23.28 16.62 6.66 12.26 8.10 5.35 3.56 12.62 16.23 123 6.0 1.8 242.03 40.34 22.41 16.00 6.41 12.13 7.92 5.59 3.62 12.56 14.97

124	6.0	1.9	246.43	41.07	21.62	15.43	6.18	12.00	7.75	5.82	3.68	12.51	14.04
125	6.0	2.0	250.68	41.78	20.89	14.92	5.97	11.88	7.59	6.03	3.75	12.46	13.31
126	6.0	2.1	254.79	42.47	20.22	14.44	5.78	11.77	7.44	6.22	3.82	12.42	12.73
127	6.0	2.2	258.77	43.13	19.60	14.00	5.61	11.67	7.31	6.40	3.91	12.38	12.26
128	6.0	2.3	262.63	43.77	19.03	13.59	5.44	11.58	7.18	6.58	4.00	12.35	11.86
129	6.0	2.4	266.39	44.40	18.50	13.21	5.29	11.48	7.06	6.74	4.10	12.32	11.53
130	6.0	2.5	270.04	45.01	18.00	12.85	5.15	11.40	6.95	6.90	4.21	12.29	11.24
131	6.0	2.6	273.59	45.60	17.54	12.52	5.02	11.31	6.85	7.05	4.32	12.27	11.00
132	6.0	2.7	277.05	46.18	17.10	12.21	4.89	11.23	6.75	7.19	4.45	12.25	10.78
133	6.1	1.7	240.09	39.36	23.15	16.53	6.62	12.19	8.02	5.43	3.55	12.59	16.20
134	6.1	1.8	244.71	40.12	22.29	15.91	6.37	12.06	7.83	5.67	3.60	12.53	14.94
135	6.1	1.9	249.16	40.85	21.50	15.35	6.15	11.93	7.66	5.89	3.67	12.47	14.01
136	6.1	2.0	253.46	41.55	20.78	14.83	5.94	11.82	7.50	6.10	3.74	12.43	13.28
137	6.1	2.1	257.61	42.23	20.11	14.36	5.75	11.71	7.36	6.29	3.82	12.38	12.70
138	6.1	2.2	261.64	42.89	19.50	13.92	5.58	11.61	7.23	6.48	3.91	12.35	12.23
139	6.1	2.3	265.55	43.53	18.93	13.51	5.41	11.51	7.10	6.65	4.01	12.32	11.83
140	6.1	2.4	269.34	44.15	18.40	13.14	5.26	11.42	6.98	6.81	4.12	12.29	11.50
141	6.1	2.5	273.03	44.76	17.90	12.78	5.12	11.33	6.88	6.96	4.23	12.26	11.22
142	6.1	2.6	276.62	45.35	17.44	12.45	4.99	11.25	6.77	7.11	4.36	12.24	10.97
143	6.1	2.7	280.12	45.92	17.01	12.14	4.86	11.17	6.68	7.26	4.49	12.22	10.75
144	6.2	1.7	242.71	39.15	23.03	16.44	6.59	12.12	7.93	5.51	3.53	12.55	16.17
145	6.2	1.8	247.38	39.90	22.17	15.83	6.34	11.99	7.75	5.75	3.59	12.49	14.91
146	6.2	1.9	251.88	40.63	21.38	15.27	6.12	11.86	7.58	5.97	3.66	12.44	13.98
147	6.2	2.0	256.22	41.33	20.66	14.75	5.91	11.75	7.42	6.17	3.74	12.39	13.25
148	6.2	2.1	260.42	42.00	20.00	14.28	5.72	11.64	7.28	6.36	3.83	12.35	12.67
149	6.2	2.2	264.49	42.66	19.39	13.85	5.55	11.54	7.15	6.54	3.92	12.31	12.20
150	6.2	2.3	268.44	43.30	18.82	13.44	5.38	11.44	7.02	6.71	4.03	12.28	11.81
151	6.2	2.4	272.27	43.92	18.30	13.06	5.23	11.35	6.91	6.88	4.14	12.25	11.47
152	6.2	2.5	276.00	44.52	17.81	12.71	5.09	11.27	6.80	7.03	4.27	12.23	11.19
153	6.2	2.6	279.64	45.10	17.35	12.39	4.96	11.18	6.70	7.18	4.40	12.20	10.94
154	6.2	2.7	283.18	45.67	16.92	12.08	4.84	11.10	6.61	7.32	4.54	12.18	10.73

Note: All the responses (η_3, η_5), exceedances (E) and bending moments (BM) are most probable maximum values, including the ones in Table 8.7 to Table 8.12.

Table 8.7: Optimap results for FPSOs of 243.7kton displacement, 920kbbl Oil storage capacity being compared with Asgard A

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E] [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.9	1.7	239.79	48.94	28.79	20.26	8.53	12.67	8.44	4.03	6.00	13.98	17.62
2	4.9	1.8	244.40	49.88	27.71	19.50	8.21	12.50	8.26	4.36	6.09	13.92	16.30
3	4.9	1.9	248.85	50.79	26.73	18.81	7.92	12.34	8.09	4.66	6.18	13.86	15.32
4	4.9	2.0	253.14	51.66	25.83	18.18	7.65	12.20	7.93	4.94	6.27	13.81	14.55
5	4.9	2.1	257.29	52.51	25.00	17.60	7.41	12.06	7.77	5.19	6.36	13.76	13.93
6	4.9	2.2	261.31	53.33									

24.24 17.06 7.18 11.93 7.63 5.43 6.45 13.72 13.43 7 4.9 2.3 265.21 54.13 23.53 16.56 6.97 11.81 7.50 5.66 6.54 13.69 13.01 8 4.9 2.4 269.00 54.90 22.87 16.10 6.78 11.70 7.37 5.87 6.63 13.66 12.65

9 4.9 2.5 272.69 55.65 22.26 15.66 6.60 11.59 7.25 6.07 6.73 13.63 12.35

10 4.9 2.6 276.28 56.38 21.69 15.26 6.43 11.49 7.14 6.25 6.83 13.60 12.08 11 4.9 2.7 279.77 57.10 21.15 14.88 6.27 11.40 7.04 6.43 6.94 13.58 11.85 12 5.0 1.7 243.04 48.61 28.59 20.12 8.47 12.57 8.35 4.18 5.98 13.93 17.57 13 5.0 1.8 247.72 49.54 27.52 19.37 8.16 12.40 8.17 4.51 6.07 13.87 16.26 14 5.0 1.9 252.22 50.44 26.55 18.68 7.87 12.24 8.00 4.81 6.15 13.81 15.27 15 5.0 2.0 256.57 51.31 25.66 18.06 7.60 12.09 7.83 5.08 6.23 13.76 14.51

16 5.0 2.1 260.78 52.16 24.84 17.48 7.36 11.96 7.68 5.33 6.32 13.72 13.89 17 5.0 2.2 264.86 52.97 24.08 16.94 7.13 11.83 7.54 5.57 6.41 13.68 13.39 18 5.0 2.3 268.81 53.76 23.37 16.45 6.93 11.72 7.41 5.79 6.50 13.64 12.97 19 5.0 2.4 272.65 54.53 22.72 15.99 6.73 11.60 7.28 6.00 6.59 13.61 12.61

20 5.0 2.5 276.38 55.28 22.11 15.56 6.55 11.50 7.16 6.20 6.69 13.58 12.31 21 5.0 2.6 280.02 56.00 21.54 15.16 6.38 11.40 7.05 6.38 6.79 13.56 12.05 22 5.0 2.7 283.57 56.71 21.00 14.78 6.22 11.30 6.95 6.56 6.90 13.53 11.82 23 5.1 1.7 246.27 48.29 28.41 19.99 8.42 12.47 8.26 4.33 5.96 13.89 17.53 24 5.1 1.8 251.01 49.22 27.34 19.24 8.10 12.30 8.08 4.65 6.04 13.82 16.21

25 5.1 1.9 255.58 50.11 26.38 18.56 7.81 12.14 7.91 4.94 6.12 13.77 15.23

26 5.1 2.0 259.98 50.98 25.49 17.94 7.55 12.00 7.74 5.22 6.20 13.72 14.47 27 5.1 2.1 264.25 51.81 24.67 17.36 7.31 11.86 7.59 5.47 6.28 13.67 13.85 28 5.1 2.2 268.37 52.62 23.92 16.83 7.09 11.74 7.45 5.70 6.36 13.63 13.35 29 5.1 2.3 272.38 53.41 23.22 16.34 6.88 11.62 7.32 5.92 6.45 13.60 12.93 30 5.1 2.4 276.27 54.17 22.57 15.88 6.69 11.51 7.19 6.12 6.54 13.57 12.58 31 5.1 2.5 280.06 54.91 21.97 15.46 6.51 11.41 7.07 6.32 6.64 13.54 12.27 32 5.1 2.6 283.74 55.64 21.40 15.06 6.34 11.31 6.96 6.50 6.75 13.51 12.01 33 5.1 2.7 287.34 56.34 20.87 14.68 6.18 11.21 6.86 6.68 6.86 13.49 11.78

34 5.2 1.7 249.48 47.98 28.22 19.86 8.36 12.37 8.18 4.47 5.93 13.84 17.48 35 5.2 1.8 254.28 48.90 27.17 19.12 8.05 12.20 7.99 4.79 6.00 13.78 16.17 36 5.2 1.9 258.91 49.79 26.20 18.44 7.76 12.04 7.81 5.08 6.08 13.72 15.19 37 5.2 2.0 263.37 50.65 25.32 17.82 7.50 11.90 7.65 5.34 6.16 13.67 14.43 38 5.2 2.1 267.69 51.48 24.51 17.25 7.26 11.77 7.50 5.59 6.24 13.63 13.81 39 5.2 2.2 271.87 52.28 23.77 16.72 7.04 11.64 7.36 5.82 6.32 13.59 13.31 40 5.2 2.3 275.93 53.06 23.07 16.24 6.84 11.53 7.23 6.04 6.41 13.55 12.89 41 5.2 2.4 279.87 53.82 22.43 15.78 6.64 11.42 7.10 6.24 6.50 13.52 12.54

42 5.2 2.5 283.71 54.56 21.82 15.36 6.47 11.31 6.98 6.44 6.60 13.49 12.24 43 5.2 2.6 287.44 55.28 21.26 14.96 6.30 11.22 6.87 6.62 6.71 13.47 11.97 44 5.2 2.7 291.08 55.98 20.73 14.59 6.14 11.12 6.77 6.79 6.82 13.45 11.75 45 5.3 1.7 252.67 47.67 28.04 19.73 8.31 12.27 8.09 4.60 5.90 13.80 17.44 46 5.3 1.8 257.53 48.59 26.99 19.00 8.00 12.10 7.90 4.92 5.97 13.74 16.13 47 5.3 1.9 262.21 49.47 26.04 18.32 7.72 11.95 7.72 5.20 6.04 13.68 15.15 48 5.3 2.0 266.74 50.33 25.16 17.71 7.46 11.81 7.56 5.47 6.12 13.63 14.39 49 5.3 2.1 271.11 51.15 24.36 17.14 7.22 11.68 7.41 5.71 6.19 13.58 13.77 50 5.3 2.2 275.35 51.95 23.61 16.62 7.00 11.55 7.27 5.94 6.28 13.54 13.27 51 5.3 2.3 279.46 52.73 22.93 16.13 6.79 11.44 7.14 6.15 6.37 13.51 12.86 52 5.3 2.4 283.45 53.48 22.28 15.68 6.60 11.33 7.01 6.36 6.46 13.48 12.50 53 5.3 2.5 287.33 54.21 21.69 15.26 6.43 11.23 6.90 6.55 6.56 13.45 12.20 54 5.3 2.6 291.11 54.93 21.13 14.87 6.26 11.13 6.79 6.72 6.67 13.43 11.94 55 5.3 2.7 294.80 55.62 20.60 14.50 6.10 11.04 6.68 6.90 6.79 13.40 11.71 56 5.4 1.7 255.84 47.38 27.87 19.61 8.26 12.17 8.00 4.73 5.87 13.76 17.40

57 5.4 1.8 260.76 48.29 26.83 18.88 7.95 12.01 7.81 5.04 5.93 13.69 16.09 58 5.4 1.9 265.50 49.17 25.88 18.21 7.67 11.86 7.63 5.32 6.00 13.64 15.11 59 5.4 2.0 270.08 50.01 25.01 17.60 7.41 11.72 7.47 5.58 6.08 13.59 14.35 60 5.4 2.1 274.51 50.83 24.21 17.03 7.17 11.59 7.32 5.83 6.15 13.54 13.74 61 5.4 2.2 278.80 51.63 23.47 16.51 6.95 11.46 7.18 6.05 6.24 13.50 13.24

62 5.4 2.3 282.96 52.40 22.78 16.03 6.75 11.35 7.05 6.26 6.33 13.47 12.82 63 5.4 2.4 287.00 53.15 22.15 15.58 6.56 11.24 6.92 6.46 6.43 13.44 12.47 64 5.4 2.5 290.94 53.88 21.55 15.17 6.39 11.14 6.81 6.65 6.53 13.41 12.17 65 5.4 2.6 294.76 54.59 20.99 14.77 6.22 11.04 6.70 6.83 6.65 13.38 11.91

66 5.4 2.7 298.50 55.28 20.47 14.41 6.07 10.95 6.60 7.00 6.77 13.36 11.68

67 5.5 1.7 258.99 47.09 27.70 19.49 8.21 12.08 7.91 4.85 5.83 13.72 17.36 68 5.5 1.8 263.97 47.99 26.66 18.76 7.90 11.92 7.72 5.16 5.90 13.65 16.05 69 5.5 1.9 268.77 48.87 25.72 18.10 7.62 11.77 7.54 5.44 5.96 13.59 15.07 70 5.5 2.0 273.40 49.71 24.85 17.49 7.36 11.63 7.38 5.70 6.04 13.55 14.31 71 5.5 2.1 277.89 50.52 24.06 16.93 7.13 11.50 7.23 5.93 6.11 13.50 13.70 72 5.5 2.2 282.23 51.31 23.32 16.41 6.91 11.38 7.09 6.16 6.20 13.46 13.20

73 5.5 2.3 286.44 52.08 22.64 15.93 6.71 11.26 6.96 6.37 6.29 13.43 12.79 74 5.5 2.4 290.54 52.82 22.01 15.49 6.52 11.16 6.84 6.56 6.40 13.40 12.43

75 5.5 2.5 294.52 53.55 21.42 15.07 6.35 11.05 6.72 6.75 6.51 13.37 12.13 76 5.5 2.6 298.39 54.25 20.87 14.68 6.18 10.96 6.61 6.92 6.63 13.34 11.87 77 5.5 2.7 302.17 54.94 20.35 14.32 6.03 10.87 6.51 7.09 6.76 13.32 11.64 78 5.6 1.7 262.12 46.81 27.53 19.38 8.16 11.99 7.82 4.97 5.80 13.67 17.32 79 5.6 1.8 267.16 47.71 26.50 18.65 7.85 11.83 7.63 5.27 5.86 13.61 16.01 80 5.6 1.9 272.02 48.57 25.57 17.99 7.58 11.68 7.46 5.55 5.92 13.55 15.03 81 5.6 2.0 276.71 49.41 24.71 17.39 7.32 11.54 7.29 5.80 6.00 13.50 14.27 82 5.6 2.1 281.25 50.22 23.92 16.83 7.09 11.41 7.14 6.04 6.08 13.46 13.66

83 5.6 2.2 285.64 51.01 23.19 16.32 6.87 11.29 7.01 6.26 6.16 13.42 13.17 84 5.6 2.3 289.90 51.77 22.51 15.84 6.67 11.18 6.87 6.46 6.26 13.39 12.75 85 5.6 2.4 294.05 52.51 21.88 15.40 6.48 11.07 6.75 6.66 6.37 13.36 12.40 86 5.6 2.5 298.08 53.23 21.29 14.98 6.31 10.97 6.64 6.84 6.49 13.33 12.10 87 5.6 2.6 302.00 53.93 20.74 14.60 6.15 10.88 6.53 7.01 6.62 13.30 11.84 88 5.6 2.7 305.82 54.61 20.23 14.23 5.99 10.79 6.43 7.18 6.76 13.28 11.61 89 5.7 1.7 265.23 46.53 27.37 19.26 8.11 11.90 7.73 5.08 5.76 13.63 17.28 90 5.7 1.8 270.33 47.43 26.35 18.54 7.81 11.74 7.54 5.38 5.82 13.57 15.97 91 5.7 1.9 275.25 48.29 25.42 17.88 7.53 11.59 7.37 5.65 5.88 13.51 15.00 92 5.7 2.0 279.99 49.12 24.56 17.28 7.28 11.45 7.21 5.90 5.96 13.46 14.24 93 5.7 2.1 284.58 49.93 23.77 16.73 7.04 11.33 7.06 6.13 6.04 13.42 13.63 94 5.7 2.2 289.03 50.71 23.05 16.22 6.83 11.21 6.92 6.35 6.13 13.38 13.13 95 5.7 2.3 293.35 51.46 22.38 15.75 6.63 11.10 6.79 6.55 6.24 13.35 12.72 96 5.7 2.4 297.54 52.20 21.75 15.31 6.44 10.99 6.67 6.75 6.35 13.32 12.37 97 5.7 2.5 301.61 52.91 21.17 14.89 6.27 10.89 6.56 6.93 6.48 13.29 12.07

98 5.7 2.6 305.58 53.61 20.62 14.51 6.11 10.80 6.45 7.10 6.62 13.26 11.81 99 5.7 2.7 309.45 54.29 20.11 14.15 5.96 10.71 6.35 7.27 6.77 13.24 11.58

100 5.8 1.7 268.32 46.26 27.21 19.15 8.06 11.81 7.64 5.19 5.72 13.59 17.24 101 5.8 1.8 273.48 47.15 26.20 18.43 7.76 11.65 7.45 5.48 5.78 13.53 15.93 102 5.8 1.9 278.46 48.01 25.27 17.78 7.49 11.51 7.28 5.75 5.85 13.48 14.96

103 5.8 2.0 283.26 48.84 24.42 17.18 7.24 11.37 7.12 6.00 5.92 13.43 14.20 104 5.8 2.1 287.90 49.64 23.64 16.63 7.00 11.25 6.97 6.23 6.01 13.38 13.59 105 5.8 2.2 292.40 50.41 22.92 16.13 6.79 11.13 6.83 6.44 6.11 13.34 13.10 106 5.8 2.3 296.77 51.17 22.25 15.65 6.59 11.02 6.71 6.64 6.22 13.31 12.68

107 5.8 2.4 301.01 51.90 21.62 15.22 6.41 10.91 6.59 6.83 6.34 13.28 12.33

108 5.8 2.5 305.13 52.61 21.04 14.81 6.24 10.81 6.47 7.01 6.48 13.25 12.03 109 5.8 2.6 309.15 53.30 20.50 14.43 6.07 10.72 6.37 7.18 6.63 13.23 11.78 110 5.8 2.7 313.06 53.98 19.99 14.07 5.92 10.63 6.27 7.35 6.80 13.20 11.55 111 5.9 1.7 271.40 46.00 27.06 19.04 8.02 11.73 7.55 5.29 5.68 13.56 17.20 112 5.9 1.8 276.62 46.88 26.05 18.33 7.72 11.57 7.37 5.58 5.74 13.49 15.90 113 5.9 1.9 281.65 47.74 25.12 17.68 7.44 11.42 7.19 5.84 5.81 13.44 14.92 114 5.9 2.0 286.50 48.56 24.28 17.09 7.19 11.29 7.03 6.09 5.89 13.39 14.17 115 5.9 2.1 291.20 49.36 23.50 16.54 6.96 11.17 6.89 6.31 5.98 13.34 13.56

116 5.9 2.2 295.75 50.13 22.79 16.03 6.75 11.05 6.75 6.52 6.09 13.30 13.07 117 5.9 2.3 300.17 50.88 22.12 15.57 6.55 10.94 6.62 6.72 6.21 13.27 12.65 118 5.9 2.4 304.46 51.60 21.50 15.13 6.37 10.83 6.50 6.91 6.35 13.24 12.30 119 5.9 2.5 308.63 52.31 20.92 14.72 6.20 10.74 6.39 7.09 6.49 13.21 12.00 120 5.9 2.6 312.69 53.00 20.38 14.34 6.04 10.64 6.29 7.26 6.66 13.19 11.74 121 5.9 2.7 316.65 53.67 19.88 13.99 5.89 10.55 6.19 7.42 6.83 13.17 11.52 122 6.0 1.7 274.46 45.74 26.91 18.93 7.97 11.64 7.47 5.38 5.64 13.52 17.16 123 6.0 1.8 279.73 46.62 25.90 18.23 7.67 11.49 7.28 5.67 5.71 13.45 15.86

124	6.0	1.9	284.82	47.47	24.98	17.58	7.40	11.34	7.11	5.93	5.78	13.40	14.89
125	6.0	2.0	289.73	48.29	24.14	16.99	7.15	11.21	6.95	6.17	5.87	13.35	14.13
126	6.0	2.1	294.48	49.08	23.37	16.45	6.93	11.09	6.80	6.39	5.97	13.31	13.53
127	6.0	2.2	299.09	49.85	22.66	15.94	6.71	10.97	6.67	6.60	6.08	13.27	13.03
128	6.0	2.3	303.55	50.59	22.00	15.48	6.52	10.86	6.54	6.80	6.21	13.23	12.62
129	6.0	2.4	307.89	51.31	21.38	15.05	6.34	10.76	6.42	6.99	6.36	13.20	12.27
130	6.0	2.5	312.11	52.02	20.81	14.64	6.17	10.66	6.31	7.17	6.52	13.18	11.97
131	6.0	2.6	316.21	52.70	20.27	14.26	6.01	10.57	6.21	7.33	6.70	13.15	11.71
132	6.0	2.7	320.22	53.37	19.77	13.91	5.86	10.48	6.12	7.49	6.89	13.13	11.49
133	6.1	1.7	277.50	45.49	26.76	18.83	7.93	11.56	7.38	5.47	5.61	13.48	17.13
134	6.1	1.8	282.83	46.37	25.76	18.13	7.63	11.41	7.19	5.75	5.67	13.42	15.83
135	6.1	1.9	287.98	47.21	24.85	17.48	7.36	11.27	7.02	6.01	5.75	13.36	14.86
136	6.1	2.0	292.94	48.02	24.01	16.90	7.11	11.13	6.87	6.25	5.84	13.31	14.10
137	6.1	2.1	297.75	48.81	23.24	16.36	6.89	11.01	6.72	6.47	5.95	13.27	13.50
138	6.1	2.2	302.40	49.57	22.53	15.86	6.68	10.90	6.59	6.68	6.08	13.23	13.00
139	6.1	2.3	306.91	50.31	21.88	15.39	6.48	10.79	6.46	6.88	6.22	13.20	12.59
140	6.1	2.4	311.30	51.03	21.26	14.96	6.30	10.68	6.35	7.06	6.38	13.17	12.24
141	6.1	2.5	315.56	51.73	20.69	14.56	6.13	10.59	6.24	7.24	6.56	13.14	11.94
142	6.1	2.6	319.72	52.41	20.16	14.19	5.97	10.49	6.14	7.40	6.75	13.11	11.68
143	6.1	2.7	323.76	53.08	19.66	13.83	5.82	10.40	6.04	7.56	6.96	13.09	11.46
144	6.2	1.7	280.52	45.25	26.61	18.73	7.89	11.48	7.29	5.56	5.57	13.44	17.09
145	6.2	1.8	285.92	46.12	25.62	18.03	7.59	11.33	7.11	5.84	5.64	13.38	15.79
146	6.2	1.9	291.12	46.95	24.71	17.39	7.32	11.19	6.94	6.09	5.73	13.33	14.82
147	6.2	2.0	296.14	47.76	23.88	16.81	7.08	11.06	6.78	6.33	5.83	13.28	14.07
148	6.2	2.1	300.99	48.55	23.12	16.27	6.85	10.94	6.64	6.55	5.95	13.23	13.46
149	6.2	2.2	305.70	49.31	22.41	15.77	6.64	10.82	6.51	6.75	6.09	13.20	12.97
150	6.2	2.3	310.26	50.04	21.76	15.31	6.45	10.71	6.38	6.95	6.24	13.16	12.56
151	6.2	2.4	314.69	50.76	21.15	14.88	6.27	10.61	6.27	7.13	6.42	13.13	12.21
152	6.2	2.5	319.00	51.45	20.58	14.48	6.10	10.51	6.16	7.30	6.61	13.10	11.91
153	6.2	2.6	323.20	52.13	20.05	14.11	5.94	10.42	6.06	7.47	6.82	13.08	11.66
154	6.2	2.7	327.29	52.79	19.55	13.76	5.79	10.33	5.97	7.63	7.05	13.06	11.43

Table 8.8: Optimap results for FPSOs of 501.33kton displacement, 2200kbbl Oil storage capacity being compared with Yuum Ka'Ak Naab

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E] [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.9	1.7	302.85	61.81	36.36	26.13	10.23	6.99	6.04	3.60	11.83	15.80	19.30
2	4.9	1.8	308.67	62.99	35.00	25.15	9.84	6.77	5.87	3.99	11.88	15.72	17.96
3	4.9	1.9	314.28	64.14	33.76	24.26	9.49	6.57	5.70	4.33	11.93	15.65	16.94
4	4.9	2.0	319.70	65.25	32.62	23.45	9.18	6.38	5.55	4.64	11.97	15.60	16.14
5	4.9	2.1	324.95	66.32	31.58	22.70	8.88	6.20	5.40	4.92	12.01	15.54	15.50
6	4.9	2.2	330.02	67.35	30.61	22.00	8.61	6.04	5.26	5.17	12.06	15.50	14.96

7	4.9	2.3	334.95	68.36	29.72	21.36	8.36	5.89	5.13	5.41	12.11	15.46	14.52
8	4.9	2.4	339.74	69.33	28.89	20.76	8.13	5.76	5.00	5.62	12.17	15.42	14.14
9	4.9	2.5	344.39	70.28	28.11	20.21	7.91	5.63	4.88	5.82	12.24	15.39	13.81
10	4.9	2.6	348.92	71.21	27.39	19.69	7.70	5.50	4.77	6.01	12.32	15.36	13.52
11	4.9	2.7	353.34	72.11	26.71	19.20	7.51	5.39	4.66	6.18	12.42	15.33	13.28
12	5.0	1.7	306.95	61.39	36.11	25.96	10.16	6.86	5.96	3.77	11.75	15.74	19.24
13	5.0	1.8	312.86	62.57	34.76	24.99	9.78	6.64	5.79	4.15	11.78	15.67	17.91
14	5.0	1.9	318.55	63.71	33.53	24.10	9.43	6.44	5.62	4.48	11.81	15.60	16.89
15	5.0	2.0	324.04	64.81	32.40	23.29	9.11	6.25	5.47	4.79	11.83	15.54	16.09
16	5.0	2.1	329.35	65.87	31.37	22.54	8.82	6.08	5.32	5.06	11.86	15.49	15.45
17	5.0	2.2	334.50	66.90	30.41	21.86	8.55	5.92	5.18	5.31	11.88	15.44	14.92
18	5.0	2.3	339.49	67.90	29.52	21.22	8.30	5.77	5.04	5.54	11.92	15.40	14.47
19	5.0	2.4	344.34	68.87	28.70	20.62	8.07	5.64	4.92	5.75	11.97	15.37	14.09
20	5.0	2.5	349.06	69.81	27.92	20.07	7.85	5.51	4.80	5.94	12.03	15.33	13.77
21	5.0	2.6	353.65	70.73	27.20	19.55	7.65	5.39	4.68	6.12	12.11	15.30	13.48
22	5.0	2.7	358.13	71.63	26.53	19.07	7.46	5.28	4.58	6.29	12.21	15.28	13.23
23	5.1	1.7	311.03	60.99	35.87	25.78	10.09	6.73	5.88	3.93	11.65	15.69	19.19
24	5.1	1.8	317.01	62.16	34.53	24.82	9.71	6.51	5.71	4.30	11.67	15.62	17.86
25	5.1	1.9	322.78	63.29	33.31	23.94	9.37	6.31	5.54	4.63	11.67	15.55	16.84
26	5.1	2.0	328.35	64.38	32.19	23.14	9.05	6.13	5.38	4.92	11.68	15.49	16.05
27	5.1	2.1	333.73	65.44	31.16	22.40	8.76	5.96	5.23	5.19	11.69	15.44	15.40
28	5.1	2.2	338.94	66.46	30.21	21.71	8.50	5.80	5.09	5.43	11.71	15.39	14.87
29	5.1	2.3	344.00	67.45	29.33	21.08	8.25	5.66	4.96	5.66	11.73	15.35	14.43
30	5.1	2.4	348.92	68.42	28.51	20.49	8.02	5.52	4.83	5.86	11.77	15.32	14.05
31	5.1	2.5	353.70	69.35	27.74	19.94	7.80	5.40	4.71	6.05	11.83	15.28	13.72
32	5.1	2.6	358.35	70.27	27.03	19.42	7.60	5.28	4.60	6.22	11.90	15.25	13.44
33	5.1	2.7	362.89	71.15	26.35	18.94	7.41	5.18	4.49	6.39	11.99	15.23	13.19
34	5.2	1.7	315.08	60.59	35.64	25.62	10.02	6.60	5.80	4.09	11.54	15.64	19.14
35	5.2	1.8	321.14	61.76	34.31	24.66	9.65	6.38	5.62	4.44	11.54	15.57	17.81
36	5.2	1.9	326.98	62.88	33.10	23.79	9.31	6.19	5.46	4.76	11.53	15.50	16.80
37	5.2	2.0	332.62	63.97	31.98	22.99	9.00	6.01	5.30	5.05	11.52	15.44	16.00
38	5.2	2.1	338.08	65.01	30.96	22.25	8.71	5.84	5.15	5.31	11.52	15.39	15.36
39	5.2	2.2	343.36	66.03	30.01	21.57	8.44	5.69	5.00	5.55	11.52	15.34	14.83
40	5.2	2.3	348.49	67.02	29.14	20.94	8.19	5.55	4.87	5.77	11.54	15.30	14.38
41	5.2	2.4	353.47	67.97	28.32	20.36	7.97	5.42	4.74	5.97	11.57	15.27	14.01
42	5.2	2.5	358.31	68.91	27.56	19.81	7.75	5.29	4.62	6.15	11.62	15.23	13.68
43	5.2	2.6	363.02	69.81	26.85	19.30	7.55	5.18	4.51	6.32	11.70	15.20	13.40
44	5.2	2.7	367.62	70.70	26.18	18.82	7.36	5.07	4.40	6.48	11.79	15.18	13.15
45	5.3	1.7	319.11	60.21	35.42	25.46	9.96	6.48	5.72	4.23	11.43	15.59	19.09
46	5.3	1.8	325.25	61.37	34.09	24.50	9.59	6.26	5.54	4.58	11.40	15.52	17.76
47	5.3	1.9	331.16	62.48	32.89	23.64	9.25	6.07	5.37	4.89	11.38	15.45	16.75
48	5.3	2.0	336.87	63.56	31.78	22.84	8.94	5.89	5.21	5.17	11.35	15.39	15.96
49	5.3	2.1	342.40	64.60	30.76	22.11	8.65	5.73	5.06	5.43	11.34	15.34	15.31
50	5.3	2.2	347.75	65.61	29.82	21.44	8.39	5.58	4.92	5.66	11.33	15.30	14.78
51	5.3	2.3	352.94	66.59	28.95	20.81	8.14	5.44	4.78	5.87	11.34	15.25	14.34
52	5.3	2.4	357.98	67.54	28.14	20.23	7.92	5.31	4.66	6.06	11.37	15.22	13.96
53	5.3	2.5	362.89										

68.47 27.39 19.68 7.70 5.19 4.54 6.24 11.43 15.19 13.64 54 5.3 2.6 367.66 69.37 26.68 19.18 7.50 5.08 4.42 6.40 11.50 15.16 13.36 55 5.3 2.7 372.32 70.25 26.02 18.70 7.32 4.98 4.32 6.56 11.60 15.13 13.11

56 5.4 1.7 323.11 59.84 35.20 25.30 9.90 6.35 5.64 4.36 11.30 15.54 19.04 57 5.4 1.8 329.33 60.99 33.88 24.35 9.53 6.14 5.46 4.71 11.26 15.47 17.71 58 5.4 1.9 335.32 62.10 32.68 23.49 9.19 5.95 5.29 5.01 11.22 15.40 16.70 59 5.4 2.0 341.10 63.17 31.58 22.70 8.88 5.78 5.12 5.28 11.18 15.35 15.91 60 5.4 2.1 346.69 64.20 30.57 21.97 8.60 5.62 4.97 5.53 11.16 15.29 15.27

61 5.4 2.2 352.11 65.21 29.64 21.30 8.34 5.47 4.83 5.75 11.15 15.25 14.74 62 5.4 2.3 357.37 66.18 28.77 20.68 8.09 5.33 4.70 5.96 11.15 15.21 14.30 63 5.4 2.4 362.47 67.12 27.97 20.10 7.87 5.21 4.57 6.15 11.18 15.17 13.92 64 5.4 2.5 367.44 68.04 27.22 19.56 7.65 5.09 4.45 6.32 11.24 15.14 13.60

65 5.4 2.6 372.27 68.94 26.52 19.06 7.46 4.99 4.34 6.48 11.32 15.11 13.32

66 5.4 2.7 376.99 69.81 25.86 18.58 7.27 4.89 4.23 6.63 11.43 15.08 13.08 67 5.5 1.7 327.09 59.47 34.98 25.14 9.84 6.23 5.55 4.49 11.17 15.50 18.99 68 5.5 1.8 333.38 60.61 33.67 24.20 9.47 6.03 5.37 4.82 11.11 15.42 17.67 69 5.5 1.9 339.44 61.72 32.48 23.35 9.14 5.84 5.20 5.12 11.05 15.36 16.66 70 5.5 2.0 345.30 62.78 31.39 22.56 8.83 5.67 5.04 5.39 11.01 15.30 15.87 71 5.5 2.1 350.96 63.81 30.39 21.84 8.55 5.51 4.89 5.63 10.98 15.25 15.23 72 5.5 2.2 356.44 64.81 29.46 21.17 8.29 5.37 4.74 5.84 10.96 15.20 14.70

73 5.5 2.3 361.76 65.78 28.60 20.55 8.04 5.24 4.61 6.04 10.97 15.16 14.26 74 5.5 2.4 366.93 66.72 27.80 19.98 7.82 5.11 4.48 6.22 11.00 15.12 13.88 75 5.5 2.5 371.96 67.63 27.05 19.44 7.61 5.00 4.36 6.39 11.07 15.09 13.56 76 5.5 2.6 376.85 68.52 26.35 18.94 7.41 4.90 4.25 6.55 11.16 15.06 13.28 77 5.5 2.7 381.63 69.39 25.70 18.47 7.23 4.80 4.15 6.69 11.29 15.04 13.04

78 5.6 1.7 331.04 59.11 34.77 24.99 9.78 6.12 5.47 4.61 11.03 15.45 18.94

79 5.6 1.8 337.41 60.25 33.47 24.06 9.41 5.91 5.29 4.93 10.95 15.38 17.62 80 5.6 1.9 343.55 61.35 32.29 23.21 9.08 5.73 5.11 5.22 10.89 15.31 16.62 81 5.6 2.0 349.47 62.41 31.20 22.43 8.78 5.56 4.95 5.48 10.83 15.25 15.83

82 5.6 2.1 355.20 63.43 30.20 21.71 8.49 5.41 4.80 5.71 10.80 15.20 15.19 83 5.6 2.2 360.75 64.42 29.28 21.05 8.24 5.27 4.66 5.92 10.78 15.16 14.66 84 5.6 2.3 366.14 65.38 28.43 20.43 8.00 5.14 4.52 6.12 10.80 15.12 14.22 85 5.6 2.4 371.37 66.32 27.63 19.86 7.77 5.02 4.40 6.29 10.84 15.08 13.85 86 5.6 2.5 376.45 67.22 26.89 19.33 7.56 4.91 4.28 6.45 10.91 15.05 13.52 87 5.6 2.6 381.41 68.11 26.20 18.83 7.37 4.81 4.17 6.60 11.02 15.02 13.25 88 5.6 2.7 386.24 68.97 25.54 18.36 7.18 4.71 4.06 6.74 11.17 14.99 13.00 89 5.7 1.7 334.97 58.77 34.57 24.85 9.72 6.01 5.39 4.72 10.88 15.40 18.90 90 5.7 1.8 341.41 59.90 33.28 23.92 9.36 5.81 5.20 5.03 10.79 15.33 17.58 91 5.7 1.9 347.62 60.99 32.10 23.07 9.03 5.62 5.03 5.31 10.72 15.27 16.57 92 5.7 2.0 353.62 62.04 31.02 22.29 8.72 5.46 4.87 5.57 10.66 15.21 15.78 93 5.7 2.1 359.42 63.06 30.03 21.58 8.44 5.31 4.71 5.79 10.62 15.16 15.15 94 5.7 2.2 365.03 64.04 29.11 20.92 8.19 5.17 4.57 6.00 10.61 15.11 14.62 95 5.7 2.3 370.48 65.00 28.26 20.31 7.95 5.05 4.44 6.18 10.63 15.07 14.18 96 5.7 2.4 375.77 65.93 27.47 19.74 7.73 4.93 4.31 6.35 10.69 15.03 13.81

97 5.7 2.5 380.92 66.83 26.73 19.21 7.52 4.83 4.19 6.51 10.78 15.00 13.49 98 5.7 2.6 385.94 67.71 26.04 18.72 7.32 4.73 4.08 6.66 10.91 14.97 13.21 99 5.7 2.7 390.82 68.57 25.39 18.25 7.14 4.63 3.98 6.79 11.08 14.95 12.96

100 5.8 1.7 338.88 58.43 34.37 24.70 9.67 5.90 5.30 4.82 10.73 15.36 18.85 101 5.8 1.8 345.40 59.55 33.08 23.78 9.30 5.70 5.12 5.13 10.63 15.29 17.53

102 5.8 1.9 351.68 60.63 31.91 22.94 8.98 5.52 4.94 5.40 10.55 15.22 16.53 103 5.8 2.0 357.74 61.68 30.84 22.17 8.67 5.36 4.78 5.64 10.49 15.16 15.74 104 5.8 2.1 363.61 62.69 29.85 21.46 8.40 5.22 4.63 5.86 10.46 15.11 15.11 105 5.8 2.2 369.29 63.67 28.94 20.80 8.14 5.08 4.49 6.06 10.46 15.07 14.58

106 5.8 2.3 374.80 64.62 28.10 20.19 7.90 4.96 4.35 6.24 10.49 15.03 14.14

107 5.8 2.4 380.16 65.54 27.31 19.63 7.68 4.85 4.23 6.41 10.56 14.99 13.77 108 5.8 2.5 385.37 66.44 26.58 19.10 7.47 4.74 4.11 6.56 10.68 14.96 13.45 109 5.8 2.6 390.44 67.32 25.89 18.61 7.28 4.65 4.00 6.70 10.83 14.93 13.17 110 5.8 2.7 395.38 68.17 25.25 18.15 7.10 4.56 3.90 6.83 11.03 14.90 12.93 111 5.9 1.7 342.76 58.10 34.17 24.56 9.61 5.79 5.22 4.91 10.57

												15.32	18.81
112	5.9	1.8	349.35	59.21	32.90	23.64	9.25	5.60	5.03	5.21	10.47	15.24	17.49
113	5.9	1.9	355.71	60.29	31.73	22.81	8.92	5.42	4.86	5.48	10.39	15.18	16.49
114	5.9	2.0	361.84	61.33	30.66	22.04	8.62	5.27	4.70	5.71	10.33	15.12	15.70
115	5.9	2.1	367.77	62.33	29.68	21.33	8.35	5.13	4.54	5.92	10.30	15.07	15.07
116	5.9	2.2	373.52	63.31	28.78	20.68	8.09	5.00	4.40	6.12	10.31	15.02	14.55
117	5.9	2.3	379.10	64.25	27.94	20.08	7.86	4.88	4.27	6.29	10.37	14.98	14.11
118	5.9	2.4	384.51	65.17	27.15	19.52	7.64	4.77	4.15	6.45	10.46	14.95	13.74
119	5.9	2.5	389.78	66.06	26.43	18.99	7.43	4.67	4.03	6.60	10.60	14.92	13.42
120	5.9	2.6	394.91	66.93	25.74	18.50	7.24	4.57	3.92	6.74	10.79	14.89	13.14
121	5.9	2.7	399.91	67.78	25.10	18.04	7.06	4.48	3.82	6.86	11.02	14.86	12.89
122	6.0	1.7	346.62	57.77	33.98	24.43	9.56	5.69	5.13	5.00	10.42	15.27	18.76
123	6.0	1.8	353.29	58.88	32.71	23.51	9.20	5.50	4.95	5.29	10.31	15.20	17.45
124	6.0	1.9	359.72	59.95	31.55	22.68	8.87	5.33	4.77	5.55	10.23	15.14	16.45
125	6.0	2.0	365.92	60.99	30.49	21.92	8.58	5.18	4.61	5.77	10.18	15.08	15.66
126	6.0	2.1	371.92	61.99	29.52	21.22	8.30	5.04	4.46	5.98	10.16	15.03	15.03
127	6.0	2.2	377.73	62.96	28.62	20.57	8.05	4.91	4.32	6.17	10.19	14.98	14.51
128	6.0	2.3	383.37	63.89	27.78	19.97	7.81	4.80	4.19	6.34	10.27	14.94	14.07
129	6.0	2.4	388.85	64.81	27.00	19.41	7.59	4.69	4.06	6.49	10.39	14.91	13.70
130	6.0	2.5	394.17	65.70	26.28	18.89	7.39	4.59	3.95	6.63	10.56	14.87	13.38
131	6.0	2.6	399.36	66.56	25.60	18.40	7.20	4.50	3.84	6.77	10.79	14.85	13.10
132	6.0	2.7	404.42	67.40	24.96	17.94	7.02	4.42	3.74	6.89	11.06	14.82	12.86
133	6.1	1.7	350.46	57.45	33.80	24.29	9.51	5.59	5.05	5.08	10.27	15.23	18.72
134	6.1	1.8	357.21	58.56	32.53	23.38	9.15	5.41	4.86	5.36	10.16	15.16	17.41
135	6.1	1.9	363.70	59.62	31.38	22.55	8.83	5.24	4.69	5.61	10.08	15.09	16.41
136	6.1	2.0	369.97	60.65	30.33	21.80	8.53	5.09	4.53	5.83	10.04	15.04	15.63
137	6.1	2.1	376.04	61.65	29.36	21.10	8.26	4.96	4.38	6.03	10.04	14.99	14.99
138	6.1	2.2	381.92	62.61	28.46	20.45	8.00	4.83	4.24	6.21	10.09	14.94	14.47
139	6.1	2.3	387.62	63.54	27.63	19.86	7.77	4.72	4.10	6.37	10.20	14.90	14.04
140	6.1	2.4	393.16	64.45	26.85	19.30	7.55	4.62	3.98	6.52	10.35	14.87	13.66
141	6.1	2.5	398.54	65.33	26.13	18.78	7.35	4.52	3.87	6.66	10.56	14.83	13.35
142	6.1	2.6	403.79	66.19	25.46	18.30	7.16	4.43	3.76	6.79	10.82	14.80	13.07
143	6.1	2.7	408.90	67.03	24.83	17.84	6.98	4.35	3.66	6.91	11.13	14.78	12.83
144	6.2	1.7	354.28	57.14	33.61	24.16	9.45	5.49	4.97	5.15	10.11	15.19	18.68
145	6.2	1.8	361.10	58.24	32.36	23.26	9.10	5.31	4.78	5.42	10.01	15.12	17.37
146	6.2	1.9	367.67	59.30	31.21	22.43	8.78	5.15	4.60	5.66	9.94	15.05	16.37
147	6.2	2.0	374.01	60.32	30.16	21.68	8.48	5.01	4.44	5.88	9.91	15.00	15.59
148	6.2	2.1	380.14	61.31	29.20	20.98	8.21	4.88	4.29	6.07	9.94	14.95	14.96
149	6.2	2.2	386.08	62.27	28.30	20.34	7.96	4.76	4.15	6.24	10.02	14.90	14.44
150	6.2	2.3	391.84	63.20	27.48	19.75	7.73	4.65	4.02	6.40	10.16	14.86	14.00
151	6.2	2.4	397.44	64.10	26.71	19.20	7.51	4.55	3.90	6.55	10.35	14.83	13.63
152	6.2	2.5	402.89	64.98	25.99	18.68	7.31	4.46	3.79	6.69	10.60	14.79	13.31
153	6.2	2.6	408.19	65.84	25.32	18.20	7.12	4.37	3.69	6.81	10.90	14.76	13.04
154	6.2	2.7	413.35	66.67	24.69	17.75	6.94	4.29	3.59	6.93	11.26	14.74	12.80

Table 8.9: Optimap results for FPSOs of 273kton displacement, 1300kbbl Oil storage capacity being compared with Aker Smart 2

S/No	**L/B**	**B/D_m**	**L [m]**	**B [m]**	**D_m [m]**	**D [m]**	**F_B [m]**	**η_3 [m]**	**η_5 [deg]**	**E] [m]**	**BM [GNm]**	**$T_{n3,5}$ [s]**	**T_{n4} [s]**

1 4.9 1.7 243.82 49.76 29.27 21.95 7.32 5.60 6.05 3.93 5.21 14.33 17.49 2 4.9 1.8 248.51 50.72 28.18 21.13 7.04 5.41 5.89 4.20 5.24 14.26 16.31 3 4.9 1.9 253.03 51.64 27.18 20.38 6.79 5.24 5.73 4.45 5.26 14.19 15.40 4 4.9 2.0 257.40 52.53 26.26 19.70 6.57 5.09 5.57 4.68 5.28 14.14 14.68 5 4.9 2.1 261.62 53.39 25.42 19.07 6.36 4.94 5.43 4.88 5.29 14.09 14.10 6 4.9 2.2 265.70 54.23 24.65 18.49 6.16 4.81 5.29 5.06 5.31 14.04 13.62

7 4.9 2.3 269.67 55.03 23.93 17.95 5.98 4.68 5.15 5.23 5.33 14.00 13.21 8 4.9 2.4 273.52 55.82 23.26 17.44 5.81 4.56 5.03 5.38 5.35 13.97 12.87 9 4.9 2.5 277.27 56.59 22.63 16.98 5.66 4.46 4.91 5.52 5.38 13.93 12.57

10 4.9 2.6 280.92 57.33 22.05 16.54 5.51 4.35 4.79 5.65 5.41 13.91 12.31 11 4.9 2.7 284.48 58.06 21.50 16.13 5.38 4.26 4.68 5.77 5.44 13.88 12.08 12 5.0 1.7 247.13 49.43 29.07 21.81 7.27 5.49 5.98 4.06 5.18 14.28 17.45 13 5.0 1.8 251.88 50.38 27.99 20.99 7.00 5.31 5.81 4.33 5.20 14.21 16.26

14 5.0 1.9 256.46 51.29 27.00 20.25 6.75 5.14 5.65 4.58 5.21 14.15 15.36 15 5.0 2.0 260.89 52.18 26.09 19.57 6.52 4.98 5.49 4.79 5.22 14.09 14.64

16 5.0 2.1 265.16 53.03 25.25 18.94 6.31 4.84 5.34 4.99 5.23 14.04 14.06 17 5.0 2.2 269.31 53.86 24.48 18.36 6.12 4.70 5.20 5.17 5.24 14.00 13.58 18 5.0 2.3 273.33 54.67 23.77 17.83 5.94 4.58 5.07 5.33 5.25 13.96 13.17

19 5.0 2.4 277.23 55.45 23.10 17.33 5.78 4.47 4.94 5.48 5.27 13.92 12.83 20 5.0 2.5 281.03 56.21 22.48 16.86 5.62 4.36 4.82 5.62 5.29 13.89 12.53 21 5.0 2.6 284.73 56.95 21.90 16.43 5.48 4.26 4.71 5.74 5.32 13.86 12.27 22 5.0 2.7 288.33 57.67 21.36 16.02 5.34 4.17 4.60 5.86 5.35 13.83 12.05

23 5.1 1.7 250.41 49.10 28.88 21.66 7.22 5.38 5.90 4.19 5.14 14.23 17.40

24 5.1 1.8 255.23 50.05 27.80 20.85 6.95 5.20 5.73 4.45 5.15 14.16 16.22 25 5.1 1.9 259.87 50.96 26.82 20.11 6.70 5.03 5.57 4.69 5.16 14.10 15.31 26 5.1 2.0 264.35 51.83 25.92 19.44 6.48 4.88 5.41 4.90 5.16 14.04 14.60 27 5.1 2.1 268.69 52.68 25.09 18.82 6.27 4.74 5.26 5.09 5.16 13.99 14.02 28 5.1 2.2 272.89 53.51 24.32 18.24 6.08 4.61 5.12 5.27 5.17 13.95 13.54 29 5.1 2.3 276.96 54.31 23.61 17.71 5.90 4.49 4.98 5.43 5.17 13.91 13.13 30 5.1 2.4 280.92 55.08 22.95 17.21 5.74 4.37 4.86 5.57 5.19 13.87 12.79 31 5.1 2.5 284.77 55.84 22.33 16.75 5.58 4.27 4.73 5.70 5.20 13.84 12.49

32 5.1 2.6 288.51 56.57 21.76 16.32 5.44 4.17 4.62 5.82 5.23 13.81 12.23 33 5.1 2.7 292.17 57.29 21.22 15.91 5.30 4.08 4.51 5.94 5.26 13.79 12.01 34 5.2 1.7 253.68 48.78 28.70 21.52 7.17 5.28 5.83 4.31 5.10 14.19 17.36 35 5.2 1.8 258.56 49.72 27.62 20.72 6.91 5.10 5.65 4.57 5.10 14.12 16.17 36 5.2 1.9 263.26 50.63 26.65 19.98 6.66 4.93 5.48 4.80 5.10 14.05 15.27 37 5.2 2.0 267.80 51.50 25.75 19.31 6.44 4.78 5.33 5.01 5.10 14.00 14.56 38 5.2 2.1 272.19 52.34 24.93 18.69 6.23 4.64 5.18 5.19 5.09 13.95 13.98 39 5.2 2.2 276.44 53.16 24.16 18.12 6.04 4.51 5.03 5.36 5.09 13.90 13.50

40 5.2 2.3 280.57 53.96 23.46 17.59 5.86 4.39 4.90 5.51 5.09 13.86 13.09 41 5.2 2.4 284.58 54.73 22.80 17.10 5.70 4.28 4.77 5.65 5.10 13.83 12.75 42 5.2 2.5 288.48 55.48 22.19 16.64 5.55 4.18 4.65 5.78 5.11 13.80 12.46 43 5.2 2.6 292.27 56.21 21.62 16.21 5.40 4.09 4.53 5.90 5.14 13.77 12.20 44 5.2 2.7 295.97 56.92 21.08 15.81 5.27 4.00 4.42 6.00 5.17 13.74 11.97 45 5.3 1.7 256.92 48.48 28.51 21.39 7.13 5.17 5.75 4.42 5.06 14.14 17.31 46 5.3 1.8 261.86 49.41 27.45 20.59 6.86 4.99 5.57 4.68 5.05 14.07 16.13 47 5.3 1.9 266.62 50.31 26.48 19.86 6.62 4.83 5.40 4.90 5.04 14.01 15.23 48 5.3 2.0 271.22 51.17 25.59 19.19 6.40 4.68 5.24 5.10 5.03 13.95 14.52 49 5.3 2.1 275.67 52.01 24.77 18.58 6.19 4.54 5.09 5.28 5.02 13.90 13.94 50 5.3 2.2 279.97 52.83 24.01 18.01 6.00 4.42 4.95 5.44 5.01 13.86 13.46 51 5.3 2.3 284.15 53.61 23.31 17.48 5.83 4.30 4.81 5.59 5.01 13.82 13.06 52 5.3 2.4 288.21 54.38 22.66 16.99 5.66 4.19 4.68 5.73 5.01 13.78 12.71 53 5.3 2.5 292.16 55.13 22.05 16.54 5.51 4.09 4.56 5.85 5.03 13.75 12.42 54 5.3 2.6 296.01 55.85 21.48 16.11 5.37 4.00 4.45 5.96 5.05 13.72 12.16

55 5.3 2.7 299.75 56.56 20.95 15.71 5.24 3.92 4.34 6.07 5.08 13.70 11.94 56 5.4 1.7 260.14 48.17 28.34 21.25 7.08 5.07 5.67 4.53 5.01 14.10 17.27 57 5.4 1.8 265.14 49.10 27.28 20.46 6.82 4.89 5.49 4.78 4.99 14.03 16.09 58 5.4 1.9 269.97 49.99 26.31 19.73 6.58 4.73 5.32 4.99 4.97 13.97 15.19 59 5.4 2.0 274.62 50.86 25.43 19.07 6.36 4.59 5.16 5.19 4.96 13.91 14.48

60 5.4 2.1 279.12 51.69 24.61 18.46 6.15 4.45 5.01 5.36 4.94 13.86 13.90 61 5.4 2.2 283.49 52.50 23.86 17.90 5.97 4.33 4.86 5.52 4.93 13.82 13.42 62 5.4 2.3 287.72 53.28 23.17 17.37 5.79 4.22 4.72 5.66 4.93 13.78 13.02 63 5.4 2.4 291.83 54.04 22.52 16.89 5.63 4.11 4.60 5.79 4.93 13.74 12.68

64 5.4 2.5 295.83 54.78 21.91 16.43 5.48 4.01 4.47 5.91 4.94 13.71 12.38

65 5.4 2.6 299.72 55.50 21.35 16.01 5.34 3.92 4.36 6.02 4.97 13.68 12.13 66 5.4 2.7 303.51 56.21 20.82 15.61 5.20 3.84 4.25 6.12 5.00 13.66 11.90 67 5.5 1.7 263.34 47.88 28.16 21.12 7.04 4.97 5.59 4.63 4.95 14.06 17.23 68 5.5 1.8 268.41 48.80 27.11 20.33 6.78 4.80 5.41 4.87 4.93 13.99 16.05 69 5.5 1.9 273.29 49.69 26.15 19.61 6.54 4.64 5.23 5.08 4.91 13.92 15.15 70 5.5 2.0 278.00 50.55 25.27 18.95 6.32 4.50 5.07 5.27 4.88 13.87 14.44 71 5.5 2.1 282.56 51.37 24.46 18.35 6.12 4.36 4.92 5.44 4.86 13.82 13.86 72 5.5 2.2 286.97 52.18 23.72 17.79 5.93 4.24 4.77 5.59 4.85 13.77 13.39

73 5.5 2.3 291.26 52.96 23.02 17.27 5.76 4.13 4.64 5.73 4.84 13.74 12.98 74 5.5 2.4 295.42 53.71 22.38 16.79 5.60 4.03 4.51 5.85 4.85 13.70 12.64 75 5.5 2.5 299.47 54.45 21.78 16.33 5.44 3.94 4.39 5.97 4.86 13.67 12.35 76 5.5 2.6 303.41 55.17 21.22 15.91 5.30 3.85 4.27 6.07 4.89 13.64 12.09 77 5.5 2.7 307.25 55.86 20.69 15.52 5.17 3.77 4.16 6.17 4.93 13.61 11.87 78 5.6 1.7 266.52 47.59 28.00 21.00 7.00 4.88 5.51 4.72 4.90 14.01 17.19 79 5.6 1.8 271.65 48.51 26.95 20.21 6.74 4.70 5.32 4.96 4.87 13.94 16.01 80 5.6 1.9 276.59 49.39 26.00 19.50 6.50 4.55 5.15 5.16 4.84 13.88 15.11

81 5.6 2.0 281.36 50.24 25.12 18.84 6.28 4.41 4.99 5.34 4.81 13.83 14.40 82 5.6 2.1 285.97 51.07 24.32 18.24 6.08 4.28 4.83 5.51 4.78 13.78 13.83 83 5.6 2.2 290.44 51.86 23.57 17.68 5.89 4.16 4.69 5.65 4.77 13.73 13.35 84 5.6 2.3 294.78 52.64 22.89 17.16 5.72 4.05 4.55 5.79 4.76 13.69 12.95 85 5.6 2.4 298.99 53.39 22.25 16.68 5.56 3.95 4.42 5.91 4.77 13.66 12.61 86 5.6 2.5 303.09 54.12 21.65 16.24 5.41 3.86 4.30 6.02 4.79 13.63 12.32 87 5.6 2.6 307.07 54.83 21.09 15.82 5.27 3.78 4.19 6.12 4.82 13.60 12.06 88 5.6 2.7 310.96 55.53 20.57 15.42 5.14 3.70 4.08 6.21 4.86 13.57 11.84 89 5.7 1.7 269.69 47.31 27.83 20.87 6.96 4.78 5.42 4.81 4.84 13.97 17.15 90 5.7 1.8 274.87 48.22 26.79 20.09 6.70 4.61 5.24 5.04 4.80 13.90 15.97 91 5.7 1.9 279.87 49.10 25.84 19.38 6.46 4.46 5.07 5.24 4.76 13.84 15.08 92 5.7 2.0 284.70 49.95 24.97 18.73 6.24 4.32 4.90 5.41 4.73 13.79 14.37

93 5.7 2.1 289.37 50.77 24.17 18.13 6.04 4.20 4.75 5.57 4.71 13.74 13.79

94 5.7 2.2 293.89 51.56 23.44 17.58 5.86 4.08 4.60 5.71 4.69 13.69 13.32 95 5.7 2.3 298.28 52.33 22.75 17.06 5.69 3.98 4.47 5.84 4.69 13.65 12.92

96 5.7 2.4 302.54 53.08 22.12 16.59 5.53 3.88 4.34 5.95 4.70 13.62 12.58 97 5.7 2.5 306.68 53.80 21.52 16.14 5.38 3.79 4.22 6.06 4.72 13.59 12.28 98 5.7 2.6 310.72 54.51 20.97 15.72 5.24 3.71 4.10 6.15 4.76 13.56 12.03 99 5.7 2.7 314.65 55.20 20.45 15.33 5.11 3.63 4.00 6.24 4.81 13.53 11.80

100 5.8 1.7 272.83 47.04 27.67 20.75 6.92 4.69 5.34 4.89 4.77 13.93 17.11 101 5.8 1.8 278.08 47.94 26.64 19.98 6.66 4.52 5.15 5.11 4.73 13.86 15.94 102 5.8 1.9 283.14 48.82 25.69 19.27 6.42 4.38 4.98 5.30 4.69 13.80 15.04 103 5.8 2.0 288.02 49.66 24.83 18.62 6.21 4.24 4.82 5.47 4.66 13.75 14.33 104 5.8 2.1 292.74 50.47 24.03 18.03 6.01 4.12 4.66 5.62 4.63 13.70 13.76

105 5.8 2.2 297.32 51.26 23.30 17.48 5.83 4.01 4.52 5.76 4.62 13.65 13.28

106 5.8 2.3 301.76 52.03 22.62 16.97 5.66 3.90 4.38 5.88 4.62 13.61 12.88 107 5.8 2.4 306.07 52.77 21.99 16.49 5.50 3.81 4.25 5.99 4.63 13.58 12.54 108 5.8 2.5 310.26 53.49 21.40 16.05 5.35 3.72 4.13 6.09 4.66 13.55 12.25 109 5.8 2.6 314.34 54.20 20.85 15.63 5.21 3.64 4.02 6.19 4.71 13.52 12.00 110 5.8 2.7 318.32 54.88 20.33 15.25 5.08 3.57 3.91 6.27 4.78 13.49 11.77 111 5.9 1.7 275.96 46.77 27.51 20.64 6.88 4.60 5.26 4.97 4.71 13.89 17.07 112 5.9 1.8 281.27 47.67 26.48 19.86 6.62 4.44 5.07 5.18 4.66 13.82 15.90 113 5.9 1.9 286.38 48.54 25.55 19.16 6.39 4.29 4.90 5.36 4.62 13.76 15.00

114 5.9 2.0 291.32 49.38 24.69 18.52 6.17 4.16 4.73 5.53 4.58 13.71 14.30 115 5.9 2.1 296.10 50.19 23.90 17.92 5.97 4.04 4.58 5.67 4.56 13.66 13.72 116 5.9 2.2 300.73 50.97 23.17 17.38 5.79 3.93 4.43 5.80 4.55 13.61 13.25 117 5.9 2.3 305.21 51.73 22.49 16.87 5.62 3.83 4.30 5.92 4.56 13.58 12.85 118 5.9 2.4 309.58 52.47 21.86 16.40 5.47 3.74 4.17 6.03 4.58 13.54 12.51 119 5.9 2.5 313.82 53.19 21.28 15.96 5.32 3.66 4.05 6.12 4.62 13.51 12.22 120 5.9 2.6 317.95 53.89 20.73 15.54 5.18 3.58 3.94 6.21 4.68 13.48 11.96 121 5.9 2.7 321.97 54.57 20.21 15.16 5.05 3.51 3.83 6.30 4.76 13.46 11.74

122	6.0	1.7	279.07	46.51	27.36	20.52	6.84	4.52	5.17	5.03	4.64	13.85	17.04
123	6.0	1.8	284.44	47.41	26.34	19.75	6.58	4.36	4.99	5.24	4.59	13.78	15.86
124	6.0	1.9	289.61	48.27	25.40	19.05	6.35	4.21	4.81	5.42	4.55	13.72	14.97
125	6.0	2.0	294.60	49.10	24.55	18.41	6.14	4.09	4.65	5.57	4.51	13.67	14.26
126	6.0	2.1	299.43	49.91	23.76	17.82	5.94	3.97	4.49	5.71	4.49	13.62	13.69
127	6.0	2.2	304.11	50.69	23.04	17.28	5.76	3.86	4.35	5.84	4.49	13.58	13.22
128	6.0	2.3	308.65	51.44	22.37	16.77	5.59	3.77	4.21	5.95	4.50	13.54	12.82
129	6.0	2.4	313.06	52.18	21.74	16.31	5.44	3.68	4.09	6.05	4.53	13.50	12.48
130	6.0	2.5	317.35	52.89	21.16	15.87	5.29	3.60	3.97	6.15	4.59	13.47	12.19
131	6.0	2.6	321.53	53.59	20.61	15.46	5.15	3.52	3.86	6.23	4.66	13.44	11.93
132	6.0	2.7	325.60	54.27	20.10	15.07	5.02	3.45	3.75	6.31	4.75	13.42	11.71
133	6.1	1.7	282.16	46.26	27.21	20.41	6.80	4.43	5.09	5.10	4.58	13.82	17.00
134	6.1	1.8	287.59	47.15	26.19	19.64	6.55	4.28	4.90	5.29	4.52	13.75	15.83
135	6.1	1.9	292.82	48.00	25.26	18.95	6.32	4.14	4.73	5.46	4.48	13.69	14.93
136	6.1	2.0	297.87	48.83	24.42	18.31	6.10	4.01	4.56	5.62	4.45	13.63	14.23
137	6.1	2.1	302.75	49.63	23.63	17.73	5.91	3.90	4.41	5.75	4.43	13.58	13.66
138	6.1	2.2	307.48	50.41	22.91	17.18	5.73	3.80	4.26	5.87	4.44	13.54	13.18
139	6.1	2.3	312.07	51.16	22.24	16.68	5.56	3.70	4.13	5.98	4.46	13.50	12.79
140	6.1	2.4	316.53	51.89	21.62	16.22	5.41	3.62	4.00	6.08	4.50	13.47	12.45
141	6.1	2.5	320.87	52.60	21.04	15.78	5.26	3.54	3.89	6.17	4.57	13.43	12.16
142	6.1	2.6	325.09	53.29	20.50	15.37	5.12	3.46	3.78	6.25	4.66	13.41	11.90
143	6.1	2.7	329.21	53.97	19.99	14.99	5.00	3.40	3.67	6.33	4.77	13.38	11.68
144	6.2	1.7	285.24	46.01	27.06	20.30	6.77	4.35	5.01	5.15	4.51	13.78	16.97
145	6.2	1.8	290.72	46.89	26.05	19.54	6.51	4.20	4.82	5.34	4.46	13.71	15.79
146	6.2	1.9	296.01	47.74	25.13	18.85	6.28	4.07	4.64	5.51	4.41	13.65	14.90
147	6.2	2.0	301.11	48.57	24.28	18.21	6.07	3.94	4.48	5.65	4.39	13.59	14.19
148	6.2	2.1	306.05	49.36	23.51	17.63	5.88	3.83	4.32	5.78	4.38	13.55	13.62
149	6.2	2.2	310.83	50.13	22.79	17.09	5.70	3.73	4.18	5.90	4.39	13.50	13.15
150	6.2	2.3	315.47	50.88	22.12	16.59	5.53	3.64	4.05	6.00	4.43	13.46	12.76
151	6.2	2.4	319.98	51.61	21.50	16.13	5.38	3.56	3.92	6.10	4.48	13.43	12.42
152	6.2	2.5	324.37	52.32	20.93	15.70	5.23	3.48	3.81	6.18	4.57	13.40	12.13
153	6.2	2.6	328.63	53.01	20.39	15.29	5.10	3.41	3.70	6.26	4.67	13.37	11.87
154	6.2	2.7	332.79	53.68	19.88	14.91	4.97	3.34	3.60	6.34	4.80	13.35	11.65

Table 8.10: Optimap generated results for FPSOs of 398.59kton displacement, 1500kbbl Oil storage capacity being compared with Frade

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E] [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.9	1.7	273.3	55.8	32.8	25.5	7.3	4.88	4.17	0.92	5.60	15.31	18.10
2	4.9	1.8	278.5	56.8	31.6	24.6	7.0	4.74	4.06	1.20	5.64	15.23	16.98
3	4.9	1.9	283.6	57.9	30.5	23.7	6.8	4.62	3.96	1.45	5.67	15.16	16.11
4	4.9	2.0	288.5	58.9	29.4	22.9	6.5	4.50	3.86	1.67	5.69	15.10	15.41
5	4.9	2.1	293.2	59.8	28.5	22.2	6.3	4.40	3.77	1.88	5.71	15.04	14.83
6	4.9	2.2	297.8	60.8	27.6	21.5	6.1	4.30	3.68	2.07	5.74	14.99	14.36
7	4.9	2.3	302.2	61.7	26.8	20.9	6.0	4.20	3.59	2.24	5.76	14.95	13.95
8	4.9	2.4	306.6	62.6	26.1	20.3	5.8	4.12	3.51	2.40	5.78	14.91	13.60
9	4.9	2.5	310.8	63.4	25.4	19.7	5.6	4.04	3.44	2.55	5.80	14.87	13.30
10	4.9	2.6	314.8	64.3	24.7	19.2	5.5	3.96	3.36	2.69	5.83	14.84	13.04
11	4.9	2.7	318.8	65.1	24.1	18.7	5.4	3.89	3.29	2.82	5.86	14.81	12.81
12	5.0	1.7	277.0	55.4	32.6	25.3	7.2	4.80	4.12	1.03	5.57	15.26	18.05
13	5.0	1.8	282.3	56.5	31.4	24.4	7.0	4.67	4.01	1.31	5.60	15.18	16.93
14	5.0	1.9	287.4	57.5	30.3	23.5	6.7	4.54	3.91	1.55	5.62	15.11	16.06

15 5.0 2.0 292.4 58.5 29.2 22.7 6.5 4.43 3.81 1.77 5.64 15.05 15.36 16 5.0 2.1 297.2 59.4 28.3 22.0 6.3 4.32 3.72 1.98 5.65 14.99 14.79 17 5.0 2.2 301.8 60.4 27.4 21.3 6.1 4.22 3.63 2.16 5.67 14.94 14.31 18 5.0 2.3 306.3 61.3 26.6 20.7 5.9 4.13 3.54 2.33 5.68 14.90 13.91 19 5.0 2.4 310.7 62.1 25.9 20.1 5.8 4.05 3.46 2.49 5.70 14.86 13.56

20 5.0 2.5 315.0 63.0 25.2 19.6 5.6 3.97 3.38 2.64 5.72 14.82 13.26 21 5.0 2.6 319.1 63.8 24.5 19.1 5.5 3.89 3.31 2.77 5.74 14.79 13.00 22 5.0 2.7 323.2 64.6 23.9 18.6 5.3 3.82 3.24 2.90 5.77 14.76 12.77 23 5.1 1.7 280.7 55.0 32.4 25.2 7.2 4.72 4.07 1.14 5.54 15.21 18.01 24 5.1 1.8 286.1 56.1 31.2 24.2 6.9 4.59 3.96 1.41 5.56 15.13 16.89 25 5.1 1.9 291.3 57.1 30.1 23.4 6.7 4.46 3.86 1.65 5.57 15.06 16.02 26 5.1 2.0 296.3 58.1 29.0 22.6 6.5 4.35 3.76 1.87 5.58 15.00 15.32 27 5.1 2.1 301.1 59.0 28.1 21.9 6.2 4.25 3.66 2.07 5.59 14.94 14.75 28 5.1 2.2 305.8 60.0 27.3 21.2 6.1 4.15 3.57 2.25 5.60 14.89 14.27 29 5.1 2.3 310.4 60.9 26.5 20.6 5.9 4.06 3.49 2.42 5.60 14.85 13.87 30 5.1 2.4 314.8 61.7 25.7 20.0 5.7 3.98 3.40 2.57 5.61 14.81 13.52 31 5.1 2.5 319.2 62.6 25.0 19.5 5.6 3.90 3.33 2.71 5.63 14.77 13.22 32 5.1 2.6 323.4 63.4 24.4 19.0 5.4 3.83 3.25 2.85 5.65 14.74 12.96 33 5.1 2.7 327.5 64.2 23.8 18.5 5.3 3.76 3.18 2.97 5.67 14.71 12.73

34 5.2 1.7 284.3 54.7 32.2 25.0 7.1 4.65 4.02 1.24 5.50 15.16 17.96 35 5.2 1.8 289.8 55.7 31.0 24.1 6.9 4.51 3.91 1.51 5.51 15.08 16.84 36 5.2 1.9 295.1 56.7 29.9 23.2 6.6 4.39 3.80 1.74 5.52 15.01 15.97 37 5.2 2.0 300.1 57.7 28.9 22.4 6.4 4.28 3.70 1.96 5.52 14.95 15.27 38 5.2 2.1 305.1 58.7 27.9 21.7 6.2 4.17 3.61 2.15 5.52 14.90 14.70 39 5.2 2.2 309.8 59.6 27.1 21.1 6.0 4.08 3.52 2.33 5.52 14.85 14.23 40 5.2 2.3 314.5 60.5 26.3 20.5 5.8 3.99 3.43 2.50 5.52 14.80 13.83 41 5.2 2.4 318.9 61.3 25.6 19.9 5.7 3.91 3.35 2.65 5.53 14.76 13.48

42 5.2 2.5 323.3 62.2 24.9 19.3 5.5 3.83 3.27 2.79 5.54 14.73 13.18 43 5.2 2.6 327.6 63.0 24.2 18.8 5.4 3.76 3.20 2.92 5.56 14.69 12.92 44 5.2 2.7 331.7 63.8 23.6 18.4 5.2 3.69 3.13 3.04 5.58 14.66 12.69 45 5.3 1.7 287.9 54.3 32.0 24.9 7.1 4.57 3.97 1.34 5.46 15.11 17.91 46 5.3 1.8 293.5 55.4 30.8 23.9 6.8 4.44 3.86 1.60 5.46 15.04 16.80 47 5.3 1.9 298.8 56.4 29.7 23.1 6.6 4.32 3.75 1.83 5.46 14.97 15.93 48 5.3 2.0 304.0 57.4 28.7 22.3 6.4 4.21 3.65 2.04 5.45 14.90 15.23 49 5.3 2.1 309.0 58.3 27.8 21.6 6.2 4.11 3.55 2.23 5.44 14.85 14.66 50 5.3 2.2 313.8 59.2 26.9 20.9 6.0 4.01 3.46 2.41 5.44 14.80 14.19 51 5.3 2.3 318.5 60.1 26.1 20.3 5.8 3.92 3.38 2.57 5.44 14.75 13.79 52 5.3 2.4 323.0 60.9 25.4 19.8 5.6 3.84 3.29 2.72 5.44 14.71 13.44 53 5.3 2.5 327.4 61.8 24.7 19.2 5.5 3.77 3.22 2.85 5.45 14.68 13.14 54 5.3 2.6 331.8 62.6 24.1 18.7 5.3 3.70 3.14 2.98 5.47 14.65 12.88 55 5.3 2.7 336.0 63.4 23.5 18.3 5.2 3.63 3.07 3.10 5.49 14.62 12.66 56 5.4 1.7 291.6 54.0 31.8 24.7 7.1 4.50 3.92 1.43 5.41 15.07 17.87

57 5.4 1.8 297.2 55.0 30.6 23.8 6.8 4.37 3.81 1.69 5.41 14.99 16.75 58 5.4 1.9 302.6 56.0 29.5 22.9 6.6 4.25 3.70 1.92 5.39 14.92 15.88 59 5.4 2.0 307.8 57.0 28.5 22.2 6.3 4.14 3.60 2.12 5.38 14.86 15.19 60 5.4 2.1 312.8 57.9 27.6 21.5 6.1 4.04 3.50 2.31 5.37 14.80 14.62 61 5.4 2.2 317.7 58.8 26.7 20.8 5.9 3.95 3.41 2.48 5.36 14.75 14.15

62 5.4 2.3 322.5 59.7 26.0 20.2 5.8 3.86 3.32 2.64 5.35 14.71 13.75 63 5.4 2.4 327.1 60.6 25.2 19.6 5.6 3.78 3.24 2.78 5.35 14.67 13.40 64 5.4 2.5 331.6 61.4 24.6 19.1 5.5 3.71 3.16 2.92 5.36 14.63 13.11 65 5.4 2.6 335.9 62.2 23.9 18.6 5.3 3.64 3.09 3.04 5.38 14.60 12.85

66 5.4 2.7 340.2 63.0 23.3 18.1 5.2 3.57 3.02 3.16 5.41 14.57 12.62

67 5.5 1.7 295.1 53.7 31.6 24.6 7.0 4.42 3.87 1.52 5.36 15.02 17.82 68 5.5 1.8 300.8 54.7 30.4 23.6 6.8 4.29 3.75 1.77 5.35 14.94 16.71 69 5.5 1.9 306.3 55.7 29.3 22.8 6.5 4.18 3.64 1.99 5.33 14.87 15.84 70 5.5 2.0 311.6 56.7 28.3 22.0 6.3 4.07 3.54 2.20 5.31 14.81 15.15 71 5.5 2.1 316.7 57.6 27.4 21.3 6.1 3.97 3.44 2.38 5.29 14.76 14.58 72 5.5 2.2 321.6 58.5 26.6 20.7 5.9 3.88 3.35 2.55 5.28 14.71 14.11 73 5.5 2.3 326.4 59.4 25.8 20.1 5.7 3.80 3.27 2.70 5.27 14.66 13.71 74 5.5 2.4 331.1 60.2 25.1 19.5 5.6 3.72 3.18 2.84 5.27 14.62 13.37

75 5.5 2.5 335.6 61.0 24.4 19.0 5.4 3.65 3.11 2.97 5.28 14.59 13.07 76 5.5 2.6 340.1 61.8 23.8 18.5 5.3 3.58 3.03 3.09 5.30 14.56 12.81 77 5.5 2.7 344.4 62.6 23.2 18.0 5.2 3.52 2.97 3.21 5.33 14.53 12.58 78 5.6 1.7 298.7 53.3 31.4 24.4 7.0 4.35 3.82 1.60 5.31 14.98 17.78 79 5.6 1.8 304.5 54.4 30.2 23.5 6.7 4.23 3.70 1.85 5.28 14.90 16.67 80 5.6 1.9 310.0 55.4 29.1 22.7 6.5 4.11 3.59 2.07

5.26 14.83 15.80 81 5.6 2.0 315.3 56.3 28.2 21.9 6.3 4.00 3.49 2.27 5.23 14.77 15.11 82 5.6 2.1 320.5 57.2 27.3 21.2 6.1 3.91 3.39 2.44 5.21 14.71 14.54

83 5.6 2.2 325.5 58.1 26.4 20.6 5.9 3.82 3.30 2.61 5.20 14.66 14.07 84 5.6 2.3 330.4 59.0 25.7 20.0 5.7 3.74 3.21 2.76 5.19 14.62 13.67 85 5.6 2.4 335.1 59.8 24.9 19.4 5.5 3.66 3.13 2.90 5.19 14.58 13.33 86 5.6 2.5 339.7 60.7 24.3 18.9 5.4 3.59 3.05 3.02 5.20 14.54 13.03 87 5.6 2.6 344.2 61.5 23.6 18.4 5.3 3.52 2.98 3.14 5.22 14.51 12.78 88 5.6 2.7 348.5 62.2 23.1 17.9 5.1 3.46 2.91 3.25 5.26 14.48 12.55 89 5.7 1.7 302.3 53.0 31.2 24.3 6.9 4.28 3.77 1.68 5.25 14.93 17.74 90 5.7 1.8 308.1 54.0 30.0 23.4 6.7 4.16 3.65 1.92 5.22 14.85 16.63 91 5.7 1.9 313.7 55.0 29.0 22.5 6.4 4.04 3.54 2.14 5.19 14.79 15.76 92 5.7 2.0 319.1 56.0 28.0 21.8 6.2 3.94 3.43 2.33 5.16 14.72 15.07 93 5.7 2.1 324.3 56.9 27.1 21.1 6.0 3.85 3.34 2.51 5.13 14.67 14.51 94 5.7 2.2 329.4 57.8 26.3 20.4 5.8 3.76 3.24 2.66 5.12 14.62 14.03 95 5.7 2.3 334.3 58.6 25.5 19.8 5.7 3.68 3.16 2.81 5.11 14.58 13.64 96 5.7 2.4 339.1 59.5 24.8 19.3 5.5 3.60 3.08 2.95 5.11 14.54 13.29 97 5.7 2.5 343.7 60.3 24.1 18.8 5.4 3.54 3.00 3.07 5.13 14.50 13.00

98 5.7 2.6 348.2 61.1 23.5 18.3 5.2 3.47 2.93 3.19 5.15 14.47 12.74 99 5.7 2.7 352.7 61.9 22.9 17.8 5.1 3.41 2.86 3.30 5.20 14.44 12.51

100 5.8 1.7 305.8 52.7 31.0 24.1 6.9 4.22 3.71 1.76 5.19 14.89 17.69 101 5.8 1.8 311.7 53.7 29.9 23.2 6.6 4.09 3.59 1.99 5.15 14.81 16.59 102 5.8 1.9 317.3 54.7 28.8 22.4 6.4 3.98 3.48 2.20 5.11 14.74 15.72

103 5.8 2.0 322.8 55.7 27.8 21.6 6.2 3.88 3.38 2.39 5.08 14.68 15.03 104 5.8 2.1 328.1 56.6 26.9 21.0 6.0 3.79 3.28 2.56 5.05 14.63 14.47 105 5.8 2.2 333.2 57.5 26.1 20.3 5.8 3.70 3.19 2.72 5.04 14.58 14.00 106 5.8 2.3 338.2 58.3 25.4 19.7 5.6 3.62 3.10 2.86 5.03 14.53 13.60

107 5.8 2.4 343.0 59.1 24.6 19.2 5.5 3.55 3.02 2.99 5.04 14.50 13.26

108 5.8 2.5 347.7 60.0 24.0 18.7 5.3 3.48 2.95 3.11 5.06 14.46 12.96 109 5.8 2.6 352.3 60.7 23.4 18.2 5.2 3.42 2.87 3.23 5.10 14.43 12.71

110	5.8	2.7	356.8	61.5	22.8	17.7	5.1	3.36	2.81	3.33	5.15	14.40	12.48
111	5.9	1.7	309.3	52.4	30.8	24.0	6.9	4.15	3.66	1.83	5.12	14.85	17.65
112	5.9	1.8	315.2	53.4	29.7	23.1	6.6	4.03	3.54	2.05	5.08	14.77	16.55
113	5.9	1.9	321.0	54.4	28.6	22.3	6.4	3.92	3.43	2.26	5.04	14.70	15.69
114	5.9	2.0	326.5	55.3	27.7	21.5	6.1	3.82	3.32	2.45	5.01	14.64	15.00
115	5.9	2.1	331.9	56.2	26.8	20.8	6.0	3.73	3.23	2.61	4.98	14.59	14.43
116	5.9	2.2	337.0	57.1	26.0	20.2	5.8	3.65	3.14	2.76	4.96	14.54	13.96
117	5.9	2.3	342.1	58.0	25.2	19.6	5.6	3.57	3.05	2.90	4.96	14.49	13.56
118	5.9	2.4	347.0	58.8	24.5	19.1	5.4	3.50	2.97	3.03	4.98	14.45	13.22
119	5.9	2.5	351.7	59.6	23.8	18.5	5.3	3.43	2.89	3.15	5.01	14.42	12.93
120	5.9	2.6	356.3	60.4	23.2	18.1	5.2	3.37	2.82	3.26	5.05	14.39	12.67
121	5.9	2.7	360.9	61.2	22.7	17.6	5.0	3.31	2.75	3.37	5.12	14.36	12.45
122	6.0	1.7	312.8	52.1	30.7	23.9	6.8	4.09	3.61	1.89	5.06	14.80	17.61
123	6.0	1.8	318.8	53.1	29.5	23.0	6.6	3.97	3.49	2.12	5.01	14.73	16.51
124	6.0	1.9	324.6	54.1	28.5	22.1	6.3	3.86	3.38	2.32	4.97	14.66	15.65
125	6.0	2.0	330.2	55.0	27.5	21.4	6.1	3.76	3.27	2.50	4.93	14.60	14.96
126	6.0	2.1	335.6	55.9	26.6	20.7	5.9	3.67	3.17	2.66	4.91	14.54	14.40
127	6.0	2.2	340.8	56.8	25.8	20.1	5.7	3.59	3.08	2.81	4.90	14.50	13.93
128	6.0	2.3	345.9	57.7	25.1	19.5	5.6	3.52	3.00	2.94	4.90	14.45	13.53
129	6.0	2.4	350.9	58.5	24.4	19.0	5.4	3.45	2.92	3.07	4.92	14.41	13.19

130	6.0	2.5	355.7	59.3	23.7	18.4	5.3	3.38	2.84	3.19	4.96	14.38	12.90
131	6.0	2.6	360.4	60.1	23.1	18.0	5.1	3.32	2.77	3.30	5.02	14.35	12.64
132	6.0	2.7	364.9	60.8	22.5	17.5	5.0	3.27	2.70	3.40	5.10	14.32	12.41
133	6.1	1.7	316.2	51.8	30.5	23.7	6.8	4.03	3.55	1.95	4.99	14.76	17.58
134	6.1	1.8	322.3	52.8	29.4	22.8	6.5	3.91	3.43	2.17	4.94	14.69	16.47
135	6.1	1.9	328.2	53.8	28.3	22.0	6.3	3.80	3.32	2.37	4.89	14.62	15.61
136	6.1	2.0	333.8	54.7	27.4	21.3	6.1	3.71	3.22	2.54	4.86	14.56	14.92
137	6.1	2.1	339.3	55.6	26.5	20.6	5.9	3.62	3.12	2.70	4.84	14.50	14.36
138	6.1	2.2	344.6	56.5	25.7	20.0	5.7	3.54	3.03	2.85	4.84	14.46	13.89
139	6.1	2.3	349.8	57.3	24.9	19.4	5.5	3.47	2.94	2.98	4.85	14.41	13.50
140	6.1	2.4	354.8	58.2	24.2	18.8	5.4	3.40	2.86	3.10	4.88	14.37	13.16
141	6.1	2.5	359.6	59.0	23.6	18.3	5.2	3.34	2.79	3.22	4.93	14.34	12.86
142	6.1	2.6	364.4	59.7	23.0	17.9	5.1	3.28	2.72	3.32	5.01	14.31	12.61
143	6.1	2.7	369.0	60.5	22.4	17.4	5.0	3.22	2.65	3.42	5.10	14.28	12.38
144	6.2	1.7	319.7	51.6	30.3	23.6	6.7	3.97	3.50	2.01	4.92	14.72	17.54
145	6.2	1.8	325.8	52.6	29.2	22.7	6.5	3.85	3.38	2.22	4.87	14.65	16.43
146	6.2	1.9	331.8	53.5	28.2	21.9	6.3	3.75	3.27	2.41	4.83	14.58	15.57
147	6.2	2.0	337.5	54.4	27.2	21.2	6.0	3.65	3.16	2.59	4.79	14.52	14.89
148	6.2	2.1	343.0	55.3	26.3	20.5	5.9	3.57	3.07	2.74	4.78	14.47	14.33
149	6.2	2.2	348.4	56.2	25.5	19.9	5.7	3.49	2.98	2.88	4.78	14.42	13.86
150	6.2	2.3	353.6	57.0	24.8	19.3	5.5	3.42	2.89	3.01	4.81	14.37	13.46
151	6.2	2.4	358.6	57.8	24.1	18.7	5.4	3.35	2.81	3.13	4.85	14.33	13.13
152	6.2	2.5	363.5	58.6	23.5	18.2	5.2	3.29	2.74	3.25	4.92	14.30	12.83
153	6.2	2.6	368.3	59.4	22.8	17.8	5.1	3.23	2.67	3.35	5.01	14.27	12.58
154	6.2	2.7	373.0	60.2	22.3	17.3	5.0	3.18	2.60	3.45	5.12	14.24	12.35

Table 8.11: Optimap results for FPSOs of 223.35kton displacement, 932kbbl Oil storage capacity being compared with Abo

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E] [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.9	1.7	228.04	46.54	27.38	20.53	6.84	2.50	2.36	-3.10	1.46	13.86	17.04
2	4.9	1.8	232.43	47.43	26.35	19.76	6.59	2.44	2.30	-2.85	1.47	13.79	15.87
3	4.9	1.9	236.66	48.30	25.42	19.06	6.35	2.38	2.24	-2.61	1.48	13.73	14.97
4	4.9	2.0	240.74	49.13	24.57	18.42	6.14	2.33	2.19	-2.40	1.49	13.67	14.26

5	4.9	2.1	244.68	49.94	23.78	17.83	5.94	2.29	2.14	-2.21	1.50	13.62	13.69
6	4.9	2.2	248.51	50.72	23.05	17.29	5.76	2.24	2.09	-2.03	1.50	13.58	13.22
7	4.9	2.3	252.22	51.47	22.38	16.78	5.59	2.20	2.04	-1.86	1.51	13.54	12.82
8	4.9	2.4	255.82	52.21	21.75	16.32	5.44	2.16	2.00	-1.70	1.52	13.51	12.48
9	4.9	2.5	259.33	52.92	21.17	15.88	5.29	2.13	1.96	-1.56	1.53	13.48	12.19
10	4.9	2.6	262.74	53.62	20.62	15.47	5.16	2.10	1.92	-1.42	1.54	13.45	11.94
11	4.9	2.7	266.07	54.30	20.11	15.08	5.03	2.06	1.88	-1.30	1.55	13.42	11.72
12	5.0	1.7	231.13	46.23	27.19	20.39	6.80	2.46	2.33	-3.03	1.45	13.81	17.00
13	5.0	1.8	235.58	47.12	26.18	19.63	6.54	2.40	2.27	-2.78	1.46	13.74	15.82
14	5.0	1.9	239.87	47.97	25.25	18.94	6.31	2.35	2.21	-2.55	1.47	13.68	14.93
15	5.0	2.0	244.00	48.80	24.40	18.30	6.10	2.30	2.16	-2.33	1.47	13.63	14.22
16	5.0	2.1	248.00	49.60	23.62	17.71	5.90	2.25	2.11	-2.14	1.48	13.58	13.65
17	5.0	2.2	251.88	50.38	22.90	17.17	5.72	2.21	2.06	-1.96	1.49	13.53	13.18
18	5.0	2.3	255.64	51.13	22.23	16.67	5.56	2.17	2.01	-1.80	1.49	13.50	12.78
19	5.0	2.4	259.29	51.86	21.61	16.21	5.40	2.13	1.97	-1.64	1.50	13.46	12.44
20	5.0	2.5	262.84	52.57	21.03	15.77	5.26	2.10	1.93	-1.50	1.51	13.43	12.15
21	5.0	2.6	266.30	53.26	20.48	15.36	5.12	2.06	1.89	-1.37	1.52	13.40	11.90
22	5.0	2.7	269.67	53.93	19.98	14.98	4.99	2.03	1.85	-1.24	1.53	13.38	11.68
23	5.1	1.7	234.21	45.92	27.01	20.26	6.75	2.43	2.30	-2.96	1.44	13.77	16.95
24	5.1	1.8	238.71	46.81	26.00	19.50	6.50	2.37	2.24	-2.71	1.45	13.70	15.78
25	5.1	1.9	243.05	47.66	25.08	18.81	6.27	2.31	2.19	-2.48	1.45	13.64	14.89
26	5.1	2.0	247.24	48.48	24.24	18.18	6.06	2.27	2.13	-2.27	1.46	13.58	14.18
27	5.1	2.1	251.30	49.27	23.46	17.60	5.87	2.22	2.08	-2.08	1.46	13.53	13.61
28	5.1	2.2	255.23	50.04	22.75	17.06	5.69	2.18	2.03	-1.90	1.47	13.49	13.14
29	5.1	2.3	259.04	50.79	22.08	16.56	5.52	2.14	1.98	-1.74	1.47	13.45	12.74
30	5.1	2.4	262.74	51.52	21.47	16.10	5.37	2.10	1.94	-1.59	1.48	13.42	12.41
31	5.1	2.5	266.34	52.22	20.89	15.67	5.22	2.07	1.90	-1.45	1.49	13.39	12.12
32	5.1	2.6	269.84	52.91	20.35	15.26	5.09	2.04	1.86	-1.32	1.49	13.36	11.86
33	5.1	2.7	273.26	53.58	19.84	14.88	4.96	2.00	1.82	-1.19	1.50	13.33	11.64
34	5.2	1.7	237.26	45.63	26.84	20.13	6.71	2.39	2.28	-2.89	1.43	13.72	16.91
35	5.2	1.8	241.82	46.50	25.84	19.38	6.46	2.34	2.21	-2.64	1.44	13.65	15.74
36	5.2	1.9	246.22	47.35	24.92	18.69	6.23	2.28	2.16	-2.42	1.44	13.59	14.85
37	5.2	2.0	250.47	48.17	24.08	18.06	6.02	2.23	2.10	-2.21	1.44	13.54	14.14
38	5.2	2.1	254.57	48.96	23.31	17.48	5.83	2.19	2.05	-2.02	1.44	13.49	13.57
39	5.2	2.2	258.55	49.72	22.60	16.95	5.65	2.15	2.00	-1.85	1.45	13.45	13.10
40	5.2	2.3	262.41	50.46	21.94	16.46	5.49	2.11	1.95	-1.69	1.45	13.41	12.71
41	5.2	2.4	266.16	51.18	21.33	16.00	5.33	2.07	1.91	-1.54	1.46	13.37	12.37
42	5.2	2.5	269.81	51.89	20.75	15.57	5.19	2.04	1.87	-1.40	1.46	13.34	12.08
43	5.2	2.6	273.36	52.57	20.22	15.16	5.05	2.01	1.83	-1.27	1.47	13.32	11.83
44	5.2	2.7	276.82	53.23	19.72	14.79	4.93	1.98	1.79	-1.14	1.48	13.29	11.61
45	5.3	1.7	240.29	45.34	26.67	20.00	6.67	2.36	2.25	-2.83	1.42	13.68	16.87
46	5.3	1.8	244.91	46.21	25.67	19.25	6.42	2.30	2.19	-2.58	1.42	13.61	15.70
47	5.3	1.9	249.37	47.05	24.76	18.57	6.19	2.25	2.13	-2.36	1.42	13.55	14.81
48	5.3	2.0	253.67	47.86	23.93	17.95	5.98	2.20	2.07	-2.15	1.42	13.49	14.11
49	5.3	2.1	257.83	48.65	23.16	17.37	5.79	2.16	2.02	-1.97	1.43	13.45	13.54
50	5.3	2.2	261.85	49.41	22.46	16.84	5.61	2.12	1.97	-1.79	1.43	13.40	13.07
51	5.3	2.3	265.76	50.14	21.80	16.35							

5.45 2.08 1.92 -1.63 1.43 13.37 12.67 52 5.3 2.4 269.56 50.86 21.19 15.89 5.30 2.04 1.88 -1.49 1.44 13.33 12.34 53 5.3 2.5 273.25 51.56 20.62 15.47 5.16 2.01 1.84 -1.35 1.44 13.30 12.05 54 5.3 2.6 276.85 52.24 20.09 15.07 5.02 1.98 1.80 -1.22 1.45 13.27 11.80 55 5.3 2.7 280.35 52.90 19.59 14.69 4.90 1.95 1.76 -1.10 1.46 13.25 11.57

56 5.4 1.7 243.30 45.06 26.50 19.88 6.63 2.33 2.22 -2.76 1.41 13.63 16.83 57 5.4 1.8 247.98 45.92 25.51 19.13 6.38 2.27 2.16 -2.52 1.41 13.57 15.66 58 5.4 1.9 252.49 46.76 24.61 18.46 6.15 2.22 2.10 -2.30 1.41 13.51 14.77 59 5.4 2.0 256.85 47.56 23.78 17.84 5.95 2.17 2.04 -2.10 1.41 13.45 14.07 60 5.4 2.1 261.06 48.34 23.02 17.27 5.76 2.13 1.99 -1.91 1.41 13.40 13.50

61 5.4 2.2 265.14 49.10 22.32 16.74 5.58 2.09 1.94 -1.74 1.41 13.36 13.03 62 5.4 2.3 269.10 49.83 21.67 16.25 5.42 2.05 1.89 -1.58 1.41 13.32 12.64 63 5.4 2.4 272.94 50.54 21.06 15.80 5.27 2.01 1.85 -1.44 1.42 13.29 12.30 64 5.4 2.5 276.68 51.24 20.49 15.37 5.12 1.98 1.81 -1.30 1.42 13.26 12.01

65 5.4 2.6 280.32 51.91 19.97 14.97 4.99 1.95 1.77 -1.17 1.43 13.23 11.76

66 5.4 2.7 283.87 52.57 19.47 14.60 4.87 1.92 1.74 -1.06 1.44 13.21 11.54 67 5.5 1.7 246.30 44.78 26.34 19.76 6.59 2.30 2.19 -2.70 1.39 13.59 16.79 68 5.5 1.8 251.04 45.64 25.36 19.02 6.34 2.24 2.13 -2.46 1.39 13.53 15.62 69 5.5 1.9 255.60 46.47 24.46 18.34 6.11 2.19 2.07 -2.24 1.39 13.47 14.73 70 5.5 2.0 260.01 47.27 23.64 17.73 5.91 2.14 2.01 -2.04 1.39 13.41 14.03 71 5.5 2.1 264.27 48.05 22.88 17.16 5.72 2.10 1.96 -1.86 1.39 13.36 13.47 72 5.5 2.2 268.40 48.80 22.18 16.64 5.55 2.06 1.91 -1.69 1.39 13.32 13.00

73 5.5 2.3 272.41 49.53 21.53 16.15 5.38 2.02 1.86 -1.54 1.39 13.28 12.60 74 5.5 2.4 276.30 50.24 20.93 15.70 5.23 1.99 1.82 -1.39 1.40 13.25 12.27 75 5.5 2.5 280.09 50.92 20.37 15.28 5.09 1.96 1.78 -1.26 1.40 13.22 11.98 76 5.5 2.6 283.77 51.59 19.84 14.88 4.96 1.93 1.74 -1.13 1.41 13.19 11.73 77 5.5 2.7 287.36 52.25 19.35 14.51 4.84 1.90 1.71 -1.02 1.43 13.17 11.51 78 5.6 1.7 249.27 44.51 26.18 19.64 6.55 2.26 2.16 -2.64 1.38 13.55 16.75 79 5.6 1.8 254.07 45.37 25.21 18.90 6.30 2.21 2.10 -2.41 1.38 13.48 15.59 80 5.6 1.9 258.69 46.19 24.31 18.23 6.08 2.16 2.04 -2.19 1.37 13.42 14.70 81 5.6 2.0 263.15 46.99 23.50 17.62 5.87 2.11 1.98 -1.99 1.37 13.37 14.00

82 5.6 2.1 267.47 47.76 22.74 17.06 5.69 2.07 1.93 -1.81 1.37 13.32 13.43 83 5.6 2.2 271.65 48.51 22.05 16.54 5.51 2.03 1.88 -1.65 1.37 13.28 12.96 84 5.6 2.3 275.70 49.23 21.41 16.05 5.35 2.00 1.84 -1.49 1.37 13.24 12.57 85 5.6 2.4 279.64 49.94 20.81 15.60 5.20 1.96 1.79 -1.35 1.38 13.21 12.23 86 5.6 2.5 283.47 50.62 20.25 15.19 5.06 1.93 1.75 -1.22 1.38 13.18 11.95 87 5.6 2.6 287.20 51.29 19.73 14.79 4.93 1.90 1.71 -1.09 1.40 13.15 11.70 88 5.6 2.7 290.84 51.94 19.24 14.43 4.81 1.87 1.68 -0.98 1.41 13.13 11.48 89 5.7 1.7 252.23 44.25 26.03 19.52 6.51 2.23 2.13 -2.59 1.36 13.51 16.72 90 5.7 1.8 257.09 45.10 25.06 18.79 6.26 2.18 2.07 -2.35 1.36 13.45 15.55 91 5.7 1.9 261.76 45.92 24.17 18.13 6.04 2.13 2.01 -2.14 1.35 13.39 14.66 92 5.7 2.0 266.27 46.71 23.36 17.52 5.84 2.08 1.95 -1.95 1.35 13.33 13.96 93 5.7 2.1 270.64 47.48 22.61 16.96 5.65 2.04 1.90 -1.77 1.35 13.28 13.40 94 5.7 2.2 274.87 48.22 21.92 16.44 5.48 2.00 1.85 -1.60 1.35 13.24 12.93 95 5.7 2.3 278.97 48.94 21.28 15.96 5.32 1.97 1.81 -1.45 1.35 13.20 12.54 96 5.7 2.4 282.96 49.64 20.68 15.51 5.17 1.94 1.76 -1.31 1.36 13.17 12.20

97 5.7 2.5 286.84 50.32 20.13 15.10 5.03 1.90 1.72 -1.18 1.37 13.14 11.92 98 5.7 2.6 290.61 50.98 19.61 14.71 4.90 1.88 1.68 -1.06 1.38 13.11 11.67 99 5.7 2.7 294.29 51.63 19.12 14.34 4.78 1.85 1.65 -0.94 1.40 13.09 11.45

100 5.8 1.7 255.17 44.00 25.88 19.41 6.47 2.21 2.10 -2.54 1.35 13.47 16.68 101 5.8 1.8 260.08 44.84 24.91 18.68 6.23 2.15 2.04 -2.30 1.34 13.41 15.51

102 5.8 1.9 264.81 45.66 24.03 18.02 6.01 2.10 1.98 -2.09 1.34 13.35 14.63 103 5.8 2.0 269.38 46.44 23.22 17.42 5.81 2.06 1.92 -1.90 1.33 13.29 13.93 104 5.8 2.1 273.80 47.21 22.48 16.86 5.62 2.02 1.87 -1.73 1.33 13.25 13.36 105 5.8 2.2 278.08 47.94 21.79 16.34 5.45 1.98 1.82 -1.56 1.33 13.20 12.90

106 5.8 2.3 282.23 48.66 21.16 15.87 5.29 1.94 1.78 -1.41 1.34 13.17 12.50

107	5.8	2.4	286.26	49.35	20.56	15.42	5.14	1.91	1.73	-1.27	1.34	13.13	12.17
108	5.8	2.5	290.18	50.03	20.01	15.01	5.00	1.88	1.69	-1.14	1.36	13.10	11.88
109	5.8	2.6	294.00	50.69	19.50	14.62	4.87	1.85	1.66	-1.02	1.37	13.08	11.63
110	5.8	2.7	297.72	51.33	19.01	14.26	4.75	1.83	1.62	-0.91	1.39	13.05	11.42
111	5.9	1.7	258.10	43.75	25.73	19.30	6.43	2.18	2.07	-2.49	1.33	13.44	16.64
112	5.9	1.8	263.06	44.59	24.77	18.58	6.19	2.12	2.01	-2.26	1.32	13.37	15.48
113	5.9	1.9	267.85	45.40	23.89	17.92	5.97	2.08	1.95	-2.05	1.32	13.31	14.59
114	5.9	2.0	272.47	46.18	23.09	17.32	5.77	2.03	1.89	-1.86	1.31	13.26	13.90
115	5.9	2.1	276.93	46.94	22.35	16.76	5.59	1.99	1.84	-1.68	1.31	13.21	13.33
116	5.9	2.2	281.26	47.67	21.67	16.25	5.42	1.95	1.79	-1.52	1.32	13.17	12.86
117	5.9	2.3	285.46	48.38	21.04	15.78	5.26	1.92	1.75	-1.38	1.32	13.13	12.47
118	5.9	2.4	289.54	49.07	20.45	15.34	5.11	1.89	1.71	-1.24	1.33	13.10	12.14
119	5.9	2.5	293.51	49.75	19.90	14.92	4.97	1.86	1.67	-1.11	1.35	13.07	11.85
120	5.9	2.6	297.37	50.40	19.39	14.54	4.85	1.83	1.63	-0.99	1.36	13.04	11.60
121	5.9	2.7	301.13	51.04	18.90	14.18	4.73	1.80	1.59	-0.88	1.39	13.01	11.39
122	6.0	1.7	261.01	43.50	25.59	19.19	6.40	2.15	2.04	-2.44	1.31	13.40	16.61
123	6.0	1.8	266.03	44.34	24.63	18.47	6.16	2.10	1.98	-2.21	1.31	13.33	15.45
124	6.0	1.9	270.87	45.14	23.76	17.82	5.94	2.05	1.92	-2.00	1.30	13.27	14.56
125	6.0	2.0	275.54	45.92	22.96	17.22	5.74	2.01	1.87	-1.82	1.30	13.22	13.86
126	6.0	2.1	280.05	46.68	22.23	16.67	5.56	1.97	1.81	-1.65	1.30	13.17	13.30
127	6.0	2.2	284.43	47.41	21.55	16.16	5.39	1.93	1.77	-1.49	1.30	13.13	12.83
128	6.0	2.3	288.68	48.11	20.92	15.69	5.23	1.90	1.72	-1.34	1.31	13.09	12.44
129	6.0	2.4	292.80	48.80	20.33	15.25	5.08	1.86	1.68	-1.20	1.32	13.06	12.11
130	6.0	2.5	296.81	49.47	19.79	14.84	4.95	1.84	1.64	-1.08	1.34	13.03	11.82
131	6.0	2.6	300.72	50.12	19.28	14.46	4.82	1.81	1.60	-0.96	1.36	13.00	11.58
132	6.0	2.7	304.53	50.75	18.80	14.10	4.70	1.78	1.57	-0.85	1.39	12.98	11.36
133	6.1	1.7	263.90	43.26	25.45	19.09	6.36	2.12	2.02	-2.39	1.30	13.36	16.57
134	6.1	1.8	268.98	44.09	24.50	18.37	6.12	2.07	1.95	-2.17	1.29	13.29	15.41
135	6.1	1.9	273.87	44.90	23.63	17.72	5.91	2.02	1.89	-1.96	1.28	13.23	14.53
136	6.1	2.0	278.59	45.67	22.84	17.13	5.71	1.98	1.84	-1.78	1.28	13.18	13.83
137	6.1	2.1	283.16	46.42	22.10	16.58	5.53	1.94	1.79	-1.61	1.28	13.14	13.27
138	6.1	2.2	287.58	47.14	21.43	16.07	5.36	1.91	1.74	-1.45	1.29	13.09	12.80
139	6.1	2.3	291.88	47.85	20.80	15.60	5.20	1.87	1.69	-1.31	1.30	13.06	12.41
140	6.1	2.4	296.05	48.53	20.22	15.17	5.06	1.84	1.65	-1.17	1.31	13.02	12.08
141	6.1	2.5	300.10	49.20	19.68	14.76	4.92	1.81	1.61	-1.05	1.34	12.99	11.79
142	6.1	2.6	304.05	49.84	19.17	14.38	4.79	1.79	1.58	-0.93	1.36	12.97	11.55
143	6.1	2.7	307.90	50.48	18.69	14.02	4.67	1.76	1.54	-0.82	1.39	12.94	11.33
144	6.2	1.7	266.78	43.03	25.31	18.98	6.33	2.10	1.99	-2.35	1.28	13.32	16.54
145	6.2	1.8	271.91	43.86	24.36	18.27	6.09	2.05	1.92	-2.13	1.27	13.26	15.38
146	6.2	1.9	276.85	44.65	23.50	17.63	5.88	2.00	1.86	-1.93	1.27	13.20	14.49
147	6.2	2.0	281.63	45.42	22.71	17.03	5.68	1.96	1.81	-1.74	1.27	13.15	13.80
148	6.2	2.1	286.24	46.17	21.98	16.49	5.50	1.92	1.76	-1.57	1.27	13.10	13.24
149	6.2	2.2	290.72	46.89	21.31	15.99	5.33	1.88	1.71	-1.42	1.28	13.06	12.77
150	6.2	2.3	295.06	47.59	20.69	15.52	5.17	1.85	1.67	-1.28	1.29	13.02	12.38
151	6.2	2.4	299.27	48.27	20.11	15.08	5.03	1.82	1.62	-1.14	1.31	12.99	12.05
152	6.2	2.5	303.37	48.93	19.57	14.68	4.89	1.79	1.59	-1.02	1.34	12.96	11.77
153	6.2	2.6	307.37	49.58	19.07	14.30	4.77	1.77	1.55	-0.90	1.37	12.93	11.52
154	6.2	2.7	311.26	50.20	18.59	13.95	4.65	1.74	1.52	-0.79	1.41	12.91	11.30

Table 8.12: Optimap results for FPSOs of 436.51kton displacement, 1800kbbl Oil storage capacity being compared with Agbami

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E] [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.9	1.7	289.19	59.02	34.72	24.95	9.76	2.17	1.92	-5.62	3.10	15.44	18.93
2	4.9	1.8	294.75	60.15	33.42	24.02	9.40	2.10	1.86	-5.25	3.11	15.36	17.61
3	4.9	1.9	300.11	61.25	32.24	23.17	9.07	2.04	1.81	-4.92	3.12	15.30	16.60
4	4.9	2.0	305.28	62.30	31.15	22.39	8.76	1.98	1.76	-4.62	3.13	15.24	15.81
5	4.9	2.1	310.29	63.32	30.15	21.67	8.48	1.93	1.72	-4.34	3.14	15.19	15.18
6	4.9	2.2	315.14	64.31	29.23	21.01	8.22	1.88	1.67	-4.09	3.16	15.14	14.65
7	4.9	2.3	319.84	65.27	28.38	20.40	7.98	1.84	1.63	-3.85	3.17	15.10	14.21
8	4.9	2.4	324.41	66.21	27.59	19.83	7.76	1.80	1.59	-3.63	3.19	15.07	13.84
9	4.9	2.5	328.86	67.11	26.85	19.30	7.55	1.76	1.55	-3.43	3.20	15.03	13.51
10	4.9	2.6	333.18	68.00	26.15	18.80	7.36	1.72	1.52	-3.24	3.23	15.01	13.24
11	4.9	2.7	337.40	68.86	25.50	18.33	7.17	1.69	1.49	-3.06	3.25	14.98	12.99
12	5.0	1.7	293.11	58.62	34.48	24.78	9.70	2.13	1.89	-5.52	3.07	15.38	18.88
13	5.0	1.8	298.74	59.75	33.19	23.86	9.34	2.06	1.84	-5.16	3.08	15.31	17.56
14	5.0	1.9	304.18	60.84	32.02	23.01	9.01	2.00	1.79	-4.83	3.09	15.25	16.55
15	5.0	2.0	309.42	61.88	30.94	22.24	8.70	1.94	1.74	-4.53	3.10	15.19	15.77
16	5.0	2.1	314.50	62.90	29.95	21.53	8.42	1.89	1.69	-4.26	3.10	15.14	15.13
17	5.0	2.2	319.41	63.88	29.04	20.87	8.17	1.85	1.65	-4.01	3.11	15.09	14.61
18	5.0	2.3	324.18	64.84	28.19	20.26	7.93	1.80	1.60	-3.78	3.12	15.05	14.17
19	5.0	2.4	328.81	65.76	27.40	19.69	7.71	1.76	1.56	-3.56	3.13	15.02	13.79
20	5.0	2.5	333.32	66.66	26.67	19.17	7.50	1.72	1.53	-3.36	3.15	14.98	13.47
21	5.0	2.6	337.70	67.54	25.98	18.67	7.31	1.69	1.49	-3.17	3.17	14.95	13.19
22	5.0	2.7	341.98	68.40	25.33	18.21	7.12	1.65	1.46	-3.00	3.19	14.93	12.95
23	5.1	1.7	297.00	58.24	34.26	24.62	9.63	2.09	1.87	-5.43	3.05	15.33	18.83
24	5.1	1.8	302.71	59.36	32.98	23.70	9.27	2.02	1.81	-5.07	3.05	15.26	17.51
25	5.1	1.9	308.22	60.44	31.81	22.86	8.95	1.96	1.76	-4.75	3.06	15.20	16.51
26	5.1	2.0	313.54	61.48	30.74	22.09	8.65	1.91	1.71	-4.45	3.06	15.14	15.72
27	5.1	2.1	318.68	62.49	29.75	21.39	8.37	1.86	1.66	-4.18	3.06	15.09	15.09
28	5.1	2.2	323.66	63.46	28.85	20.73	8.11	1.81	1.62	-3.93	3.06	15.04	14.56
29	5.1	2.3	328.49	64.41	28.00	20.13	7.88	1.77	1.58	-3.70	3.07	15.00	14.12
30	5.1	2.4	333.18	65.33	27.22	19.56	7.66	1.73	1.54	-3.49	3.08	14.97	13.75
31	5.1	2.5	337.75	66.22	26.49	19.04	7.45	1.69	1.50	-3.29	3.10	14.93	13.43
32	5.1	2.6	342.19	67.10	25.81	18.55	7.26	1.65	1.46	-3.11	3.12	14.91	13.15
33	5.1	2.7	346.52	67.95	25.16	18.09	7.08	1.62	1.43	-2.94	3.14	14.88	12.91
34	5.2	1.7	300.87	57.86	34.04	24.46	9.57	2.05	1.84	-5.34	3.02	15.28	18.78
35	5.2	1.8	306.66	58.97	32.76	23.55	9.21	1.98	1.79	-4.99	3.02	15.21	17.46
36	5.2	1.9	312.24	60.05	31.60	22.71	8.89	1.93	1.73	-4.67	3.02	15.15	16.46
37	5.2	2.0	317.62	61.08	30.54	21.95	8.59	1.87	1.68	-4.38	3.02	15.09	15.68
38	5.2	2.1	322.83	62.08	29.56	21.25	8.31	1.82	1.64	-4.11	3.02	15.04	15.04
39	5.2	2.2	327.87	63.05	28.66	20.60	8.06	1.78	1.59	-3.86	3.02	14.99	14.52
40	5.2	2.3	332.77	63.99	27.82	20.00	7.83	1.73	1.55	-3.64	3.02	14.95	14.08
41	5.2	2.4	337.52	64.91	27.05	19.44	7.61	1.69	1.51	-3.43	3.03	14.92	13.71
42	5.2	2.5	342.15	65.80	26.32	18.92	7.40	1.66	1.47	-3.23	3.04	14.89	13.39
43	5.2	2.6	346.65	66.66	25.64	18.43	7.21	1.62	1.44	-3.05	3.06	14.86	13.11
44	5.2	2.7	351.04	67.51	25.00	17.97	7.03	1.59	1.40	-2.88	3.09	14.83	12.87
45	5.3	1.7	304.72	57.49	33.82	24.31	9.51	2.01	1.82	-5.26	2.99	15.24	18.73
46	5.3	1.8	310.58	58.60	32.56	23.40	9.16	1.95	1.76	-4.91	2.98	15.16	17.41
47	5.3	1.9	316.23	59.67	31.40	22.57	8.83	1.89	1.71	-4.59	2.98	15.10	16.42
48	5.3	2.0	321.68	60.69	30.35	21.81	8.54	1.84	1.66	-4.30	2.97	15.04	15.63
49	5.3	2.1	326.95	61.69	29.38	21.11	8.26	1.79	1.61	-4.04	2.97	14.99	15.00
50	5.3	2.2	332.06	62.65	28.48	20.47	8.01	1.74	1.56	-3.80	2.97	14.95	14.48
51	5.3	2.3	337.02	63.59	27.65	19.87	7.78	1.70	1.52	-3.57	2.97	14.91	14.04
52	5.3	2.4	341.84	64.50	26.87	19.32	7.56	1.66	1.48	-3.36	2.98	14.87	13.67
53	5.3	2.5	346.52	65.38	26.15	18.80	7.36	1.63	1.45	-3.17	2.99	14.84	13.35
54	5.3	2.6	351.08	66.24	25.48	18.31	7.17	1.59	1.41	-2.99	3.01	14.81	13.07

55 5.3 2.7 355.52 67.08 24.84 17.86 6.99 1.56 1.38 -2.82 3.04 14.78 12.83 56 5.4 1.7 308.54 57.14 33.61 24.16 9.45 1.98 1.79 -5.18 2.96 15.19 18.68 57 5.4 1.8 314.47 58.24 32.35 23.25 9.10 1.91 1.73 -4.83 2.95 15.12 17.37 58 5.4 1.9 320.19 59.29 31.21 22.43 8.78 1.85 1.68 -4.52 2.94 15.05 16.37 59 5.4 2.0 325.71 60.32 30.16 21.68 8.48 1.80 1.63 -4.23 2.93 15.00 15.59

60 5.4 2.1 331.05 61.31 29.19 20.98 8.21 1.75 1.58 -3.97 2.92 14.94 14.96 61 5.4 2.2 336.23 62.26 28.30 20.34 7.96 1.71 1.54 -3.73 2.92 14.90 14.44 62 5.4 2.3 341.25 63.19 27.48 19.75 7.73 1.67 1.50 -3.51 2.92 14.86 14.00 63 5.4 2.4 346.12 64.10 26.71 19.20 7.51 1.63 1.46 -3.31 2.93 14.82 13.63

64 5.4 2.5 350.86 64.97 25.99 18.68 7.31 1.60 1.42 -3.12 2.94 14.79 13.31

65 5.4 2.6 355.48 65.83 25.32 18.20 7.12 1.56 1.38 -2.94 2.97 14.76 13.04 66 5.4 2.7 359.98 66.66 24.69 17.75 6.94 1.53 1.35 -2.77 2.99 14.74 12.79 67 5.5 1.7 312.34 56.79 33.40 24.01 9.40 1.94 1.76 -5.10 2.92 15.14 18.63

68 5.5 1.8 318.34 57.88 32.16 23.11 9.04 1.88 1.71 -4.76 2.91 15.07 17.32

69 5.5 1.9 324.13 58.93 31.02 22.29 8.72 1.82 1.65 -4.45 2.89 15.01 16.33 70 5.5 2.0 329.72 59.95 29.97 21.54 8.43 1.77 1.60 -4.17 2.88 14.95 15.55 71 5.5 2.1 335.13 60.93 29.02 20.85 8.16 1.72 1.55 -3.91 2.87 14.90 14.92 72 5.5 2.2 340.37 61.88 28.13 20.22 7.91 1.68 1.51 -3.67 2.87 14.85 14.40 73 5.5 2.3 345.45 62.81 27.31 19.63 7.68 1.64 1.47 -3.45 2.87 14.81 13.96 74 5.5 2.4 350.38 63.71 26.54 19.08 7.47 1.60 1.43 -3.25 2.88 14.78 13.59 75 5.5 2.5 355.18 64.58 25.83 18.57 7.27 1.57 1.39 -3.06 2.90 14.75 13.27 76 5.5 2.6 359.86 65.43 25.16 18.09 7.08 1.54 1.36 -2.89 2.92 14.72 13.00 77 5.5 2.7 364.41 66.26 24.54 17.64 6.90 1.51 1.32 -2.72 2.96 14.69 12.76 78 5.6 1.7 316.11 56.45 33.20 23.87 9.34 1.90 1.74 -5.02 2.89 15.10 18.59 79 5.6 1.8 322.19 57.53 31.96 22.97 8.99 1.84 1.68 -4.69 2.87 15.02 17.28 80 5.6 1.9 328.05 58.58 30.83 22.16 8.67 1.79 1.63 -4.38 2.85 14.96 16.28

81 5.6 2.0 333.71 59.59 29.80 21.42 8.38 1.74 1.58 -4.10 2.84 14.90 15.50 82 5.6 2.1 339.18 60.57 28.84 20.73 8.11 1.69 1.53 -3.85 2.83 14.85 14.88 83 5.6 2.2 344.48 61.51 27.96 20.10 7.86 1.65 1.48 -3.62 2.82 14.81 14.36 84 5.6 2.3 349.62 62.43 27.14 19.51 7.63 1.61 1.44 -3.40 2.83 14.77 13.92 85 5.6 2.4 354.62 63.32 26.39 18.96 7.42 1.58 1.40 -3.20 2.84 14.73 13.55 86 5.6 2.5 359.47 64.19 25.68 18.46 7.22 1.54 1.36 -3.01 2.86 14.70 13.24 87 5.6 2.6 364.20 65.04 25.01 17.98 7.04 1.51 1.33 -2.84 2.89 14.67 12.96 88 5.6 2.7 368.82 65.86 24.39 17.53 6.86 1.48 1.30 -2.68 2.93 14.65 12.72 89 5.7 1.7 319.86 56.12 33.01 23.73 9.28 1.87 1.71 -4.95 2.85 15.05 18.54 90 5.7 1.8 326.01 57.20 31.78 22.84 8.94 1.81 1.65 -4.62 2.83 14.98 17.23 91 5.7 1.9 331.94 58.24 30.65 22.03 8.62 1.76 1.60 -4.32 2.81 14.92 16.24 92 5.7 2.0 337.67 59.24 29.62 21.29 8.33 1.71 1.55 -4.04 2.79 14.86 15.46 93 5.7 2.1 343.20 60.21 28.67 20.61 8.06 1.66 1.50 -3.79 2.78 14.81 14.84 94 5.7 2.2 348.57 61.15 27.80 19.98 7.82 1.62 1.46 -3.56 2.78 14.77 14.32 95 5.7 2.3 353.77 62.07 26.98 19.40 7.59 1.58 1.41 -3.35 2.79 14.73 13.89

96 5.7 2.4 358.83 62.95 26.23 18.85 7.38 1.55 1.38 -3.15 2.80 14.69 13.52 97 5.7 2.5 363.74 63.81 25.53 18.35 7.18 1.52 1.34 -2.97 2.83 14.66 13.20 98 5.7 2.6 368.53 64.65 24.87 17.87 6.99 1.49 1.30 -2.79 2.86 14.63 12.93 99 5.7 2.7 373.19 65.47 24.25 17.43 6.82 1.46 1.27 -2.63 2.90 14.61 12.69

100 5.8 1.7 323.59 55.79 32.82 23.59 9.23 1.84 1.68 -4.89 2.81 15.01 18.50

101 5.8 1.8 329.82 56.86 31.59 22.71 8.89 1.78 1.63 -4.56 2.78 14.94 17.19 102 5.8 1.9 335.81 57.90 30.47 21.90 8.57 1.73 1.57 -4.26 2.76 14.87 16.20 103 5.8 2.0 341.61 58.90 29.45 21.17 8.28 1.68 1.52 -3.99 2.75 14.82 15.42 104 5.8 2.1 347.21 59.86 28.51 20.49 8.02 1.63 1.47 -3.74 2.74 14.77 14.80

105 5.8 2.2 352.63 60.80 27.64 19.86 7.77 1.59 1.43 -3.51 2.74 14.72 14.28

106 5.8 2.3 357.90 61.71 26.83 19.28 7.55 1.56 1.39 -3.30 2.75 14.68 13.85

107	5.8	2.4	363.01	62.59	26.08	18.74	7.33	1.52	1.35	-3.10	2.77	14.65	13.48
108	5.8	2.5	367.98	63.45	25.38	18.24	7.14	1.49	1.31	-2.92	2.80	14.62	13.17
109	5.8	2.6	372.83	64.28	24.72	17.77	6.95	1.46	1.28	-2.75	2.84	14.59	12.89
110	5.8	2.7	377.55	65.09	24.11	17.33	6.78	1.43	1.25	-2.59	2.89	14.56	12.65
111	5.9	1.7	327.30	55.47	32.63	23.45	9.18	1.81	1.66	-4.82	2.77	14.97	18.45
112	5.9	1.8	333.60	56.54	31.41	22.58	8.83	1.75	1.60	-4.50	2.74	14.89	17.15
113	5.9	1.9	339.66	57.57	30.30	21.78	8.52	1.70	1.55	-4.20	2.72	14.83	16.16
114	5.9	2.0	345.52	58.56	29.28	21.05	8.24	1.65	1.49	-3.93	2.71	14.78	15.39
115	5.9	2.1	351.19	59.52	28.34	20.37	7.97	1.61	1.45	-3.69	2.70	14.73	14.76
116	5.9	2.2	356.67	60.45	27.48	19.75	7.73	1.57	1.40	-3.46	2.70	14.68	14.24
117	5.9	2.3	362.00	61.36	26.68	19.17	7.50	1.53	1.36	-3.25	2.72	14.64	13.81
118	5.9	2.4	367.17	62.23	25.93	18.64	7.29	1.50	1.32	-3.06	2.74	14.61	13.45
119	5.9	2.5	372.20	63.08	25.23	18.14	7.10	1.47	1.29	-2.88	2.78	14.58	13.13
120	5.9	2.6	377.10	63.92	24.58	17.67	6.91	1.44	1.25	-2.71	2.83	14.55	12.86
121	5.9	2.7	381.87	64.72	23.97	17.23	6.74	1.41	1.22	-2.56	2.89	14.52	12.62
122	6.0	1.7	330.99	55.16	32.45	23.32	9.13	1.78	1.63	-4.76	2.73	14.92	18.41
123	6.0	1.8	337.36	56.23	31.24	22.45	8.79	1.72	1.57	-4.44	2.70	14.85	17.11
124	6.0	1.9	343.49	57.25	30.13	21.66	8.47	1.67	1.52	-4.15	2.68	14.79	16.12
125	6.0	2.0	349.41	58.24	29.12	20.93	8.19	1.62	1.47	-3.88	2.67	14.73	15.35
126	6.0	2.1	355.14	59.19	28.19	20.26	7.93	1.58	1.42	-3.64	2.66	14.68	14.72
127	6.0	2.2	360.69	60.12	27.33	19.64	7.69	1.54	1.38	-3.42	2.67	14.64	14.21
128	6.0	2.3	366.08	61.01	26.53	19.07	7.46	1.51	1.34	-3.21	2.69	14.60	13.78
129	6.0	2.4	371.31	61.88	25.79	18.53	7.25	1.48	1.30	-3.02	2.72	14.57	13.41
130	6.0	2.5	376.39	62.73	25.09	18.04	7.06	1.45	1.26	-2.84	2.77	14.54	13.10
131	6.0	2.6	381.35	63.56	24.45	17.57	6.88	1.42	1.23	-2.68	2.83	14.51	12.82
132	6.0	2.7	386.18	64.36	23.84	17.13	6.70	1.39	1.20	-2.52	2.90	14.48	12.59
133	6.1	1.7	334.66	54.86	32.27	23.20	9.08	1.75	1.61	-4.70	2.69	14.88	18.37
134	6.1	1.8	341.09	55.92	31.06	22.33	8.74	1.69	1.55	-4.38	2.66	14.81	17.07
135	6.1	1.9	347.30	56.93	29.97	21.54	8.43	1.64	1.49	-4.10	2.64	14.75	16.09
136	6.1	2.0	353.29	57.92	28.96	20.81	8.14	1.60	1.44	-3.83	2.63	14.69	15.31
137	6.1	2.1	359.08	58.87	28.03	20.15	7.88	1.56	1.39	-3.60	2.63	14.64	14.69
138	6.1	2.2	364.69	59.79	27.18	19.53	7.64	1.52	1.35	-3.38	2.65	14.60	14.17
139	6.1	2.3	370.13	60.68	26.38	18.96	7.42	1.48	1.31	-3.17	2.67	14.56	13.74
140	6.1	2.4	375.42	61.54	25.64	18.43	7.21	1.45	1.27	-2.98	2.71	14.53	13.38
141	6.1	2.5	380.57	62.39	24.96	17.94	7.02	1.42	1.24	-2.81	2.77	14.50	13.06
142	6.1	2.6	385.57	63.21	24.31	17.47	6.84	1.40	1.20	-2.64	2.84	14.47	12.79
143	6.1	2.7	390.45	64.01	23.71	17.04	6.67	1.37	1.17	-2.49	2.92	14.44	12.55
144	6.2	1.7	338.30	54.57	32.10	23.07	9.03	1.72	1.58	-4.65	2.65	14.84	18.33
145	6.2	1.8	344.81	55.61	30.90	22.21	8.69	1.66	1.52	-4.33	2.62	14.77	17.03
146	6.2	1.9	351.08	56.63	29.80	21.42	8.38	1.62	1.47	-4.05	2.60	14.71	16.05
147	6.2	2.0	357.14	57.60	28.80	20.70	8.10	1.57	1.42	-3.79	2.60	14.65	15.27
148	6.2	2.1	362.99	58.55	27.88	20.04	7.84	1.53	1.37	-3.55	2.61	14.60	14.65
149	6.2	2.2	368.66	59.46	27.03	19.43	7.60	1.50	1.33	-3.34	2.63	14.56	14.14
150	6.2	2.3	374.17	60.35	26.24	18.86	7.38	1.46	1.29	-3.13	2.66	14.52	13.71
151	6.2	2.4	379.51	61.21	25.50	18.33	7.17	1.43	1.25	-2.95	2.71	14.49	13.34
152	6.2	2.5	384.71	62.05	24.82	17.84	6.98	1.40	1.21	-2.77	2.78	14.46	13.03
153	6.2	2.6	389.78	62.87	24.18	17.38	6.80	1.38	1.18	-2.61	2.86	14.43	12.76
154	6.2	2.7	394.71	63.66	23.58	16.95	6.63	1.35	1.15	-2.46	2.95	14.40	12.52

Note: Overall Optimal Principal Dimensions of a 436.5053kton FPSO, with up to -4.9m permissible freeboard exceedance level for operation in wave (H_s 3.7m, T_z 13.9s) is:

Length [m]	Beam [m]	Depth [m]	Draught [m]
319.8616	56.1161	33.0095	23.7255

Overall Optimal Principal Dimensions of a 436.5053kton FPSO, with up to -4.77m permissible freeboard exceedance level for operation in wave

(H_s 3.7m, T_z 13.9s) is:

Length [m]	Beam [m]	Depth [m]	Draught [m]
327.3007	55.4747	32.6322	23.4544

Where negative freeboard exceedance indicates a level below the top of the main by the amount given.

8.5 Effects of Different Extreme Sea States on the Optimal Dimensions of 243.65kTon FPSO Asgard A

The severity of an extreme sea state determines the extent of the response as well as the vulnerability of the vessel to green water. Consider the operation of the FPSO vessel (Asgard A) in different extreme sea states as shown in Table 8.13. The maximum permissible freeboard exceedance is held constant (say e= 5.62m) and the geometric constraints for the analysis are given by:

$$4.5 \leq x_b \leq 6.2 \qquad (8.10)$$

$$1.4 \leq y_d \leq 2.4 \qquad (8.11)$$

Table 8.13: Examples of Extreme Sea States

No	H_s [m]	T_z [s]
(a)	16.50	17.50
(b)	16.50	15.00
(c)	15.05	12.20
(d)	13.49	11.00
(e)	11.15	10.00

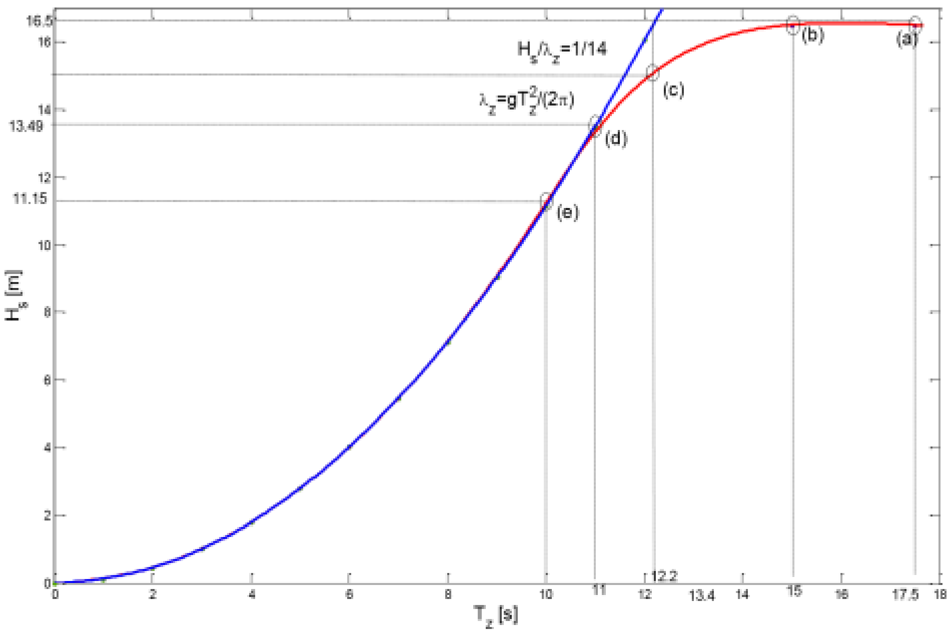


Figure 8.9: Design Extreme Sea States

Figure 8.9 shows the positions of the selected extreme sea states on the design H_s-T_z contour.

The results show that the sea state (c) defined by H_s (15.05m) and T_z (12.2s) is the most critical in terms of freeboard exceedance (See Table 8.14 and Figure 8.10), the given constraints are not satisfied (and so, the programme displays 'Not feasible').

Table 8.14: Effect of Different Sea States on FPSO Asgard A (with Length 280.52m, Breadth 45.25m, and Draught 18.73m)

Extreme Sea State	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]
(a) H_s 16.5m, T_z 17.5s	11.48	7.29	5.56	5.57
(b) H_s 16.5m, T_z 15s	9.86	8.09	8.63	6.00
(c) Hs 15.05m, Tz 12.2s	6.46	7.66	10.29	6.09
(d) Hs 13.49m, Tz 11s	4.52	6.53	9.07	5.72
(e) Hs 11.15m, Tz 10s	2.78	4.86	6.07	4.81

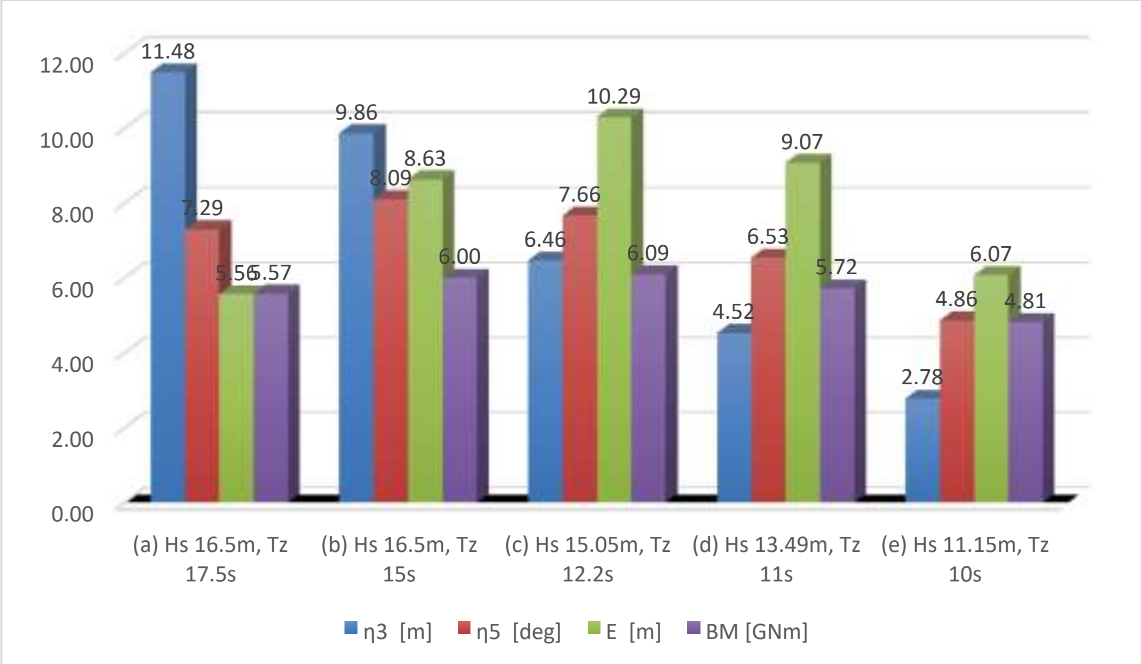


Figure 8.10: Effects of Different Extreme Sea States on 243.65kTon FPSO Asgard A (with Length 280.52m, Breadth 45.25m, and Draught 18.73m)

Along the H_s-T_z contour, sea state (a), H_s, 16.5m and T_z, 17.5s induced the highest heave motion while the most influential with regards to the pitch motion (8.08 deg) is sea state (b). However, the most critical sea state, in terms of its effect on freeboard exceedance, is (c); i.e. H_s, 15.05m and T_z, 12.2s.

Furthermore, optimal dimensions required to overcome the effect of green water for the given extreme sea states has been efficiently predicted (See Table 8.15, Table 8.[5] and Figure 8.11). Another example is also shown in Appendix C.7.

Table 8.15: Optimal Dimensions of 243.65kT FPSO required to curb the effects of green water (e=5.62m) in different extreme sea states

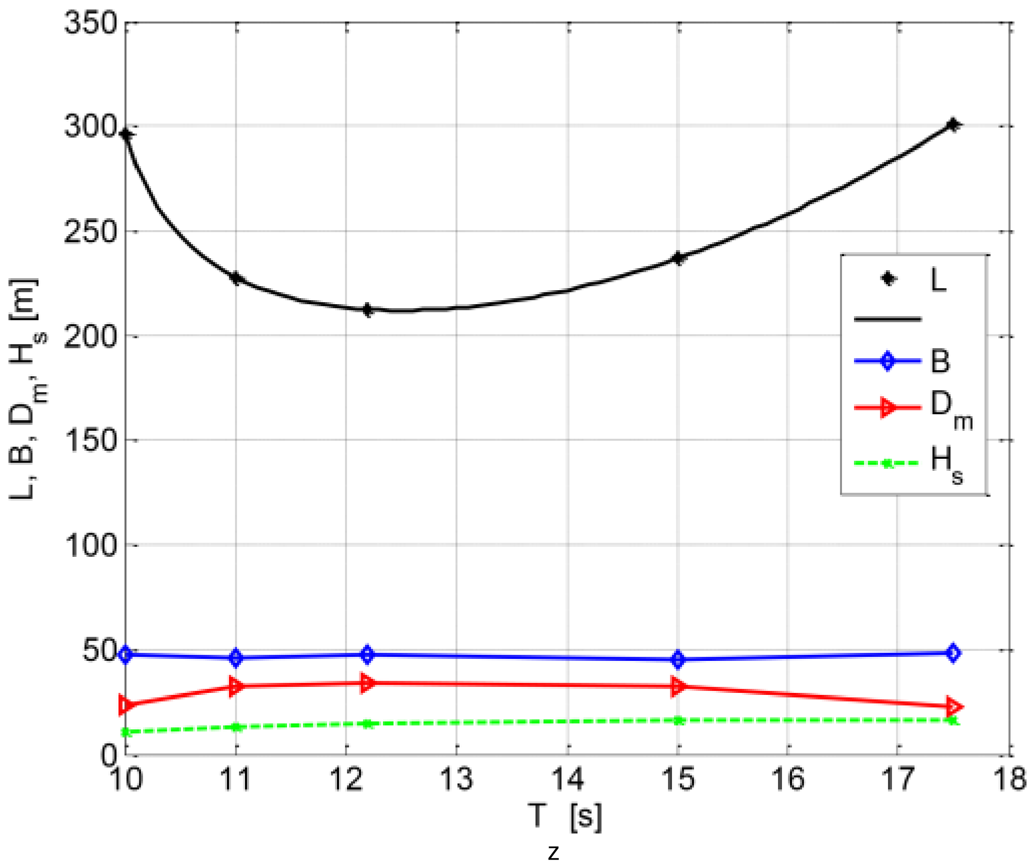
H_s	T_z	L	B	D_m	D	L/B	B/D_m
[m]	[s]	[m]	[m]	[m]	[m]		
16.50	17.50	280.52	45.25	26.61	18.73	6.20	1.70
16.50	15.00	218.61	46.51	33.22	23.38	4.70	1.40
15.05	12.20	-	-	-	-	-	-
13.49	11.00	212.36	47.19	33.71	23.72	4.50	1.40
11.15	10.00	269.06	43.40	28.93	20.36	6.20	1.50

[5] 6.50 17.50 48.55 23.12 16.27 6.20 2.10

Table 8.[67]: Optimal Dimensions of 243.65kT FPSO required to curb the effects of green water (e=6.62m) in different extreme sea states

H_s	T_z	L [m]	B	D_m	D	L/B	B/D_m
[m]	[s]	300.99					

[m] [m] [m]



[6] .50 15.00 236.84 44.69 31.92 22.46 5.30 1.40 15.05 12.20 212.36 47.19 33.71 23.72 4.50 1.40 13.49 11.00 227.81 45.56 32.54 22.90 5.00 1.40

[7] 1.15 10.00 296.14 47.76 23.88 16.81 6.20 2.00

Figure 8.11: Effect of Extreme Sea States on the Optimal Dimensions of 243.65kTon FPSO (required to curb the effects of green water: e=6.62m)

Note: The optimal dimensions of the FPSO at each of the different extreme sea states are indicative of the level of criticality of the sea state. At the most critical state, the depth is highest while the length is shortest.

Generally, the result shows that longer and wider vessel have better (lower) heave and peach motion amplitude but more vulnerable to green water. Conclusively, the selection of suitable principal dimensions can easily be achieved following this prescribed method which applies specified critical sea state(s) and pre-defined geometric and functional constraints and the required oil storage capacities.

8.6 Concluding Remarks

The optimal design programme is a robust and an effective design tool equipped with the capacity to predict the principal dimensions of new vessels to meet specific field output and environmental condition, and also to optimize already existing vessels operating in different sea states. It has been shown (in this Chapter) to be useful in the evaluation of relevant design data of vessels, for operation in multiple ocean regions/different extreme sea states.

Seven selected vessels (Aoka Mizu, Asgard A, Yuum Ka'Ak Naab, Aker Smart 2, Frade, Abo and Agbami) were analysed and optimised. Improvements were made on their dynamic performances; the heave and pitch motions as well as the wave bending moments amidships were reduced.

Furthermore, it must be emphasised that, apart from the effects of size, the sea state at the operating location plays a predominant role too (in the wave loading evaluation). The effects of different extreme sea states on Asgard A FPSO have been discussed. The wavelength, as well as the vessel length, is a major factor in determining the effect of green water on the vessel. To reduce the effects of green water at the bow, the forecastle deck is required.

The significant wave height has a more linear effect on the heave response. Generally, for a given wave period, the most probable maximum response amplitude is directly proportional to the significant wave height.

CHAPTER 9

9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The application of Floating Production, Storage and Offloading (FPSO) vessels has increased very rapidly, and will remain a mainstay (and the preferred system) in the oil and gas industry for many years to come as they provide the flexibility and sound economics of producing and storing at the offshore well sites. The evaluation of the optimal principal dimensions of the system for oil field development in extreme wave condition, which is one of the most critical tasks at the initial design stage of the vessel has been made. Specifically, the objectives of this research have been met, which are:

- Investigation of the wave spectral models suitable for design of the floating production, storage and offloading system.
- Prediction of extreme vessel motion responses associated with some specified marine environments (and the vessel dimensions/size).
- Development of simpler methodology and computational tools for quick determination of design data.
- Evaluation of the dynamic wave bending moment amidships. This is required in order to ensure that the hull girder has sufficient strength to withstand the induced stress.

- Prediction of the optimal design suitable for the avoidance or mitigation of green water occurrence due to extreme wave (of phenomenally high amplitude).

A simplified and efficacious methodology, with robust and efficient computer-aided design tools (Optimal design programme) had been developed to enable offshore industries and designers carry out swift evaluation of the dynamics of Floating Production and Offloading vessels, and determine the optimal sets of principal dimensions suitable for specific storage capacities and wave conditions. The application of the optimal design programme (Optimap) has been extensively demonstrated not only on predicting new single set of dimensions but also analysing multiple FPSOs operating in different extreme sea conditions or regions, and displaying the best sets of principal dimensions. It evaluates and compares the most probable maximum responses (such as heave and pitch) and other related effects of the sea loads and responses (such as bending moment and green water susceptibility) with which the overall performance indexes known as the relative goodness (or Optimap) numbers are determined. The relative goodness method is an innovative and ideal way of determining the best design (considering multiple response characteristics) from the lots analysed for each extreme wave condition.

Spectral analyses were carried out to obtain all the extreme response characteristics including those of the wave bending moment and greenwater freeboard exceedances using the modified Pierson-Moskowitz spectrum which has been reportedly the most representative of the global ocean and has also been found useful in representing a severe storm wave in offshore structural design. It was first recommended by the International Towing Tank Conference in 1966.

Furthermore, from the results of the analyses, it follows that:

(i) In order to accurately determine the required dimensions of any prospective Floating Production, Storage and Offloading system, the relevant factors which comprise first, the provision of required oil storage capacity, second, the provision of sufficient topside space for safe layout of the process plants, accommodation and the various utilities, and finally, the provision of the needed displacement and ballast capacity, as well as the dynamic responses, must be correctly accounted for.

(ii) Generally, the mean principal dimensions of the worldwide FPSOs have been found to be directly proportional to the cube root of the cubic numbers, which in turn depend on the required storage capacities. The Length, Breadth, and moulded Depth have been found to be approximately 4, 3/4, and 1/3 of the cube root of the cubic number, respectively.

(iii) The relative goodness values of the FPSO vessels are good measures of the sea-keeping ranks of the vessels as they highlight the applicability or operability of such vessels.

(iv) The programme which has been developed using this relative goodness method is known as OPTIMAP and it incorporates the principal dimensions, motion (ProMot), bending moment (WavBem) and green water analyses (ProGreen) programmes (Akandu et al., 2014a; Akandu et al., 2015a; Akandu et al., 2015b). This computer aided design tool (OPTIMAP) effectively evaluates and selects the best design (vessel with the overall optimal response) by finding from the vessel with the maximum relative value from the ones satisfy the geometric and functional constraints for any given sea state.

(v) The susceptibility to green water problem of the vessel is accounted for or minimized using the above optimal design programme (OPTIMAP) by setting the green water constraint as the major constraint.

(vi) The most probable maximum relative motion is greatly influenced by the selected length-breadth ratio while the freeboard is highly influenced by the breadth-depth ratio.

(vii) The freeboard exceedance increases with increase in both lengthbreadth and breadth-depth ratios.

(viii) The optimal design for curbing problem of green water indicates a preference of higher depths (smaller breadth-depth ratios) which ensure that there are both sufficient freeboard and lower wave bending moment amidships, and larger length-breadth for improvements on the heave and pitch motions.

(ix) The approach presented is very advantageous in preliminary design of FPSOs. It can also be used in swift evaluation of the most probable extreme responses, and the freeboard exceedances and therefore essential for making necessary contingency plans for existing vessels and for optimising new builds.

(x) The cost of building a new vessel could equally be reduced through optimisation of the bending moment. Optimap gives the overall optimal principal dimensions (also known as the *optimal design*) of the vessel, which not only helps in reducing the responses, it helps not to overestimate the bending moment as lower values will lead to lower cost of construction of the vessel (depending on required strength of the steel materials).

(xi) Optimap also helps in evaluating the criticality of the sea states. The evaluated optimal design of FPSO for oil field development in extreme wave environment such as the North Sea is necessary to reduce or avoid green water on deck and its adverse effects.

(xii) For a given breadth-depth ratio, increase in length-breadth ratio leads to reduction in heave and pitch motions (whereas the relative motion and freeboard exceedance also increase). Similarly, for a given length-breadth ratio, increase in breadthdepth ratio also leads to reduction in heave and pitch motions (whereas the relative motion and freeboard exceedance also increase).

These developed computational tools were written in MATLAB and had been equipped with the capacity to predict the principal dimensions of new vessels to meet specific field output and environmental condition, and also to optimize already existing vessels operating in different sea states.

9.2 Recommendations for further Research Works

Since several aspects of FPSO design analyses have been covered in this research, which include the wave spectral models, prediction of dynamic wave-induced loads and responses, prediction of wave bending moment distribution, evaluation of the susceptibility of FPSO vessels to green water, determination of optimal principal dimensions of FPSOs, optimisation of existing vessels operating in different ocean regions and application of developed optimal design programme (Optimap) to determine the effects of different extreme sea states, it would be expected that more in-depth research works focusing on each of these areas may still be desirable. Nevertheless, this study has already provided the essential framework and analysis tools for a broader or more detailed design analysis of FPSO for operation in extreme sea states despite the time constraints.

In a nutshell, the following areas are recommended for further research:

(i) A series of formulae have been derived for various areas of the analysis. Some of them however require further validation through other computational tools or model tests.

(ii) The evaluation of the wave-induced loads and extreme responses were based on the assumption that the modes of motion were uncoupled and then analysed separately. Moreover, only few modes of motion were computed and used in the evaluation of the relative goodness of the vessels. However, it may be desirable to include additional modes or the entire six degree-of-freedom motions in such evaluation. Furthermore, wave frequency surge motion as well as the low frequency wave drift may also require inclusion depending on the assigned weighting factor or its comparative importance in the selection of the optimal design.

(iii) The most probable maximum responses and other related effects of extreme wave conditions were evaluated and used in determining the optimal dimensions (based on the computed Optimap numbers). However, the optimal design can also be determined by computing the Optimap numbers using either the root-mean-square values of the response spectra or the peak values of the response amplitude operators. Therefore, further work is recommended in order to compare results obtained in these different ways and also reduce computation time.

(iv) To reduce the effects of green water at the bow, the forecastle deck is required. Further work is therefore required to evaluate its effects on the freeboard exceedance in different extreme sea states, and to predict the required height of the forecastle deck from the main deck in these different extreme sea states.

APPENDICES

APPENDIX A: FPSOS FOR OFFSHORE WEST AFRICA

Table A. 1: Results of Response Analyses of 2Mbbl Capacity FPSOs for Offshore West Africa (Hs, 2.7m; Tz, 7.6s)

No	L/B	B/D_m	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.5	1.4	249.56	55.46	39.61	27.73	11.88	0.19	0.30	-9.34	1.01	15.63	28.90
2	4.5	1.5	255.36	56.75	37.83	26.48	11.35	0.19	0.30	-8.80	1.10	15.53	23.86

3	4.5	1.6	260.92	57.98	36.24	25.37	10.87	0.18	0.30	-8.32	1.19	15.43	20.95
4	4.5	1.7	266.24	59.17	34.80	24.36	10.44	0.17	0.30	-7.88	1.29	15.35	19.03
5	4.5	1.8	271.37	60.30	33.50	23.45	10.05	0.16	0.29	-7.48	1.39	15.28	17.66
6	4.5	1.9	276.30	61.40	32.32	22.62	9.69	0.15	0.29	-7.12	1.51	15.22	16.62
7	4.5	2.0	281.06	62.46	31.23	21.86	9.37	0.14	0.28	-6.79	1.62	15.16	15.81
8	4.5	2.1	285.67	63.48	30.23	21.16	9.07	0.13	0.27	-6.49	1.74	15.11	15.16
9	4.5	2.2	290.14	64.48	29.31	20.51	8.79	0.12	0.26	-6.21	1.87	15.07	14.62
10	4.5	2.3	294.47	65.44	28.45	19.92	8.54	0.12	0.26	-5.95	2.00	15.03	14.17
11	4.5	2.4	298.68	66.37	27.66	19.36	8.30	0.11	0.25	-5.71	2.14	15.00	13.79
12	4.6	1.4	253.24	55.05	39.32	27.53	11.80	0.19	0.30	-9.25	1.02	15.58	28.84
13	4.6	1.5	259.13	56.33	37.56	26.29	11.27	0.18	0.30	-8.71	1.11	15.47	23.80
14	4.6	1.6	264.77	57.56	35.97	25.18	10.79	0.17	0.30	-8.23	1.20	15.38	20.89
15	4.6	1.7	270.17	58.73	34.55	24.18	10.36	0.16	0.30	-7.80	1.29	15.30	18.97
16	4.6	1.8	275.37	59.86	33.26	23.28	9.98	0.15	0.29	-7.40	1.40	15.23	17.60
17	4.6	1.9	280.38	60.95	32.08	22.46	9.62	0.14	0.29	-7.05	1.51	15.16	16.57
18	4.6	2.0	285.21	62.00	31.00	21.70	9.30	0.13	0.28	-6.72	1.62	15.11	15.76
19	4.6	2.1	289.89	63.02	30.01	21.01	9.00	0.13	0.27	-6.42	1.74	15.06	15.11
20	4.6	2.2	294.42	64.00	29.09	20.37	8.73	0.12	0.26	-6.14	1.87	15.02	14.57
21	4.6	2.3	298.82	64.96	28.24	19.77	8.47	0.11	0.26	-5.89	2.00	14.98	14.13
22	4.6	2.4	303.08	65.89	27.45	19.22	8.24	0.10	0.25	-5.65	2.14	14.94	13.75
23	4.7	1.4	256.90	54.66	39.04	27.33	11.71	0.19	0.31	-9.16	1.03	15.52	28.79
24	4.7	1.5	262.88	55.93	37.29	26.10	11.19	0.18	0.31	-8.62	1.11	15.41	23.74
25	4.7	1.6	268.59	57.15	35.72	25.00	10.72	0.17	0.30	-8.15	1.20	15.32	20.83
26	4.7	1.7	274.08	58.31	34.30	24.01	10.29	0.16	0.30	-7.72	1.30	15.24	18.92
27	4.7	1.8	279.35	59.44	33.02	23.11	9.91	0.15	0.29	-7.33	1.40	15.17	17.55
28	4.7	1.9	284.43	60.52	31.85	22.30	9.56	0.14	0.28	-6.97	1.51	15.11	16.51
29	4.7	2.0	289.33	61.56	30.78	21.55	9.23	0.13	0.28	-6.65	1.62	15.05	15.71
30	4.7	2.1	294.08	62.57	29.79	20.86	8.94	0.12	0.27	-6.35	1.74	15.01	15.06
31	4.7	2.2	298.67	63.55	28.89	20.22	8.67	0.11	0.26	-6.08	1.86	14.96	14.52 32
	4.7	2.3	303.13	64.50	28.04	19.63	8.41	0.10	0.25	-5.82	1.99	14.92	14.08
33	4.7	2.4	307.46	65.42	27.26	19.08	8.18	0.10	0.24	-5.59	2.13	14.89	13.70
34	4.8	1.4	260.53	54.28	38.77	27.14	11.63	0.18	0.31	-9.07	1.04	15.47	28.73
35	4.8	1.5	266.59	55.54	37.03	25.92	11.11	0.17	0.31	-8.54	1.12	15.36	23.68
36	4.8	1.6	272.39	56.75	35.47	24.83	10.64	0.16	0.30	-8.07	1.21	15.27	20.78
37	4.8	1.7	277.95	57.91	34.06	23.84	10.22	0.15	0.30	-7.64	1.30	15.19	18.86
38	4.8	1.8	283.30	59.02	32.79	22.95	9.84	0.14	0.29	-7.25	1.40	15.12	17.50
39	4.8	1.9	288.45	60.09	31.63	22.14	9.49	0.13	0.28	-6.90	1.51	15.06	16.46
40	4.8	2.0	293.42	61.13	30.56	21.40	9.17	0.12	0.28	-6.58	1.62	15.00	15.66
41	4.8	2.1	298.23	62.13	29.59	20.71	8.88	0.11	0.27	-6.28	1.74	14.95	15.01
42	4.8	2.2	302.89	63.10	28.68	20.08	8.60	0.11	0.26	-6.01	1.86	14.91	14.48

43	4.8	2.3	307.41	64.04	27.85	19.49	8.35	0.10	0.25	-5.76	1.99	14.87	14.03
44	4.8	2.4	311.81	64.96	27.07	18.95	8.12	0.09	0.24	-5.53	2.12	14.84	13.66
45	4.9	1.4	264.14	53.91	38.50	26.95	11.55	0.18	0.31	-8.99	1.05	15.41	28.67
46	4.9	1.5	270.28	55.16	36.77	25.74	11.03	0.17	0.31	-8.46	1.13	15.31	23.62
47	4.9	1.6	276.16	56.36	35.22	24.66	10.57	0.16	0.30	-7.99	1.21	15.22	20.72
48	4.9	1.7	281.80	57.51	33.83	23.68	10.15	0.14	0.30	-7.56	1.30	15.14	18.81
49	4.9	1.8	287.22	58.62	32.56	22.79	9.77	0.13	0.29	-7.18	1.40	15.07	17.44
50	4.9	1.9	292.44	59.68	31.41	21.99	9.42	0.12	0.28	-6.83	1.51	15.01	16.41
51	4.9	2.0	297.48	60.71	30.36	21.25	9.11	0.12	0.27	-6.51	1.62	14.95	15.61
52	4.9	2.1	302.36	61.71	29.38	20.57	8.82	0.11	0.26	-6.22	1.73	14.90	14.96
53	4.9	2.2	307.09	62.67	28.49	19.94	8.55	0.10	0.26	-5.95	1.85	14.86	14.43
54	4.9	2.3	311.67	63.61	27.65	19.36	8.30	0.09	0.25	-5.70	1.98	14.82	13.99
55	4.9	2.4	316.12	64.51	26.88	18.82	8.06	0.09	0.24	-5.47	2.12	14.79	13.61
56	5.0	1.4	267.72	53.54	38.25	26.77	11.47	0.17	0.31	-8.90	1.05	15.36	28.62
57	5.0	1.5	273.95	54.79	36.53	25.57	10.96	0.16	0.31	-8.38	1.13	15.26	23.57
58	5.0	1.6	279.90	55.98	34.99	24.49	10.50	0.15	0.30	-7.91	1.22	15.17	20.67
59	5.0	1.7	285.62	57.12	33.60	23.52	10.08	0.14	0.30	-7.49	1.31	15.09	18.76
60	5.0	1.8	291.11	58.22	32.35	22.64	9.70	0.13	0.29	-7.11	1.40	15.02	17.39
61	5.0	1.9	296.41	59.28	31.20	21.84	9.36	0.12	0.28	-6.76	1.50	14.95	16.37
62	5.0	2.0	301.52	60.30	30.15	21.11	9.05	0.11	0.27	-6.45	1.61	14.90	15.56
63	5.0	2.1	306.46	61.29	29.19	20.43	8.76	0.10	0.26	-6.16	1.73	14.85	14.92
64	5.0	2.2	311.25	62.25	28.30	19.81	8.49	0.10	0.25	-5.89	1.85	14.81	14.39
65	5.0	2.3	315.90	63.18	27.47	19.23	8.24	0.09	0.24	-5.64	1.98	14.77	13.95
66	5.0	2.4	320.41	64.08	26.70	18.69	8.01	0.08	0.23	-5.41	2.11	14.74	13.57
67	5.1	1.4	271.28	53.19	37.99	26.60	11.40	0.17	0.31	-8.82	1.06	15.31	28.57
68	5.1	1.5	277.59	54.43	36.29	25.40	10.89	0.16	0.31	-8.30	1.14	15.21	23.51
69	5.1	1.6	283.62	55.61	34.76	24.33	10.43	0.14	0.30	-7.84	1.22	15.12	20.62
70	5.1	1.7	289.41	56.75	33.38	23.37	10.01	0.13	0.30	-7.42	1.31	15.04	18.71
71	5.1	1.8	294.98	57.84	32.13	22.49	9.64	0.12	0.29	-7.04	1.40	14.97	17.35
72	5.1	1.9	300.34	58.89	31.00	21.70	9.30	0.11	0.28	-6.70	1.50	14.91	16.32
73	5.1	2.0	305.52	59.91	29.95	20.97	8.99	0.10	0.27	-6.38	1.61	14.85	15.52
74	5.1	2.1	310.53	60.89	28.99	20.30	8.70	0.10	0.26	-6.10	1.72	14.80	14.87
75	5.1	2.2	315.39	61.84	28.11	19.68	8.43	0.09	0.25	-5.83	1.85	14.76	14.35
76	5.1	2.3	320.09	62.76	27.29	19.10	8.19	0.09	0.24	-5.59	1.97	14.72	13.90
77	5.1	2.4	324.67	63.66	26.53	18.57	7.96	0.08	0.23	-5.36	2.10	14.69	13.53
78	5.2	1.4	274.81	52.85	37.75	26.42	11.32	0.16	0.31	-8.74	1.07	15.26	28.52
79	5.2	1.5	281.20	54.08	36.05	25.24	10.82	0.15	0.31	-8.23	1.14	15.16	23.46
80	5.2	1.6	287.32	55.25	34.53	24.17	10.36	0.14	0.30	-7.76	1.22	15.07	20.56
81	5.2	1.7	293.18	56.38	33.17	23.22	9.95	0.13	0.29	-7.35	1.31	14.99	18.66
82	5.2	1.8	298.82	57.47	31.93	22.35	9.58	0.12	0.28	-6.97	1.40	14.92	17.30

83	5.2	1.9	304.26	58.51	30.80	21.56	9.24	0.11	0.27	-6.63	1.50	14.86	16.27
84	5.2	2.0	309.50	59.52	29.76	20.83	8.93	0.10	0.26	-6.32	1.61	14.80	15.47
85	5.2	2.1	314.58	60.50	28.81	20.17	8.64	0.09	0.25	-6.04	1.72	14.76	14.83
86	5.2	2.2	319.50	61.44	27.93	19.55	8.38	0.09	0.24	-5.78	1.84	14.71	14.30
87	5.2	2.3	324.26	62.36	27.11	18.98	8.13	0.08	0.23	-5.53	1.97	14.67	13.86
88	5.2	2.4	328.90	63.25	26.35	18.45	7.91	0.08	0.22	-5.31	2.10	14.64	13.49
89	5.3	1.4	278.32	52.51	37.51	26.26	11.25	0.16	0.31	-8.66	1.07	15.21	28.47
90	5.3	1.5	284.80	53.74	35.82	25.08	10.75	0.14	0.31	-8.15	1.14	15.11	23.41
91	5.3	1.6	290.99	54.90	34.31	24.02	10.29	0.13	0.30	-7.69	1.22	15.02	20.51
92	5.3	1.7	296.93	56.02	32.96	23.07	9.89	0.12	0.29	-7.28	1.31	14.94	18.61
93	5.3	1.8	302.64	57.10	31.72	22.21	9.52	0.11	0.28	-6.91	1.40	14.87	17.25
94	5.3	1.9	308.15	58.14	30.60	21.42	9.18	0.10	0.27	-6.57	1.50	14.81	16.23
95	5.3	2.0	313.46	59.14	29.57	20.70	8.87	0.10	0.26	-6.26	1.60	14.76	15.43
96	5.3	2.1	318.60	60.11	28.63	20.04	8.59	0.09	0.25	-5.98	1.72	14.71	14.79
97	5.3	2.2	323.58	61.05	27.75	19.43	8.33	0.09	0.24	-5.72	1.84	14.67	14.26
98	5.3	2.3	328.41	61.96	26.94	18.86	8.08	0.08	0.23	-5.48	1.96	14.63	13.82
99	5.3	2.4	333.10	62.85	26.19	18.33	7.86	0.08	0.22	-5.26	2.09	14.59	13.45
100	5.4	1.4	281.81	52.19	37.28	26.09	11.18	0.15	0.31	-8.59	1.08	15.17	28.43
101	5.4	1.5	288.37	53.40	35.60	24.92	10.68	0.14	0.31	-8.08	1.15	15.06	23.36
102	5.4	1.6	294.64	54.56	34.10	23.87	10.23	0.13	0.30	-7.63	1.22	14.97	20.47
103	5.4	1.7	300.65	55.68	32.75	22.93	9.83	0.12	0.29	-7.22	1.31	14.89	18.56
104	5.4	1.8	306.44	56.75	31.53	22.07	9.46	0.11	0.28	-6.85	1.40	14.82	17.21
105	5.4	1.9	312.01	57.78	30.41	21.29	9.12	0.10	0.27	-6.51	1.50	14.76	16.19
106	5.4	2.0	317.39	58.78	29.39	20.57	8.82	0.09	0.26	-6.21	1.60	14.71	15.39
107	5.4	2.1	322.59	59.74	28.45	19.91	8.53	0.09	0.25	-5.93	1.71	14.66	14.75
108	5.4	2.2	327.64	60.67	27.58	19.31	8.27	0.08	0.23	-5.67	1.83	14.62	14.22
109	5.4	2.3	332.53	61.58	26.77	18.74	8.03	0.08	0.22	-5.43	1.96	14.58	13.78
110	5.4	2.4	337.28	62.46	26.02	18.22	7.81	0.08	0.21	-5.21	2.09	14.55	13.41
111	5.5	1.4	285.28	51.87	37.05	25.93	11.11	0.15	0.31	-8.52	1.08	15.12	28.38
112	5.5	1.5	291.92	53.08	35.38	24.77	10.62	0.13	0.30	-8.01	1.15	15.02	23.31
113	5.5	1.6	298.27	54.23	33.89	23.73	10.17	0.12	0.30	-7.56	1.23	14.93	20.42
114	5.5	1.7	304.35	55.34	32.55	22.79	9.77	0.11	0.29	-7.15	1.31	14.85	18.52
115	5.5	1.8	310.21	56.40	31.33	21.93	9.40	0.10	0.27	-6.79	1.40	14.78	17.16
116	5.5	1.9	315.85	57.43	30.22	21.16	9.07	0.09	0.26	-6.46	1.50	14.72	16.14
117	5.5	2.0	321.30	58.42	29.21	20.45	8.76	0.09	0.25	-6.15	1.60	14.67	15.35
118	5.5	2.1	326.57	59.38	28.27	19.79	8.48	0.09	0.24	-5.87	1.71	14.62	14.71
119	5.5	2.2	331.67	60.30	27.41	19.19	8.22	0.08	0.23	-5.62	1.83	14.58	14.18
120	5.5	2.3	336.62	61.20	26.61	18.63	7.98	0.08	0.22	-5.38	1.95	14.54	13.75
121	5.5	2.4	341.43	62.08	25.87	18.11	7.76	0.08	0.21	-5.16	2.08	14.50	13.37
122	5.6	1.4	288.73	51.56	36.83	25.78	11.05	0.14	0.31	-8.45	1.08	15.07	28.34

123	5.6	1.5	295.45	52.76	35.17	24.62	10.55	0.13	0.30	-7.94	1.15	14.97	23.26
124	5.6	1.6	301.87	53.91	33.69	23.58	10.11	0.12	0.29	-7.50	1.23	14.88	20.37
125	5.6	1.7	308.03	55.01	32.36	22.65	9.71	0.11	0.28	-7.09	1.31	14.80	18.47
126	5.6	1.8	313.96	56.06	31.15	21.80	9.34	0.10	0.27	-6.73	1.40	14.74	17.12
127	5.6	1.9	319.67	57.08	30.04	21.03	9.01	0.09	0.26	-6.40	1.49	14.67	16.10
128	5.6	2.0	325.18	58.07	29.03	20.32	8.71	0.09	0.25	-6.10	1.60	14.62	15.31
129	5.6	2.1	330.51	59.02	28.10	19.67	8.43	0.09	0.24	-5.82	1.71	14.57	14.67
130	5.6	2.2	335.68	59.94	27.25	19.07	8.17	0.09	0.22	-5.57	1.83	14.53	14.14
131	5.6	2.3	340.69	60.84	26.45	18.52	7.94	0.09	0.21	-5.33	1.95	14.49	13.71
132	5.6	2.4	345.56	61.71	25.71	18.00	7.71	0.09	0.20	-5.12	2.08	14.46	13.34
133	5.7	1.4	292.16	51.26	36.61	25.63	10.98	0.13	0.31	-8.38	1.09	15.03	28.29
134	5.7	1.5	298.95	52.45	34.97	24.48	10.49	0.12	0.30	-7.88	1.15	14.93	23.21
135	5.7	1.6	305.45	53.59	33.49	23.44	10.05	0.11	0.29	-7.43	1.23	14.84	20.33
136	5.7	1.7	311.69	54.68	32.17	22.52	9.65	0.10	0.28	-7.03	1.31	14.76	18.43
137	5.7	1.8	317.68	55.73	30.96	21.67	9.29	0.09	0.27	-6.67	1.40	14.69	17.08
138	5.7	1.9	323.46	56.75	29.87	20.91	8.96	0.09	0.25	-6.35	1.49	14.63	16.06
139	5.7	2.0	329.04	57.73	28.86	20.20	8.66	0.09	0.24	-6.05	1.60	14.58	15.27
140	5.7	2.1	334.43	58.67	27.94	19.56	8.38	0.09	0.23	-5.77	1.71	14.53	14.63
141	5.7	2.2	339.66	59.59	27.09	18.96	8.13	0.09	0.22	-5.52	1.83	14.49	14.11
142	5.7	2.3	344.73	60.48	26.30	18.41	7.89	0.09	0.21	-5.29	1.95	14.45	13.67
143	5.7	2.4	349.66	61.34	25.56	17.89	7.67	0.09	0.20	-5.07	2.08	14.42	13.30
144	5.8	1.4	295.56	50.96	36.40	25.48	10.92	0.13	0.31	-8.31	1.09	14.99	28.25
145	5.8	1.5	302.44	52.14	34.76	24.33	10.43	0.12	0.30	-7.81	1.16	14.88	23.17
146	5.8	1.6	309.02	53.28	33.30	23.31	9.99	0.11	0.29	-7.37	1.23	14.80	20.28
147	5.8	1.7	315.32	54.37	31.98	22.39	9.59	0.10	0.27	-6.98	1.31	14.72	18.39
148	5.8	1.8	321.39	55.41	30.78	21.55	9.24	0.09	0.26	-6.62	1.40	14.65	17.03
149	5.8	1.9	327.23	56.42	29.69	20.79	8.91	0.09	0.25	-6.30	1.49	14.59	16.02
150	5.8	2.0	332.88	57.39	28.70	20.09	8.61	0.09	0.24	-6.00	1.60	14.54	15.23
151	5.8	2.1	338.33	58.33	27.78	19.44	8.33	0.09	0.22	-5.73	1.71	14.49	14.59
152	5.8	2.2	343.62	59.25	26.93	18.85	8.08	0.09	0.21	-5.48	1.82	14.45	14.07
153	5.8	2.3	348.75	60.13	26.14	18.30	7.84	0.09	0.20	-5.25	1.95	14.41	13.63
154	5.8	2.4	353.73	60.99	25.41	17.79	7.62	0.10	0.19	-5.03	2.08	14.38	13.27

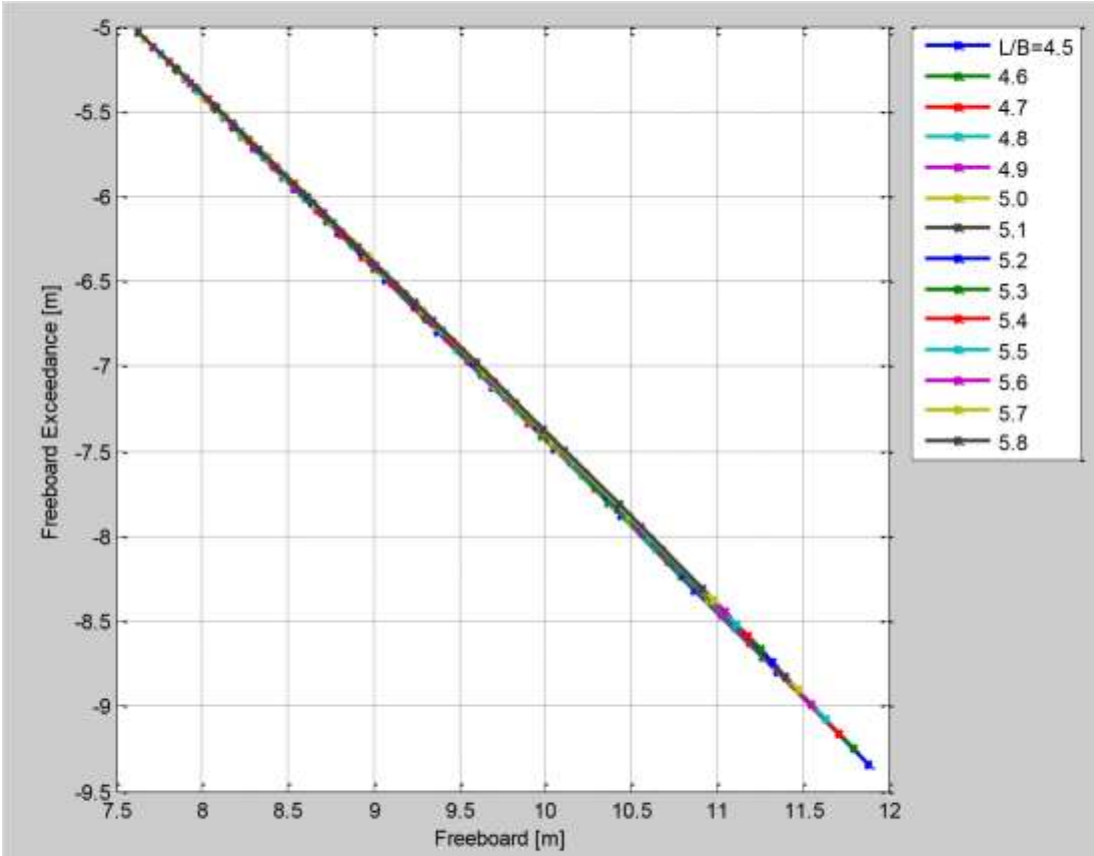


Figure A. 1: Freeboard Exceedance versus Freeboard

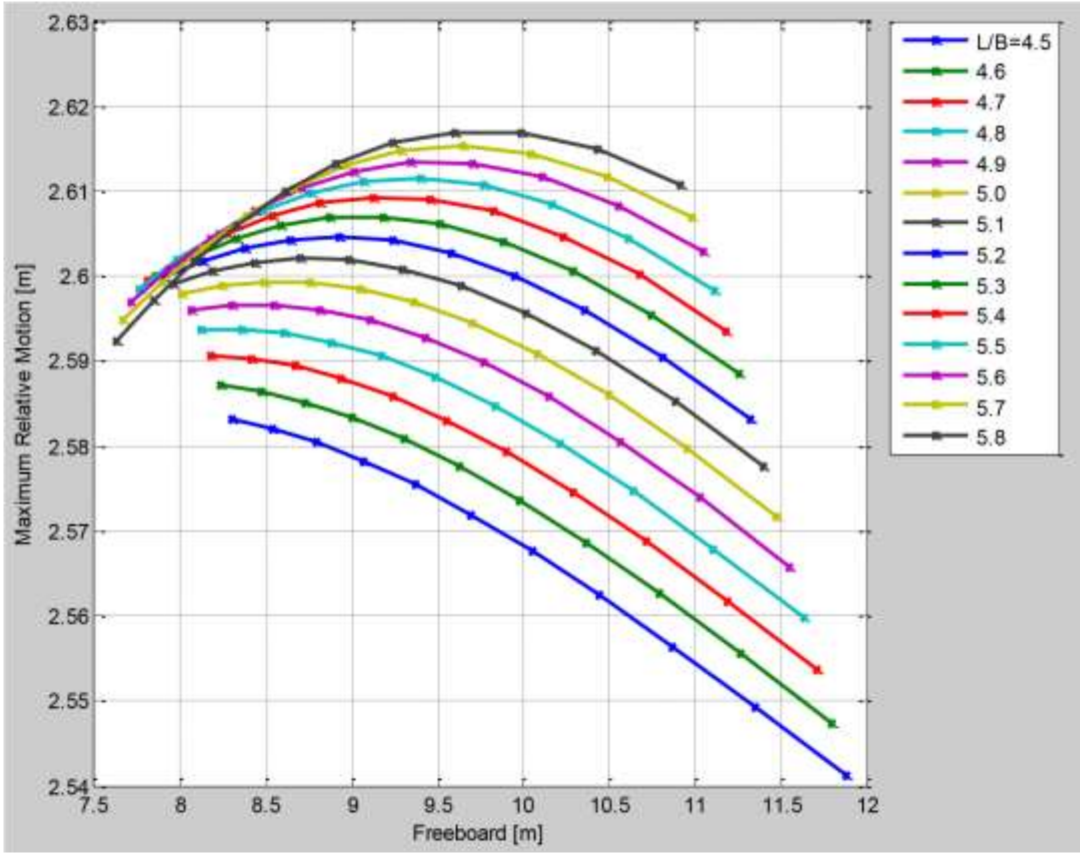


Figure A. 2: The Variation of maximum Relative Motion with Freeboard

APPENDIX B: ANALYSES OF FPSOS FOR 100YEAR RETURN PERIOD STORM OF NORTH SEA

Table B. 1: Results of Response Analyses of 2Mbbl Capacity, 365kT Displacement FPSOs for the North Sea (H_s, 16.5m; T_z, 17.5s)

S/No	L/B	B/D_m	L [m]	B [m]	D_m [m]	Freeboard D_m-D [m]	Max Heave Amplitude η_3 [m]	Max Pitch Motion η_5 [Deg]	Max Relative Motion R [m]	Slamming Constraint D-R>0	Green water Constraint D_m-D-R>0	Exeedance [m] E=R-(D_m-D)	Max BM Amidships [GNm]	Natural Heave Period T_{n3} [s]	Natural Roll Period T_{n4} [s]
1	4.5	1.4	249.56	55.46	39.61	13.86	13.11	8.56	13.40	12.34	0.46	-0.46	9.30	15.33	31.06
2	4.5	1.5	255.36	56.75	37.83	13.24	12.85	8.35	13.41	11.18	-0.17	0.17	9.49	15.23	24.65
3	4.5	1.6	260.92	57.98	36.24	12.68	12.62	8.15	13.42	10.14	-0.74	0.74	9.67	15.15	21.26
4	4.5	1.7	266.24	59.17	34.80	12.18	12.41	7.96	13.43	9.19	-1.25	1.25	9.84	15.07	19.12
5	4.5	1.8	271.37	60.30	33.50	11.73	12.21	7.78	13.44	8.34	-1.71	1.71	10.01	15.01	17.63
6	4.5	1.9	276.30	61.40	32.32	11.31	12.03	7.61	13.45	7.55	-2.14	2.14	10.17	14.95	16.53
7	4.5	2	281.06	62.46	31.23	10.93	11.86	7.46	13.47	6.83	-2.53	2.53	10.32	14.91	15.68
8	4.5	2.1	285.67	63.48	30.23	10.58	11.70	7.31	13.48	6.17	-2.90	2.90	10.48	14.86	15.00
9	4.5	2.2	290.14	64.48	29.31	10.26	11.56	7.17	13.49	5.56	-3.24	3.24	10.64	14.82	14.45
10	4.5	2.3	294.47	65.44	28.45	9.96	11.42	7.04	13.51	4.98	-3.55	3.55	10.80	14.79	13.99
11	4.5	2.4	298.68	66.37	27.66	9.68	11.29	6.92	13.53	4.45	-3.85	3.85	10.96	14.76	13.60
12	4.6	1.4	253.24	55.05	39.32	13.76	12.98	8.48	13.53	12.03	0.24	-0.24	9.31	15.27	31.00
13	4.6	1.5	259.13	56.33	37.56	13.14	12.72	8.26	13.53	10.88	-0.39	0.39	9.49	15.18	24.59
14	4.6	1.6	264.77	57.56	35.97	12.59	12.49	8.06	13.54	9.84	-0.95	0.95	9.66	15.09	21.20
15	4.6	1.7	270.17	58.73	34.55	12.09	12.28	7.87	13.55	8.91	-1.46	1.46	9.82	15.02	19.07
16	4.6	1.8	275.37	59.86	33.26	11.64	12.08	7.69	13.56	8.06	-1.92	1.92	9.97	14.96	17.58
17	4.6	1.9	280.38	60.95	32.08	11.23	11.90	7.52	13.57	7.28	-2.34	2.34	10.12	14.90	16.47
18	4.6	2	285.21	62.00	31.00	10.85	11.74	7.37	13.58	6.57	-2.73	2.73	10.26	14.85	15.62
19	4.6	2.1	289.89	63.02	30.01	10.50	11.58	7.22	13.60	5.91	-3.09	3.09	10.41	14.81	14.95
20	4.6	2.2	294.42	64.00	29.09	10.18	11.44	7.08	13.61	5.30	-3.43	3.43	10.56	14.77	14.40
21	4.6	2.3	298.82	64.96	28.24	9.89	11.30	6.95	13.63	4.73	-3.74	3.74	10.71	14.74	13.94
22	4.6	2.4	303.08	65.89	27.45	9.61	11.18	6.83	13.64	4.20	-4.03	4.03	10.87	14.71	13.56
23	4.7	1.4	256.90	54.66	39.04	13.66	12.85	8.40	13.65	11.73	0.02	-0.02	9.31	15.22	30.95
24	4.7	1.5	262.88	55.93	37.29	13.05	12.60	8.18	13.65	10.59	-0.60	0.60	9.48	15.12	24.53
25	4.7	1.6	268.59	57.15	35.72	12.50	12.36	7.97	13.66	9.56	-1.16	1.16	9.63	15.04	21.14
26	4.7	1.7	274.08	58.31	34.30	12.01	12.15	7.78	13.67	8.63	-1.66	1.66	9.78	14.97	19.01
27	4.7	1.8	279.35	59.44	33.02	11.56	11.96	7.60	13.68	7.79	-2.12	2.12	9.92	14.90	17.52
28	4.7	1.9	284.43	60.52	31.85	11.15	11.78	7.43	13.69	7.02	-2.54	2.54	10.06	14.85	16.42
29	4.7	2	289.33	61.56	30.78	10.77	11.62	7.28	13.70	6.31	-2.92	2.92	10.19	14.80	15.57
30	4.7	2.1	294.08	62.57	29.79	10.43	11.46	7.13	13.71	5.66	-3.28	3.28	10.33	14.75	14.90
31	4.7	2.2	298.67	63.55	28.89	10.11	11.32	6.99	13.72	5.05	-3.61	3.61	10.47	14.72	14.35
32	4.7	2.3	303.13	64.50	28.04	9.81	11.19	6.86	13.73	4.49	-3.92	3.92	10.62	14.68	13.89
33	4.7	2.4	307.46	65.42	27.26	9.54	11.06	6.74	13.75	3.97	-4.21	4.21	10.77	14.65	13.51
34	4.8	1.4	260.53	54.28	38.77	13.57	12.72	8.31	13.76	11.44	-0.19	0.19	9.30	15.16	30.89
35	4.8	1.5	266.59	55.54	37.03	12.96	12.47	8.09	13.77	10.30	-0.81	0.81	9.46	15.07	24.47
36	4.8	1.6	272.39	56.75	35.47	12.41	12.24	7.89	13.77	9.28	-1.36	1.36	9.60	14.99	21.09
37	4.8	1.7	277.95	57.91	34.06	11.92	12.03	7.69	13.78	8.36	-1.86	1.86	9.73	14.91	18.95
38	4.8	1.8	283.30	59.02	32.79	11.48	11.84	7.51	13.79	7.53	-2.31	2.31	9.86	14.85	17.47
39	4.8	1.9	288.45	60.09	31.63	11.07	11.66	7.34	13.79	6.76	-2.72	2.72	9.99	14.79	16.37
40	4.8	2	293.42	61.13	30.56	10.70	11.50	7.19	13.80	6.06	-3.10	3.10	10.12	14.75	15.53
41	4.8	2.1	298.23	62.13	29.59	10.36	11.35	7.04	13.81	5.42	-3.46	3.46	10.25	14.70	14.85
42	4.8	2.2	302.89	63.10	28.68	10.04	11.20	6.90	13.82	4.82	-3.79	3.79	10.38	14.67	14.30
43	4.8	2.3	307.41	64.04	27.85	9.75	11.07	6.77	13.84	4.26	-4.09	4.09	10.52	14.63	13.85
44	4.8	2.4	311.81	64.96	27.07	9.47	10.95	6.65	13.85	3.74	-4.38	4.38	10.67	14.60	13.47

45	4.9	1.4	264.14	53.91	38.50	13.48	12.60	8.23	13.87	11.16	-0.39	0.39	9.29	15.11	30.84
46	4.9	1.5	270.28	55.16	36.77	12.87	12.35	8.01	13.87	10.03	-1.00	1.00	9.43	15.02	24.41
47	4.9	1.6	276.16	56.36	35.22	12.33	12.12	7.80	13.88	9.02	-1.55	1.55	9.56	14.93	21.03
48	4.9	1.7	281.80	57.51	33.83	11.84	11.91	7.60	13.88	8.11	-2.04	2.04	9.68	14.86	18.90
49	4.9	1.8	287.22	58.62	32.56	11.40	11.72	7.42	13.89	7.28	-2.49	2.49	9.80	14.80	17.42
50	4.9	1.9	292.44	59.68	31.41	10.99	11.54	7.25	13.89	6.52	-2.90	2.90	9.92	14.74	16.32
51	4.9	2	297.48	60.71	30.36	10.62	11.38	7.10	13.90	5.83	-3.28	3.28	10.04	14.70	15.48
52	4.9	2.1	302.36	61.71	29.38	10.28	11.23	6.95	13.91	5.19	-3.63	3.63	10.16	14.65	14.81
53	4.9	2.2	307.09	62.67	28.49	9.97	11.09	6.81	13.92	4.60	-3.95	3.95	10.29	14.62	14.26
54	4.9	2.3	311.67	63.61	27.65	9.68	10.96	6.68	13.93	4.04	-4.25	4.25	10.42	14.58	13.81
55	4.9	2.4	316.12	64.51	26.88	9.41	10.84	6.56	13.94	3.53	-4.54	4.54	10.57	14.55	13.42
56	5	1.4	267.72	53.54	38.25	13.39	12.48	8.14	13.98	10.88	-0.59	0.59	9.27	15.06	30.79
57	5	1.5	273.95	54.79	36.53	12.78	12.22	7.92	13.98	9.76	-1.19	1.19	9.39	14.97	24.35
58	5	1.6	279.90	55.98	34.99	12.25	12.00	7.71	13.98	8.76	-1.73	1.73	9.51	14.88	20.98
59	5	1.7	285.62	57.12	33.60	11.76	11.79	7.51	13.98	7.86	-2.22	2.22	9.62	14.81	18.85
60	5	1.8	291.11	58.22	32.35	11.32	11.60	7.33	13.99	7.04	-2.66	2.66	9.73	14.75	17.37
61	5	1.9	296.41	59.28	31.20	10.92	11.43	7.16	13.99	6.29	-3.07	3.07	9.84	14.69	16.28
62	5	2	301.52	60.30	30.15	10.55	11.27	7.01	14.00	5.60	-3.44	3.44	9.95	14.65	15.43
63	5	2.1	306.46	61.29	29.19	10.22	11.12	6.86	14.00	4.97	-3.79	3.79	10.07	14.60	14.76
64	5	2.2	311.25	62.25	28.30	9.90	10.98	6.72	14.01	4.38	-4.11	4.11	10.19	14.57	14.22
65	5	2.3	315.90	63.18	27.47	9.61	10.85	6.59	14.02	3.83	-4.41	4.41	10.33	14.53	13.76
66	5	2.4	320.41	64.08	26.70	9.35	10.73	6.47	14.03	3.32	-4.69	4.69	10.47	14.50	13.38
67	5.1	1.4	271.28	53.19	37.99	13.30	12.36	8.06	14.08	10.62	-0.78	0.78	9.24	15.01	30.74
68	5.1	1.5	277.59	54.43	36.29	12.70	12.11	7.83	14.08	9.51	-1.38	1.38	9.35	14.92	24.30
69	5.1	1.6	283.62	55.61	34.76	12.17	11.88	7.62	14.08	8.52	-1.91	1.91	9.46	14.84	20.92
70	5.1	1.7	289.41	56.75	33.38	11.68	11.68	7.42	14.08	7.62	-2.39	2.39	9.56	14.76	18.80
71	5.1	1.8	294.98	57.84	32.13	11.25	11.49	7.24	14.08	6.81	-2.83	2.83	9.66	14.70	17.32
72	5.1	1.9	300.34	58.89	31.00	10.85	11.32	7.07	14.08	6.07	-3.23	3.23	9.76	14.65	16.23
73	5.1	2	305.52	59.91	29.95	10.48	11.16	6.92	14.08	5.39	-3.60	3.60	9.86	14.60	15.39
74	5.1	2.1	310.53	60.89	28.99	10.15	11.01	6.77	14.09	4.76	-3.94	3.94	9.97	14.56	14.72
75	5.1	2.2	315.39	61.84	28.11	9.84	10.88	6.63	14.09	4.18	-4.26	4.26	10.10	14.52	14.17
76	5.1	2.3	320.09	62.76	27.29	9.55	10.75	6.50	14.10	3.63	-4.55	4.55	10.23	14.48	13.72
77	5.1	2.4	324.67	63.66	26.53	9.28	10.62	6.38	14.11	3.13	-4.83	4.83	10.37	14.46	13.34
78	5.2	1.4	274.81	52.85	37.75	13.21	12.24	7.97	14.17	10.36	-0.96	0.96	9.20	14.96	30.70
79	5.2	1.5	281.20	54.08	36.05	12.62	11.99	7.74	14.17	9.26	-1.55	1.55	9.30	14.87	24.24
80	5.2	1.6	287.32	55.25	34.53	12.09	11.77	7.53	14.17	8.28	-2.08	2.08	9.39	14.79	20.87
81	5.2	1.7	293.18	56.38	33.17	11.61	11.56	7.33	14.16	7.39	-2.56	2.56	9.48	14.72	18.75
82	5.2	1.8	298.82	57.47	31.93	11.17	11.38	7.15	14.16	6.59	-2.99	2.99	9.58	14.65	17.27
83	5.2	1.9	304.26	58.51	30.80	10.78	11.21	6.98	14.16	5.85	-3.38	3.38	9.67	14.60	16.18
84	5.2	2	309.50	59.52	29.76	10.42	11.05	6.83	14.16	5.18	-3.75	3.75	9.77	14.55	15.34
85	5.2	2.1	314.58	60.50	28.81	10.08	10.91	6.68	14.17	4.56	-4.08	4.08	9.88	14.51	14.67
86	5.2	2.2	319.50	61.44	27.93	9.77	10.77	6.54	14.17	3.98	-4.40	4.40	10.00	14.47	14.13
87	5.2	2.3	324.26	62.36	27.11	9.49	10.64	6.41	14.18	3.44	-4.69	4.69	10.13	14.44	13.68
88	5.2	2.4	328.90	63.25	26.35	9.22	10.52	6.29	14.19	2.94	-4.96	4.96	10.28	14.41	13.30
89	5.3	1.4	278.32	52.51	37.51	13.13	12.12	7.89	14.26	10.12	-1.14	1.14	9.15	14.92	30.65
90	5.3	1.5	284.80	53.74	35.82	12.54	11.88	7.65	14.26	9.03	-1.72	1.72	9.24	14.82	24.19
91	5.3	1.6	290.99	54.90	34.31	12.01	11.66	7.44	14.25	8.05	-2.24	2.24	9.33	14.74	20.82
92	5.3	1.7	296.93	56.02	32.96	11.53	11.46	7.25	14.25	7.17	-2.71	2.71	9.41	14.67	18.70
93	5.3	1.8	302.64	57.10	31.72	11.10	11.27	7.06	14.24	6.38	-3.14	3.14	9.49	14.61	17.23
94	5.3	1.9	308.15	58.14	30.60	10.71	11.10	6.89	14.24	5.65	-3.53	3.53	9.58	14.55	16.14
95	5.3	2	313.46	59.14	29.57	10.35	10.95	6.74	14.24	4.98	-3.89	3.89	9.68	14.50	15.30
96	5.3	2.1	318.60	60.11	28.63	10.02	10.80	6.59	14.24	4.37	-4.22	4.22	9.79	14.46	14.63
97	5.3	2.2	323.58	61.05	27.75	9.71	10.67	6.45	14.24	3.79	-4.53	4.53	9.91	14.43	14.09
98	5.3	2.3	328.41	61.96	26.94	9.43	10.54	6.32	14.25	3.26	-4.82	4.82	10.05	14.39	13.64
99	5.3	2.4	333.10	62.85	26.19	9.17	10.42	6.21	14.25	2.77	-5.09	5.09	10.20	14.36	13.26
100	5.4	1.4	281.81	52.19	37.28	13.05	12.01	7.80	14.35	9.88	-1.30	1.30	9.11	14.87	30.61
101	5.4	1.5	288.37	53.40	35.60	12.46	11.77	7.57	14.34	8.80	-1.88	1.88	9.18	14.78	24.14
102	5.4	1.6	294.64	54.56	34.10	11.94	11.55	7.35	14.33	7.83	-2.40	2.40	9.26	14.69	20.77
103	5.4	1.7	300.65	55.68	32.75	11.46	11.35	7.16	14.32	6.96	-2.86	2.86	9.33	14.62	18.65
104	5.4	1.8	306.44	56.75	31.53	11.03	11.17	6.97	14.32	6.18	-3.28	3.28	9.41	14.56	17.18
105	5.4	1.9	312.01	57.78	30.41	10.64	11.00	6.80	14.31	5.45	-3.67	3.67	9.49	14.51	16.09
106	5.4	2	317.39	58.78	29.39	10.29	10.85	6.65	14.31	4.79	-4.02	4.02	9.59	14.46	15.26
107	5.4	2.1	322.59	59.74	28.45	9.96	10.70	6.50	14.31	4.18	-4.35	4.35	9.70	14.42	14.59
108	5.4	2.2	327.64	60.67	27.58	9.65	10.57	6.37	14.31	3.62	-4.66	4.66	9.83	14.38	14.05
109	5.4	2.3	332.53	61.58	26.77	9.37	10.45	6.24	14.31	3.09	-4.94	4.94	9.97	14.35	13.60
110	5.4	2.4	337.28	62.46	26.02	9.11	10.33	6.12	14.32	2.60	-5.21	5.21	10.13	14.32	13.22
111	5.5	1.4	285.28	51.87	37.05	12.97	11.90	7.71	14.43	9.65	-1.46	1.46	9.05	14.82	30.56
112	5.5	1.5	291.92	53.08	35.38	12.38	11.66	7.48	14.42	8.58	-2.03	2.03	9.12	14.73	24.09
113	5.5	1.6	298.27	54.23	33.89	11.86	11.44	7.26	14.41	7.62	-2.54	2.54	9.18	14.65	20.72
114	5.5	1.7	304.35	55.34	32.55	11.39	11.24	7.07	14.40	6.76	-3.00	3.00	9.25	14.58	18.61
115	5.5	1.8	310.21	56.40	31.33	10.97	11.07	6.88	14.39	5.98	-3.42	3.42	9.32	14.52	17.14

116	5.5	1.9	315.85	57.43	30.22	10.58	10.90	6.72	14.38	5.27	-3.80	3.80	9.41	14.46	16.05
117	5.5	2	321.30	58.42	29.21	10.22	10.75	6.56	14.37	4.61	-4.15	4.15	9.50	14.42	15.22
118	5.5	2.1	326.57	59.38	28.27	9.90	10.61	6.41	14.37	4.01	-4.47	4.47	9.62	14.37	14.55
119	5.5	2.2	331.67	60.30	27.41	9.59	10.48	6.28	14.37	3.45	-4.77	4.77	9.75	14.34	14.01
120	5.5	2.3	336.62	61.20	26.61	9.31	10.35	6.15	14.37	2.93	-5.06	5.06	9.90	14.30	13.56
121	5.5	2.4	341.43	62.08	25.87	9.05	10.23	6.03	14.37	2.44	-5.32	5.32	10.07	14.27	13.19
122	5.6	1.4	288.73	51.56	36.83	12.89	11.79	7.62	14.51	9.43	-1.62	1.62	8.99	14.78	30.52
123	5.6	1.5	295.45	52.76	35.17	12.31	11.55	7.39	14.49	8.37	-2.18	2.18	9.05	14.69	24.04
124	5.6	1.6	301.87	53.91	33.69	11.79	11.34	7.18	14.48	7.42	-2.68	2.68	9.10	14.61	20.68
125	5.6	1.7	308.03	55.01	32.36	11.32	11.14	6.98	14.46	6.57	-3.14	3.14	9.16	14.54	18.56
126	5.6	1.8	313.96	56.06	31.15	10.90	10.97	6.80	14.45	5.80	-3.55	3.55	9.24	14.47	17.09
127	5.6	1.9	319.67	57.08	30.04	10.52	10.80	6.63	14.44	5.09	-3.92	3.92	9.32	14.42	16.01
128	5.6	2	325.18	58.07	29.03	10.16	10.65	6.47	14.43	4.44	-4.27	4.27	9.42	14.37	15.17
129	5.6	2.1	330.51	59.02	28.10	9.84	10.51	6.33	14.43	3.84	-4.59	4.59	9.54	14.33	14.51
130	5.6	2.2	335.68	59.94	27.25	9.54	10.38	6.19	14.42	3.29	-4.89	4.89	9.69	14.29	13.97
131	5.6	2.3	340.69	60.84	26.45	9.26	10.26	6.07	14.42	2.77	-5.17	5.17	9.85	14.26	13.53
132	5.6	2.4	345.56	61.71	25.71	9.00	10.14	5.95	14.43	2.29	-5.43	5.43	10.04	14.23	13.15
133	5.7	1.4	292.16	51.26	36.61	12.81	11.68	7.54	14.58	9.22	-1.77	1.77	8.93	14.74	30.48
134	5.7	1.5	298.95	52.45	34.97	12.24	11.45	7.30	14.56	8.17	-2.32	2.32	8.97	14.64	24.00
135	5.7	1.6	305.45	53.59	33.49	11.72	11.23	7.09	14.54	7.23	-2.82	2.82	9.02	14.56	20.63
136	5.7	1.7	311.69	54.68	32.17	11.26	11.04	6.89	14.52	6.39	-3.26	3.26	9.08	14.49	18.52
137	5.7	1.8	317.68	55.73	30.96	10.84	10.87	6.71	14.51	5.62	-3.67	3.67	9.15	14.43	17.05
138	5.7	1.9	323.46	56.75	29.87	10.45	10.71	6.54	14.49	4.92	-4.04	4.04	9.24	14.38	15.97
139	5.7	2	329.04	57.73	28.86	10.10	10.56	6.39	14.48	4.28	-4.38	4.38	9.35	14.33	15.14
140	5.7	2.1	334.43	58.67	27.94	9.78	10.42	6.24	14.48	3.68	-4.70	4.70	9.48	14.29	14.47
141	5.7	2.2	339.66	59.59	27.09	9.48	10.29	6.11	14.47	3.13	-4.99	4.99	9.63	14.25	13.94
142	5.7	2.3	344.73	60.48	26.30	9.20	10.17	5.98	14.47	2.62	-5.27	5.27	9.81	14.22	13.49
143	5.7	2.4	349.66	61.34	25.56	8.95	10.05	5.87	14.47	2.14	-5.53	5.53	10.02	14.19	13.11
144	5.8	1.4	295.56	50.96	36.40	12.74	11.58	7.45	14.65	9.01	-1.91	1.91	8.86	14.69	30.44
145	5.8	1.5	302.44	52.14	34.76	12.17	11.34	7.21	14.62	7.97	-2.46	2.46	8.90	14.60	23.95
146	5.8	1.6	309.02	53.28	33.30	11.65	11.14	7.00	14.60	7.04	-2.95	2.95	8.94	14.52	20.58
147	5.8	1.7	315.32	54.37	31.98	11.19	10.95	6.80	14.58	6.21	-3.39	3.39	9.00	14.45	18.47
148	5.8	1.8	321.39	55.41	30.78	10.77	10.77	6.62	14.56	5.45	-3.79	3.79	9.07	14.39	17.01
149	5.8	1.9	327.23	56.42	29.69	10.39	10.61	6.45	14.54	4.76	-4.15	4.15	9.17	14.34	15.93
150	5.8	2	332.88	57.39	28.70	10.04	10.47	6.30	14.53	4.12	-4.49	4.49	9.28	14.29	15.10
151	5.8	2.1	338.33	58.33	27.78	9.72	10.33	6.16	14.52	3.53	-4.80	4.80	9.43	14.25	14.44
152	5.8	2.2	343.62	59.25	26.93	9.43	10.20	6.03	14.52	2.99	-5.09	5.09	9.59	14.21	13.90
153	5.8	2.3	348.75	60.13	26.14	9.15	10.08	5.90	14.51	2.48	-5.36	5.36	9.79	14.18	13.45
154	5.8	2.4	353.73	60.99	25.41	8.89	9.97	5.79	14.51	2.00	-5.62	5.62	10.02	14.15	13.08

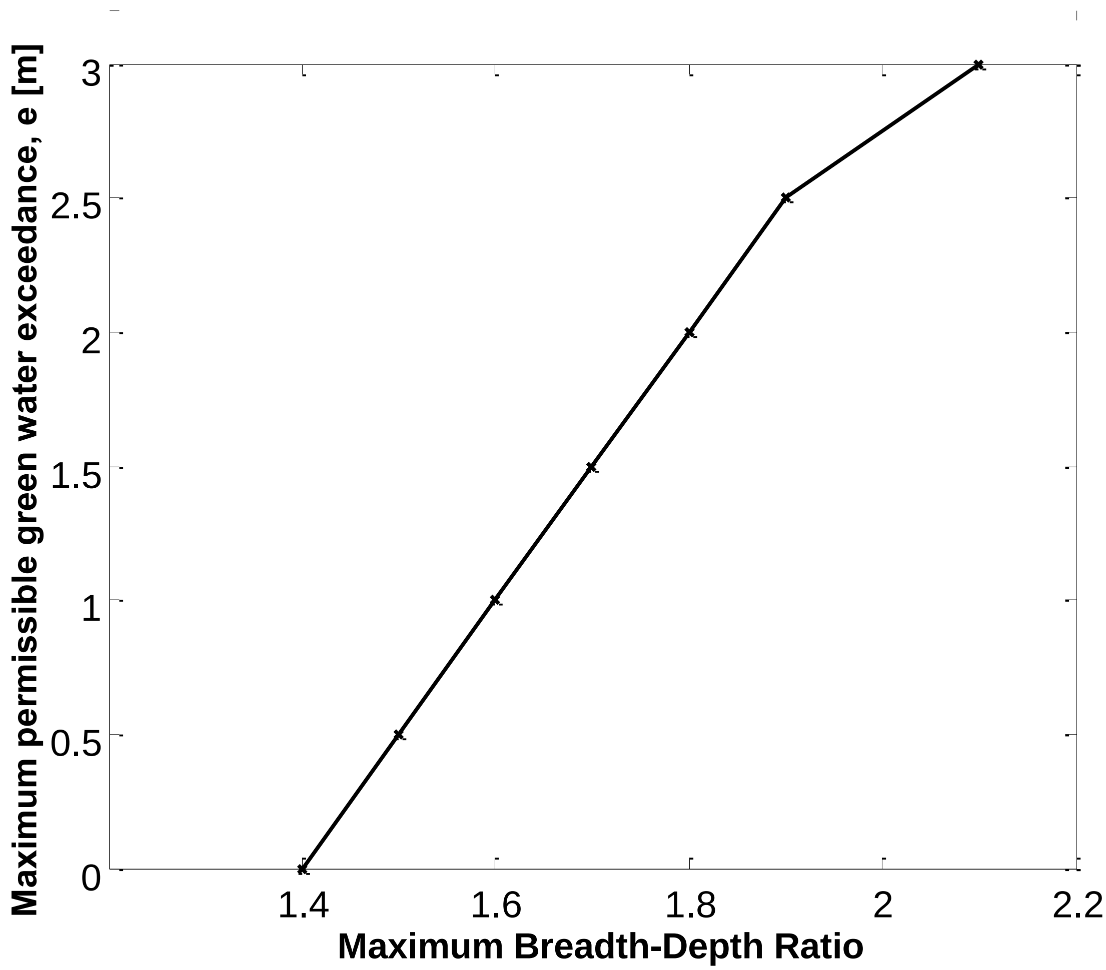


Figure B. 1: Relationship between the maximum allowable green water exceedance and maximum possible breadth-depth ratio for 365.26 kt FPSOs

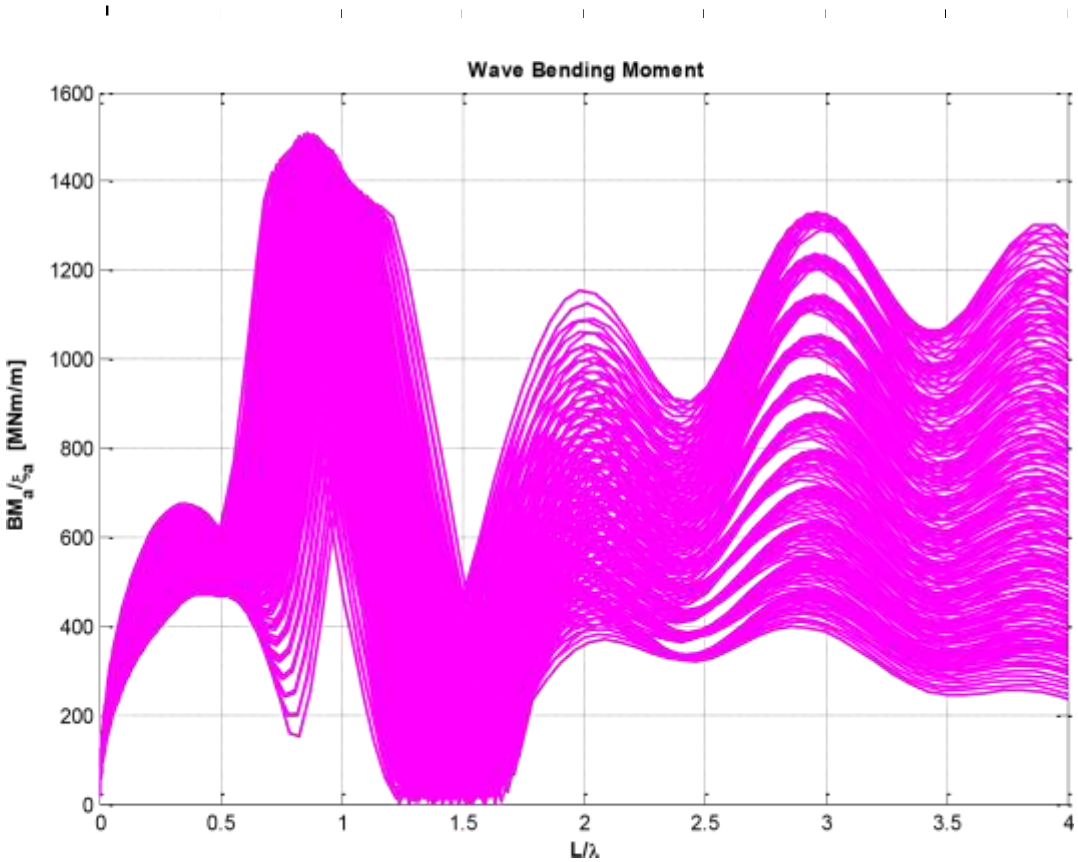


Figure B. 2: Amidships Bending Moment RAOs for 154 FPSO vessels used in the analyses

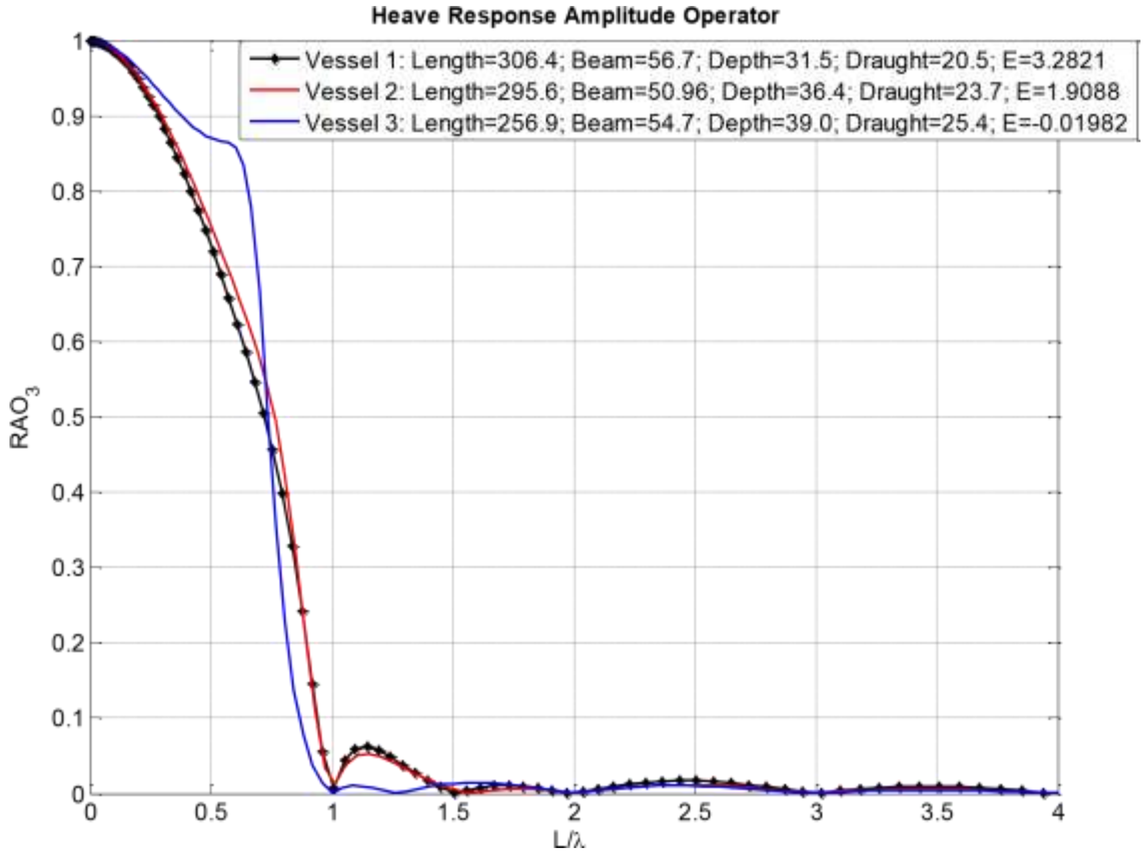


Figure B. 3: Comparing the Heave RAOs with Green Water Exceedances and main particulars of some selected FPSOs

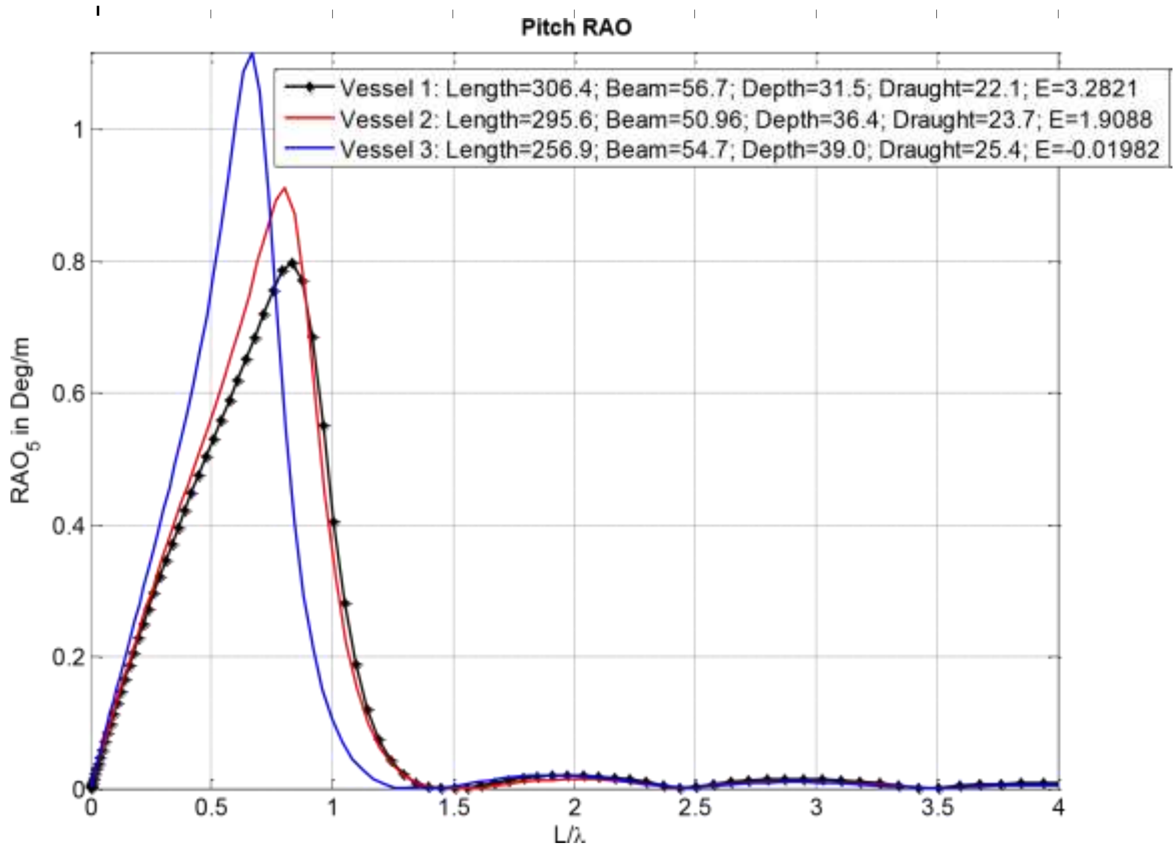


Figure B. 4: Comparing the Pitch RAOs with Green Water Exceedances and main particulars of some selected FPSOs

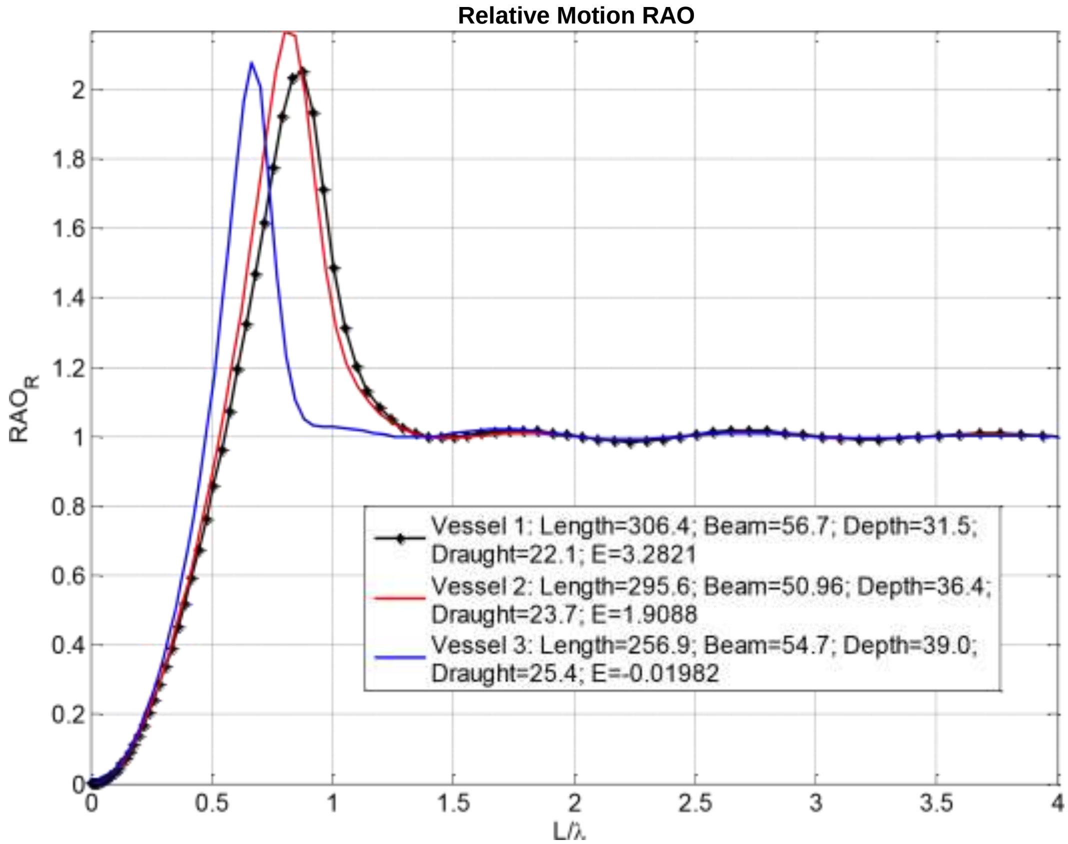


Figure B. 5: Comparing the Relative Motion RAOs with Green Water Exceedances and main particulars of some selected FPSOs

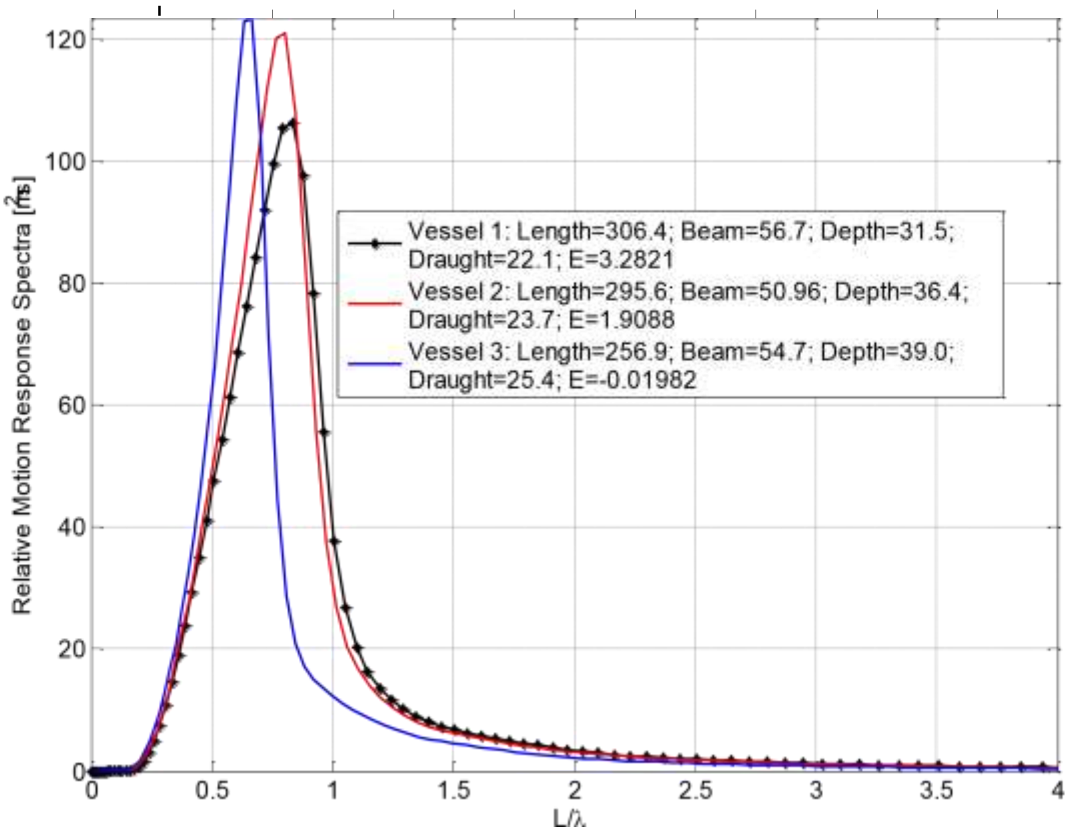


Figure B. 6: The Variation of Relative Motion Spectra with Green Water Exceedances and main particulars of some selected FPSOs

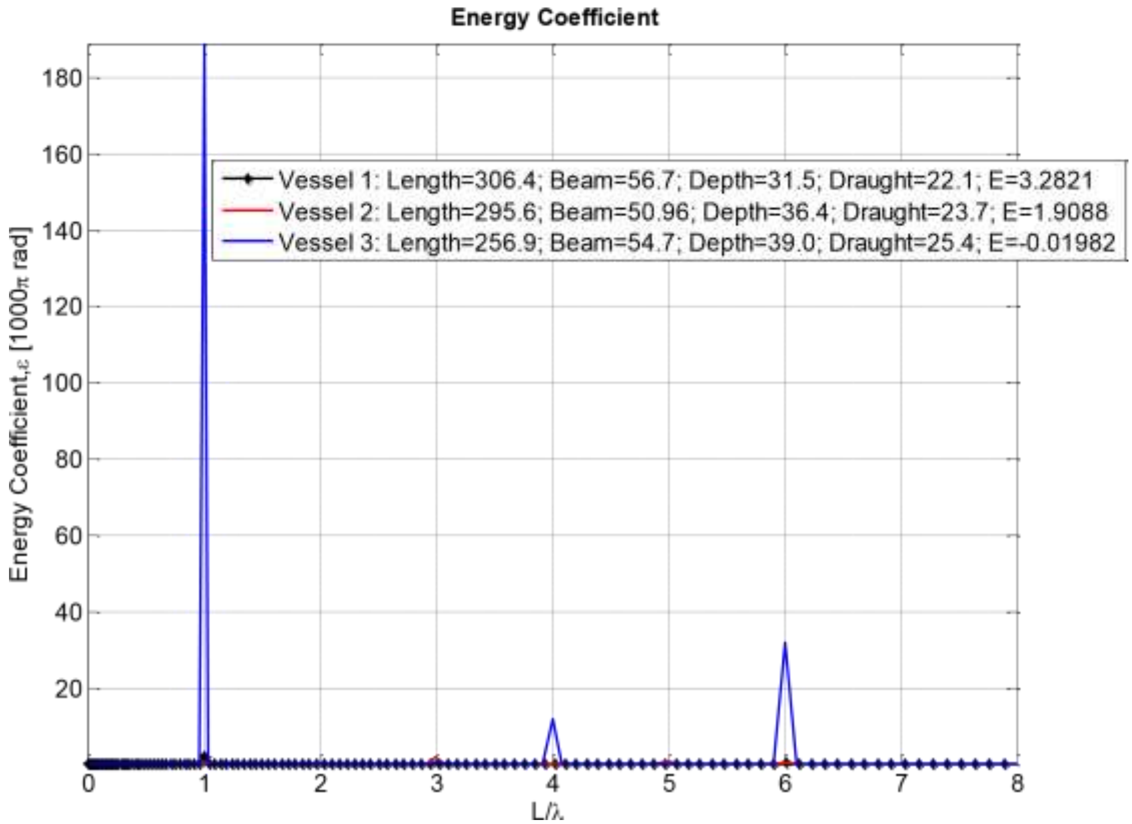


Figure B. 7: Characteristics of Energy Coefficients of FPSO vessels

APPENDIX C: RESULTS OF ANALYSES OF FPSOS FOR VARIOUS SEA STATES USING OPTIMAP

C.1: OPTIMAL DESIGN PROGRAM FOR 2MBBL OIL STORAGE CAPACITY FPSO, SEA STATE 6

Given: Storage Capacity, S_c=2Mbbl; Sea State 6⇒(H_s, 5m; T_z, 8.8s).

Please enter the sea state number: 6

Please enter the maximum allowable green water exceedance level: -5 Optimal/Overall Optimal Principal Dimensions for up to -5m permissible green water exceedance level:

Length	Beam	Depth	Draught	
323.5	56.7	29.9	19.4	[m]

Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
345.6	61.7	25.7	16.7	[m]

Overall Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
348.8	60.1	26.1	17.0	[m]

Table C. 1: Principal Dimensions, Natural Periods and Most Probable

Responses of 154, 2Mbbl Capacity FPSOs evaluated for Sea State 6

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.5	1.4	249.6	55.5	39.6	25.7	13.9	1.1	1.5	-8.8	2.8	15.3	31.1
2	4.5	1.5	255.4	56.7	37.8	24.6	13.2	1.0	1.5	-8.1	2.9	15.2	24.6
3	4.5	1.6	260.9	58.0	36.2	23.6	12.7	1.0	1.4	-7.5	3.0	15.1	21.3
4	4.5	1.7	266.2	59.2	34.8	22.6	12.2	0.9	1.4	-7.0	3.2	15.1	19.1
5	4.5	1.8	271.4	60.3	33.5	21.8	11.7	0.9	1.4	-6.5	3.3	15.0	17.6
6	4.5	1.9	276.3	61.4	32.3	21.0	11.3	0.8	1.3	-6.1	3.4	15.0	16.5
7	4.5	2.0	281.1	62.5	31.2	20.3	10.9	0.8	1.3	-5.7	3.6	14.9	15.7
8	4.5	2.1	285.7	63.5	30.2	19.6	10.6	0.7	1.2	-5.4	3.7	14.9	15.0
9	4.5	2.2	290.1	64.5	29.3	19.0	10.3	0.7	1.2	-5.0	3.9	14.8	14.4
10	4.5	2.3	294.5	65.4	28.5	18.5	10.0	0.6	1.2	-4.7	4.0	14.8	14.0
11	4.5	2.4	298.7	66.4	27.7	18.0	9.7	0.6	1.1	-4.5	4.2	14.8	13.6
12	4.6	1.4	253.2	55.1	39.3	25.6	13.8	1.0	1.5	-8.6	2.8	15.3	31.0
13	4.6	1.5	259.1	56.3	37.6	24.4	13.1	1.0	1.5	-8.0	2.9	15.2	24.6
14	4.6	1.6	264.8	57.6	36.0	23.4	12.6	0.9	1.4	-7.4	3.0	15.1	21.2
15	4.6	1.7	270.2	58.7	34.5	22.5	12.1	0.9	1.4	-6.9	3.2	15.0	19.1
16	4.6	1.8	275.4	59.9	33.3	21.6	11.6	0.8	1.4	-6.4	3.3	15.0	17.6
17	4.6	1.9	280.4	61.0	32.1	20.9	11.2	0.8	1.3	-6.0	3.4	14.9	16.5
18	4.6	2.0	285.2	62.0	31.0	20.2	10.9	0.7	1.3	-5.6	3.6	14.9	15.6
19	4.6	2.1	289.9	63.0	30.0	19.5	10.5	0.7	1.2	-5.2	3.7	14.8	14.9

20	4.6	2.2	294.4	64.0	29.1	18.9	10.2	0.6	1.2	-4.9	3.9
	14.8	14.4									
21	4.6	2.3	298.8	65.0	28.2	18.4	9.9	0.6	1.2	-4.6	4.0
	14.7	13.9									
22	4.6	2.4	303.1	65.9	27.5	17.8	9.6	0.6	1.1	-4.4	4.2
	14.7	13.6									
23	4.7	1.4	256.9	54.7	39.0	25.4	13.7	1.0	1.5	-8.5	2.8
	15.2	30.9									
24	4.7	1.5	262.9	55.9	37.3	24.2	13.1	1.0	1.5	-7.8	2.9
	15.1	24.5									
25	4.7	1.6	268.6	57.1	35.7	23.2	12.5	0.9	1.4	-7.3	3.1
	15.0	21.1									
26	4.7	1.7	274.1	58.3	34.3	22.3	12.0	0.8	1.4	-6.7	3.2
	15.0	19.0									
27	4.7	1.8	279.3	59.4	33.0	21.5	11.6	0.8	1.3	-6.3	3.3
	14.9	17.5									
28	4.7	1.9	284.4	60.5	31.9	20.7	11.1	0.7	1.3	-5.9	3.4
	14.8	16.4									
29	4.7	2.0	289.3	61.6	30.8	20.0	10.8	0.7	1.3	-5.5	3.5
	14.8	15.6									
30	4.7	2.1	294.1	62.6	29.8	19.4	10.4	0.7	1.2	-5.1	3.7
	14.8	14.9									
31	4.7	2.2	298.7	63.5	28.9	18.8	10.1	0.6	1.2	-4.8	3.8
	14.7	14.4									
32	4.7	2.3	303.1	64.5	28.0	18.2	9.8	0.6	1.1	-4.5	4.0
	14.7	13.9									
33	4.7	2.4	307.5	65.4	27.3	17.7	9.5	0.5	1.1	-4.3	4.2
	14.7	13.5									
34	4.8	1.4	260.5	54.3	38.8	25.2	13.6	1.0	1.5	-8.4	2.9
	15.2	30.9									
35	4.8	1.5	266.6	55.5	37.0	24.1	13.0	0.9	1.5	-7.7	3.0
	15.1	24.5									
36	4.8	1.6	272.4	56.7	35.5	23.1	12.4	0.9	1.4	-7.1	3.1
	15.0	21.1									
37	4.8	1.7	277.9	57.9	34.1	22.1	11.9	0.8	1.4	-6.6	3.2
	14.9	19.0									
38	4.8	1.8	283.3	59.0	32.8	21.3	11.5	0.8	1.3	-6.2	3.3
	14.9	17.5									
39	4.8	1.9	288.4	60.1	31.6	20.6	11.1	0.7	1.3	-5.8	3.4
	14.8	16.4 40	4.8	2.0	293.4	61.1	30.6	19.9	10.7	0.7	1.2
	-5.4	3.5	14.7	15.5							

41	4.8 14.7	2.1 14.9	298.2	62.1	29.6	19.2	10.4	0.6	1.2	-5.0	3.7
42	4.8 14.7	2.2 14.3	302.9	63.1	28.7	18.6	10.0	0.6	1.2	-4.7	3.8
43	4.8 14.6	2.3 13.8	307.4	64.0	27.8	18.1	9.7	0.5	1.1	-4.5	4.0
44	4.8 14.6	2.4 13.5	311.8	65.0	27.1	17.6	9.5	0.5	1.1	-4.2	4.2
45	4.9 15.1	1.4 30.8	264.1	53.9	38.5	25.0	13.5	1.0	1.5	-8.2	2.9
46	4.9 15.0	1.5 24.4	270.3	55.2	36.8	23.9	12.9	0.9	1.4	-7.6	3.0
47	4.9 14.9	1.6 21.0	276.2	56.4	35.2	22.9	12.3	0.8	1.4	-7.0	3.1
48	4.9 14.9	1.7 18.9	281.8	57.5	33.8	22.0	11.8	0.8	1.4	-6.5	3.2
49	4.9 14.8	1.8 17.4	287.2	58.6	32.6	21.2	11.4	0.7	1.3	-6.1	3.3
50	4.9 14.7	1.9 16.3	292.4	59.7	31.4	20.4	11.0	0.7	1.3	-5.7	3.4
51	4.9 14.7	2.0 15.5	297.5	60.7	30.4	19.7	10.6	0.6	1.2	-5.3	3.5
52	4.9 14.7	2.1 14.8	302.4	61.7	29.4	19.1	10.3	0.6	1.2	-5.0	3.6
53	4.9 14.6	2.2 14.3	307.1	62.7	28.5	18.5	10.0	0.6	1.1	-4.7	3.8
54	4.9 14.6	2.3 13.8	311.7	63.6	27.7	18.0	9.7	0.5	1.1	-4.4	4.0
55	4.9 14.6	2.4 13.4	316.1	64.5	26.9	17.5	9.4	0.5	1.1	-4.1	4.1
56	5.0 15.1	1.4 30.8	267.7	53.5	38.2	24.9	13.4	0.9	1.5	-8.1	2.9
57	5.0 15.0	1.5 24.4	273.9	54.8	36.5	23.7	12.8	0.9	1.4	-7.5	3.0
58	5.0 14.9	1.6 21.0	279.9	56.0	35.0	22.7	12.2	0.8	1.4	-6.9	3.1
59	5.0 14.8	1.7 18.8	285.6	57.1	33.6	21.8	11.8	0.7	1.3	-6.4	3.2
60	5.0 14.7	1.8 17.4	291.1	58.2	32.3	21.0	11.3	0.7	1.3	-6.0	3.3
61	5.0 14.7	1.9 16.3	296.4	59.3	31.2	20.3	10.9	0.6	1.2	-5.6	3.4
62	5.0 14.6	2.0 15.4	301.5	60.3	30.2	19.6	10.6	0.6	1.2	-5.2	3.5
63	5.0 14.6	2.1 14.8	306.5	61.3	29.2	19.0	10.2	0.6	1.2	-4.9	3.6

64	5.0	2.2	311.2	62.2	28.3	18.4	9.9	0.5	1.1	-4.6	3.8	14.6	14.2
65	5.0	2.3	315.9	63.2	27.5	17.9	9.6	0.5	1.1	-4.3	3.9	14.5	13.8
66	5.0	2.4	320.4	64.1	26.7	17.4	9.3	0.5	1.0	-4.0	4.1	14.5	13.4
67	5.1	1.4	271.3	53.2	38.0	24.7	13.3	0.9	1.5	-8.0	2.9	15.0	30.7
68	5.1	1.5	277.6	54.4	36.3	23.6	12.7	0.8	1.4	-7.4	3.0	14.9	24.3
69	5.1	1.6	283.6	55.6	34.8	22.6	12.2	0.8	1.4	-6.8	3.1	14.8	20.9
70	5.1	1.7	289.4	56.7	33.4	21.7	11.7	0.7	1.3	-6.3	3.1	14.8	18.8
71	5.1	1.8	295.0	57.8	32.1	20.9	11.2	0.7	1.3	-5.9	3.2	14.7	17.3
72	5.1	1.9	300.3	58.9	31.0	20.1	10.8	0.6	1.2	-5.5	3.4	14.6	16.2
73	5.1	2.0	305.5	59.9	30.0	19.5	10.5	0.6	1.2	-5.1	3.5	14.6	15.4
74	5.1	2.1	310.5	60.9	29.0	18.8	10.1	0.5	1.1	-4.8	3.6	14.6	14.7
75	5.1	2.2	315.4	61.8	28.1	18.3	9.8	0.5	1.1	-4.5	3.7	14.5	14.2
76	5.1	2.3	320.1	62.8	27.3	17.7	9.6	0.5	1.0	-4.2	3.9	14.5	13.7
77	5.1	2.4	324.7	63.7	26.5	17.2	9.3	0.4	1.0	-4.0	4.1	14.5	13.3
78	5.2	1.4	274.8	52.8	37.7	24.5	13.2	0.9	1.5	-7.9	2.9	15.0	30.7
79	5.2	1.5	281.2	54.1	36.1	23.4	12.6	0.8	1.4	-7.2	3.0	14.9	24.2
80	5.2	1.6	287.3	55.3	34.5	22.4	12.1	0.7	1.4	-6.7	3.1	14.8	20.9
81	5.2	1.7	293.2	56.4	33.2	21.6	11.6	0.7	1.3	-6.2	3.1	14.7	18.7
82	5.2	1.8	298.8	57.5	31.9	20.8	11.2	0.6	1.3	-5.8	3.2	14.7	17.3
83	5.2	1.9	304.3	58.5	30.8	20.0	10.8	0.6	1.2	-5.4	3.3	14.6	16.2
84	5.2	2.0	309.5	59.5	29.8	19.3	10.4	0.5	1.2	-5.0	3.5	14.6	15.3

85	5.2 14.5	2.1 14.7	314.6	60.5	28.8	18.7	10.1	0.5	1.1	-4.7	3.6
86	5.2 14.5	2.2 14.1	319.5	61.4	27.9	18.2	9.8	0.5	1.1	-4.4	3.7
87	5.2 14.4	2.3 13.7	324.3	62.4	27.1	17.6	9.5	0.5	1.0	-4.2	3.9
88	5.2 14.4	2.4 13.3	328.9	63.2	26.4	17.1	9.2	0.4	1.0	-3.9	4.0
89	5.3 14.9	1.4 30.7	278.3	52.5	37.5	24.4	13.1	0.8	1.4	-7.7	2.9
90	5.3 14.8	1.5 24.2	284.8	53.7	35.8	23.3	12.5	0.8	1.4	-7.1	3.0
91	5.3 14.7	1.6 20.8	291.0	54.9	34.3	22.3	12.0	0.7	1.3	-6.6	3.0
92	5.3 14.7	1.7 18.7	296.9	56.0	33.0	21.4	11.5	0.7	1.3	-6.1	3.1
93	5.3 14.6	1.8 17.2	302.6	57.1	31.7	20.6	11.1	0.6	1.2	-5.7	3.2
94	5.3 14.6	1.9 16.1	308.1	58.1	30.6	19.9	10.7	0.6	1.2	-5.3	3.3
95	5.3 14.5	2.0 15.3	313.5	59.1	29.6	19.2	10.4	0.5	1.1	-5.0	3.4
96	5.3 14.5	2.1 14.6	318.6	60.1	28.6	18.6	10.0	0.5	1.1	-4.6	3.6
97	5.3 14.4	2.2 14.1	323.6	61.1	27.8	18.0	9.7	0.5	1.0	-4.4	3.7
98	5.3 14.4	2.3 13.6	328.4	62.0	26.9	17.5	9.4	0.4	1.0	-4.1	3.9
99	5.3 14.4	2.4 13.3	333.1	62.8	26.2	17.0	9.2	0.4	1.0	-3.8	4.0
100	5.4 14.9	1.4 30.6	281.8	52.2	37.3	24.2	13.0	0.8	1.4	-7.6	2.9
101	5.4 14.8	1.5 24.1	288.4	53.4	35.6	23.1	12.5	0.7	1.4	-7.0	3.0
102	5.4 14.7	1.6 20.8	294.6	54.6	34.1	22.2	11.9	0.7	1.3	-6.5	3.0
103	5.4 14.6	1.7 18.7	300.7	55.7	32.8	21.3	11.5	0.6	1.3	-6.0	3.1
104	5.4 14.6	1.8 17.2	306.4	56.7	31.5	20.5	11.0	0.6	1.2	-5.6	3.2
105	5.4 14.5	1.9 16.1	312.0	57.8	30.4	19.8	10.6	0.5	1.2	-5.2	3.3
106	5.4 14.5	2.0 15.3	317.4	58.8	29.4	19.1	10.3	0.5	1.1	-4.9	3.4
107	5.4 14.4	2.1 14.6	322.6	59.7	28.4	18.5	10.0	0.5	1.1	-4.6	3.5

108	5.4	2.2	327.6	60.7	27.6	17.9	9.7	0.4	1.0	-4.3	3.7	14.4	14.0
109	5.4	2.3	332.5	61.6	26.8	17.4	9.4	0.4	1.0	-4.0	3.8	14.3	13.6
110	5.4	2.4	337.3	62.5	26.0	16.9	9.1	0.4	0.9	-3.8	4.0	14.3	13.2
111	5.5	1.4	285.3	51.9	37.0	24.1	13.0	0.8	1.4	-7.5	2.9	14.8	30.6
112	5.5	1.5	291.9	53.1	35.4	23.0	12.4	0.7	1.4	-6.9	3.0	14.7	24.1
113	5.5	1.6	298.3	54.2	33.9	22.0	11.9	0.7	1.3	-6.4	3.0	14.6	20.7
114	5.5	1.7	304.4	55.3	32.6	21.2	11.4	0.6	1.2	-5.9	3.1	14.6	18.6
115	5.5	1.8	310.2	56.4	31.3	20.4	11.0	0.6	1.2	-5.5	3.2	14.5	17.1
116	5.5	1.9	315.9	57.4	30.2	19.6	10.6	0.5	1.1	-5.2	3.3	14.5	16.1
117	5.5	2.0	321.3	58.4	29.2	19.0	10.2	0.5	1.1	-4.8	3.4	14.4	15.2
118	5.5	2.1	326.6	59.4	28.3	18.4	9.9	0.5	1.0	-4.5	3.5	14.4	14.6
119	5.5	2.2	331.7	60.3	27.4	17.8	9.6	0.4	1.0	-4.2	3.7	14.3	14.0
120	5.5	2.3	336.6	61.2	26.6	17.3	9.3	0.4	0.9	-4.0	3.8	14.3	13.6
121	5.5	2.4	341.4	62.1	25.9	16.8	9.1	0.4	0.9	-3.7	4.0	14.3	13.2
122	5.6	1.4	288.7	51.6	36.8	23.9	12.9	0.7	1.4	-7.4	2.9	14.8	30.5
123	5.6	1.5	295.4	52.8	35.2	22.9	12.3	0.7	1.3	-6.8	2.9	14.7	24.0
124	5.6	1.6	301.9	53.9	33.7	21.9	11.8	0.6	1.3	-6.3	3.0	14.6	20.7
125	5.6	1.7	308.0	55.0	32.4	21.0	11.3	0.6	1.2	-5.9	3.1	14.5	18.6
126	5.6	1.8	314.0	56.1	31.1	20.2	10.9	0.5	1.2	-5.5	3.2	14.5	17.1
127	5.6	1.9	319.7	57.1	30.0	19.5	10.5	0.5	1.1	-5.1	3.3	14.4	16.0
128	5.6	2.0	325.2	58.1	29.0	18.9	10.2	0.5	1.1	-4.8	3.4	14.4	15.2
129	5.6	2.1	330.5	59.0	28.1	18.3	9.8	0.4	1.0	-4.5	3.5	14.3	14.5
130	5.6	2.2	335.7	59.9	27.2	17.7	9.5	0.4	1.0	-4.2	3.6	14.3	14.0
131	5.6	2.3	340.7	60.8	26.5	17.2	9.3	0.4	0.9	-3.9	3.8	14.3	13.5
132	5.6	2.4	345.6	61.7	25.7	16.7	9.0	0.4	0.9	-3.7	4.0	14.2	13.1
133	5.7	1.4	292.2	51.3	36.6	23.8	12.8	0.7	1.4	-7.3	2.9	14.7	30.5

134	5.7	1.5	299.0	52.4	35.0	22.7	12.2	0.7	1.3	-6.8	2.9	14.6	24.0
135	5.7	1.6	305.5	53.6	33.5	21.8	11.7	0.6	1.3	-6.2	3.0	14.6	20.6
136	5.7	1.7	311.7	54.7	32.2	20.9	11.3	0.5	1.2	-5.8	3.1	14.5	18.5
137	5.7	1.8	317.7	55.7	31.0	20.1	10.8	0.5	1.1	-5.4	3.1	14.4	17.0
138	5.7	1.9	323.5	56.7	29.9	19.4	10.5	0.5	1.1	-5.0	3.2	14.4	16.0
139	5.7	2.0	329.0	57.7	28.9	18.8	10.1	0.4	1.0	-4.7	3.4	14.3	15.1
140	5.7	2.1	334.4	58.7	27.9	18.2	9.8	0.4	1.0	-4.4	3.5	14.3	14.5
141	5.7	2.2	339.7	59.6	27.1	17.6	9.5	0.4	0.9	-4.1	3.6	14.3	13.9
142	5.7	2.3	344.7	60.5	26.3	17.1	9.2	0.4	0.9	-3.9	3.8	14.2	13.5
143	5.7	2.4	349.7	61.3	25.6	16.6	8.9	0.4	0.8	-3.7	4.0	14.2	13.1
144	5.8	1.4	295.6	51.0	36.4	23.7	12.7	0.7	1.4	-7.2	2.9	14.7	30.4
145	5.8	1.5	302.4	52.1	34.8	22.6	12.2	0.6	1.3	-6.7	2.9	14.6	24.0
146	5.8	1.6	309.0	53.3	33.3	21.6	11.7	0.6	1.2	-6.2	3.0	14.5	20.6
147	5.8	1.7	315.3	54.4	32.0	20.8	11.2	0.5	1.2	-5.7	3.0	14.5	18.5
148	5.8	1.8	321.4	55.4	30.8	20.0	10.8	0.5	1.1	-5.3	3.1	14.4	17.0
149	5.8	1.9	327.2	56.4	29.7	19.3	10.4	0.5	1.1	-5.0	3.2	14.3	15.9
150	5.8	2.0	332.9	57.4	28.7	18.7	10.0	0.4	1.0	-4.6	3.3	14.3	15.1
151	5.8	2.1	338.3	58.3	27.8	18.1	9.7	0.4	1.0	-4.4	3.5	14.2	14.4
152	5.8	2.2	343.6	59.2	26.9	17.5	9.4	0.4	0.9	-4.1	3.6	14.2	13.9
153	5.8	2.3	348.8	60.1	26.1	17.0	9.2	0.4	0.9	-3.8	3.8	14.2	13.5
154	5.8	2.4	353.7	61.0	25.4	16.5	8.9	0.4	0.8	-3.6	4.0	14.1	13.1

C.2: OPTIMAP FOR SEA STATE 7

Given: Storage Capacity, S_c=2Mbbl; Sea State 7⇒(H_s, 7.5m; T_z, 10.7s).

Please enter the sea state number: 7

Please enter the maximum allowable green water exceedance levels: 0

Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
353.7	61.0	25.4	16.5	[m]

Table C. 2: Principal Dimensions, Natural Periods and Most Probable

Responses of 154, 2Mbbl Capacity FPSOs evaluated for Sea State 7

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.5	1.4	249.6	55.5	39.6	25.7	13.9	3.3	3.9	-5.3	5.4		
		15.3	31.1										
2	4.5	1.5	255.4	56.7	37.8	24.6	13.2	3.2	3.8	-4.6	5.5		
		15.2	24.6										
3	4.5	1.6	260.9	58.0	36.2	23.6	12.7	3.0	3.7	-4.0	5.6		
		15.1	21.3										
4	4.5	1.7	266.2	59.2	34.8	22.6	12.2	2.9	3.6	-3.5	5.7		
		15.1	19.1										
5	4.5	1.8	271.4	60.3	33.5	21.8	11.7	2.7	3.5	-3.0	5.8		
		15.0	17.6										
6	4.5	1.9	276.3	61.4	32.3	21.0	11.3	2.6	3.3	-2.6	5.9		
		15.0	16.5										
7	4.5	2.0	281.1	62.5	31.2	20.3	10.9	2.5	3.3	-2.2	6.0		
		14.9	15.7										
8	4.5	2.1	285.7	63.5	30.2	19.6	10.6	2.4	3.2	-1.9	6.1		
		14.9	15.0										
9	4.5	2.2	290.1	64.5	29.3	19.0	10.3	2.3	3.1	-1.6	6.2		
		14.8	14.4										
10	4.5	2.3	294.5	65.4	28.5	18.5	10.0	2.2	3.0	-1.3	6.3		
		14.8	14.0										
11	4.5	2.4	298.7	66.4	27.7	18.0	9.7	2.1	2.9	-1.0	6.4		
		14.8	13.6										
12	4.6	1.4	253.2	55.1	39.3	25.6	13.8	3.2	3.8	-5.1	5.4		
		15.3	31.0										
13	4.6	1.5	259.1	56.3	37.6	24.4	13.1	3.1	3.7	-4.5	5.5		
		15.2	24.6										
14	4.6	1.6	264.8	57.6	36.0	23.4	12.6	2.9	3.6	-3.9	5.6		
		15.1	21.2										
15	4.6	1.7	270.2	58.7	34.5	22.5	12.1	2.8	3.5	-3.3	5.7		
		15.0	19.1										
16	4.6	1.8	275.4	59.9	33.3	21.6	11.6	2.7	3.4	-2.9	5.7		
		15.0	17.6										
17	4.6	1.9	280.4	61.0	32.1	20.9	11.2	2.5	3.3	-2.5	5.8		
		14.9	16.5										
18	4.6	2.0	285.2	62.0	31.0	20.2	10.9	2.4	3.2	-2.1	5.9		
		14.9	15.6										

19	4.6	2.1 14.8	289.9 14.9	63.0	30.0	19.5	10.5	2.3	3.1	-1.7	6.0
20	4.6	2.2 14.8	294.4 14.4	64.0	29.1	18.9	10.2	2.2	3.0	-1.4	6.1
21	4.6	2.3 14.7	298.8 13.9	65.0	28.2	18.4	9.9	2.1	2.9	-1.2	6.2
22	4.6	2.4 14.7	303.1 13.6	65.9	27.5	17.8	9.6	2.1	2.8	-0.9	6.4
23	4.7	1.4 15.2	256.9 30.9	54.7	39.0	25.4	13.7	3.2	3.8	-4.9	5.4
24	4.7	1.5 15.1	262.9 24.5	55.9	37.3	24.2	13.1	3.0	3.7	-4.3	5.5
25	4.7	1.6 15.0	268.6 21.1	57.1	35.7	23.2	12.5	2.8	3.6	-3.7	5.6
26	4.7	1.7 15.0	274.1 19.0	58.3	34.3	22.3	12.0	2.7	3.5	-3.2	5.6
27	4.7	1.8 14.9	279.3 17.5	59.4	33.0	21.5	11.6	2.6	3.4	-2.7	5.7
28	4.7	1.9 14.8	284.4 16.4	60.5	31.9	20.7	11.1	2.5	3.3	-2.3	5.8
29	4.7	2.0 14.8	289.3 15.6	61.6	30.8	20.0	10.8	2.3	3.2	-1.9	5.9
30	4.7	2.1 14.8	294.1 14.9	62.6	29.8	19.4	10.4	2.2	3.1	-1.6	6.0
31	4.7	2.2 14.7	298.7 14.4	63.5	28.9	18.8	10.1	2.1	3.0	-1.3	6.1
32	4.7	2.3 14.7	303.1 13.9	64.5	28.0	18.2	9.8	2.1	2.9	-1.0	6.2
33	4.7	2.4 14.7	307.5 13.5	65.4	27.3	17.7	9.5	2.0	2.8	-0.8	6.3
34	4.8	1.4 15.2	260.5 30.9	54.3	38.8	25.2	13.6	3.1	3.8	-4.7	5.4
35	4.8	1.5 15.1	266.6 24.5	55.5	37.0	24.1	13.0	2.9	3.7	-4.1	5.5
36	4.8	1.6 15.0	272.4 21.1	56.7	35.5	23.1	12.4	2.8	3.5	-3.5	5.5
37	4.8	1.7 14.9	277.9 19.0	57.9	34.1	22.1	11.9	2.6	3.4	-3.0	5.6
38	4.8	1.8 14.9	283.3 17.5	59.0	32.8	21.3	11.5	2.5	3.3	-2.6	5.7
39	4.8	1.9 14.8	288.4 16.4	60.1	31.6	20.6	11.1	2.4	3.2	-2.2	5.7
40	4.8	2.0 14.7	293.4 15.5	61.1	30.6	19.9	10.7	2.3	3.1	-1.8	5.8
41	4.8	2.1 14.7	298.2 14.9	62.1	29.6	19.2	10.4	2.2	3.0	-1.5	5.9

42	4.8	2.2 14.7	302.9 14.3	63.1	28.7	18.6	10.0	2.1	2.9	-1.2	6.0
43	4.8	2.3 14.6	307.4 13.8	64.0	27.8	18.1	9.7	2.0	2.8	-0.9	6.1
44	4.8	2.4 14.6	311.8 13.5	65.0	27.1	17.6	9.5	1.9	2.7	-0.7	6.2
45	4.9	1.4 15.1	264.1 30.8	53.9	38.5	25.0	13.5	3.0	3.7	-4.6	5.4
46	4.9	1.5 15.0	270.3 24.4	55.2	36.8	23.9	12.9	2.8	3.6	-3.9	5.5
47	4.9	1.6 14.9	276.2 21.0	56.4	35.2	22.9	12.3	2.7	3.5	-3.4	5.5
48	4.9	1.7 14.9	281.8 18.9	57.5	33.8	22.0	11.8	2.5	3.4	-2.9	5.6
49	4.9	1.8 14.8	287.2 17.4	58.6	32.6	21.2	11.4	2.4	3.3	-2.4	5.6
50	4.9	1.9 14.7	292.4 16.3	59.7	31.4	20.4	11.0	2.3	3.2	-2.0	5.7
51	4.9	2.0 14.7	297.5 15.5	60.7	30.4	19.7	10.6	2.2	3.0	-1.7	5.8
52	4.9	2.1 14.7	302.4 14.8	61.7	29.4	19.1	10.3	2.1	2.9	-1.4	5.8
53	4.9	2.2 14.6	307.1 14.3	62.7	28.5	18.5	10.0	2.0	2.8	-1.1	5.9
54	4.9	2.3 14.6	311.7 13.8	63.6	27.7	18.0	9.7	1.9	2.8	-0.8	6.0
55	4.9	2.4 14.6	316.1 13.4	64.5	26.9	17.5	9.4	1.8	2.7	-0.6	6.1
56	5.0	1.4 15.1	267.7 30.8	53.5	38.2	24.9	13.4	2.9	3.7	-4.4	5.4
57	5.0	1.5 15.0	273.9 24.4	54.8	36.5	23.7	12.8	2.8	3.6	-3.8	5.4
58	5.0	1.6 14.9	279.9 21.0	56.0	35.0	22.7	12.2	2.6	3.5	-3.2	5.5
59	5.0	1.7 14.8	285.6 18.8	57.1	33.6	21.8	11.8	2.5	3.3	-2.7	5.5
60	5.0	1.8 14.7	291.1 17.4	58.2	32.3	21.0	11.3	2.3	3.2	-2.3	5.6
61	5.0	1.9 14.7 3.0	296.4 16.3 62 -1.6	59.3 5.0 5.7	31.2 2.0 14.6	20.3 301.5 15.4	10.9 60.3	2.2 30.2	3.1 19.6	-1.9 10.6	5.6 2.1

63	5.0	2.1	306.5	61.3	29.2	19.0	10.2	2.0	2.9	-1.3	5.8
		14.6	14.8								
64	5.0	2.2	311.2	62.2	28.3	18.4	9.9	1.9	2.8	-1.0	5.8
		14.6	14.2								
65	5.0	2.3	315.9	63.2	27.5	17.9	9.6	1.9	2.7	-0.7	5.9
		14.5	13.8								
66	5.0	2.4	320.4	64.1	26.7	17.4	9.3	1.8	2.6	-0.5	6.0
		14.5	13.4								
67	5.1	1.4	271.3	53.2	38.0	24.7	13.3	2.8	3.7	-4.3	5.4
		15.0	30.7								
68	5.1	1.5	277.6	54.4	36.3	23.6	12.7	2.7	3.5	-3.6	5.4
		14.9	24.3								
69	5.1	1.6	283.6	55.6	34.8	22.6	12.2	2.5	3.4	-3.1	5.5
		14.8	20.9								
70	5.1	1.7	289.4	56.7	33.4	21.7	11.7	2.4	3.3	-2.6	5.5
		14.8	18.8								
71	5.1	1.8	295.0	57.8	32.1	20.9	11.2	2.3	3.2	-2.2	5.5
		14.7	17.3								
72	5.1	1.9	300.3	58.9	31.0	20.1	10.8	2.1	3.0	-1.8	5.6
		14.6	16.2								
73	5.1	2.0	305.5	59.9	30.0	19.5	10.5	2.0	2.9	-1.5	5.6
		14.6	15.4								
74	5.1	2.1	310.5	60.9	29.0	18.8	10.1	2.0	2.8	-1.2	5.7
		14.6	14.7								
75	5.1	2.2	315.4	61.8	28.1	18.3	9.8	1.9	2.7	-0.9	5.8
		14.5	14.2								
76	5.1	2.3	320.1	62.8	27.3	17.7	9.6	1.8	2.6	-0.6	5.9
		14.5	13.7								
77	5.1	2.4	324.7	63.7	26.5	17.2	9.3	1.7	2.6	-0.4	6.0
		14.5	13.3								
78	5.2	1.4	274.8	52.8	37.7	24.5	13.2	2.8	3.6	-4.1	5.4
		15.0	30.7								
79	5.2	1.5	281.2	54.1	36.1	23.4	12.6	2.6	3.5	-3.5	5.4
		14.9	24.2								
80	5.2	1.6	287.3	55.3	34.5	22.4	12.1	2.4	3.4	-3.0	5.4
		14.8	20.9								
81	5.2	1.7	293.2	56.4	33.2	21.6	11.6	2.3	3.2	-2.5	5.4
		14.7	18.7								
82	5.2	1.8	298.8	57.5	31.9	20.8	11.2	2.2	3.1	-2.1	5.5
		14.7	17.3								
83	5.2	1.9	304.3	58.5	30.8	20.0	10.8	2.1	3.0	-1.7	5.5
		14.6	16.2								
84	5.2	2.0	309.5	59.5	29.8	19.3	10.4	2.0	2.9	-1.4	5.6
		14.6	15.3								
85	5.2	2.1	314.6	60.5	28.8	18.7	10.1	1.9	2.8	-1.1	5.6
		14.5	14.7								

86	5.2	2.2 14.5	319.5 14.1	61.4	27.9	18.2	9.8	1.8	2.7	-0.8	5.7
87	5.2	2.3 14.4	324.3 13.7	62.4	27.1	17.6	9.5	1.7	2.6	-0.5	5.8
88	5.2	2.4 14.4	328.9 13.3	63.2	26.4	17.1	9.2	1.7	2.5	-0.3	5.9
89	5.3	1.4 14.9	278.3 30.7	52.5	37.5	24.4	13.1	2.7	3.6	-4.0	5.3
90	5.3	1.5 14.8	284.8 24.2	53.7	35.8	23.3	12.5	2.5	3.4	-3.4	5.4
91	5.3	1.6 14.7	291.0 20.8	54.9	34.3	22.3	12.0	2.4	3.3	-2.8	5.4
92	5.3	1.7 14.7	296.9 18.7	56.0	33.0	21.4	11.5	2.2	3.2	-2.4	5.4
93	5.3	1.8 14.6	302.6 17.2	57.1	31.7	20.6	11.1	2.1	3.1	-2.0	5.4
94	5.3	1.9 14.6	308.1 16.1	58.1	30.6	19.9	10.7	2.0	2.9	-1.6	5.4
95	5.3	2.0 14.5	313.5 15.3	59.1	29.6	19.2	10.4	1.9	2.8	-1.3	5.5
96	5.3	2.1 14.5	318.6 14.6	60.1	28.6	18.6	10.0	1.8	2.7	-1.0	5.5
97	5.3	2.2 14.4	323.6 14.1	61.1	27.8	18.0	9.7	1.7	2.6	-0.7	5.6
98	5.3	2.3 14.4	328.4 13.6	62.0	26.9	17.5	9.4	1.7	2.5	-0.5	5.7
99	5.3	2.4 14.4	333.1 13.3	62.8	26.2	17.0	9.2	1.6	2.4	-0.3	5.8
100	5.4	1.4 14.9	281.8 30.6	52.2	37.3	24.2	13.0	2.6	3.5	-3.8	5.3
101	5.4	1.5 14.8	288.4 24.1	53.4	35.6	23.1	12.5	2.4	3.4	-3.2	5.3
102	5.4	1.6 14.7 3.1	294.6 20.8 103 -2.3	54.6 5.4 5.3	34.1 1.7 14.6	22.2 300.7 18.7	11.9 55.7	2.3 32.8	3.3 21.3	-2.7 11.5	5.3 2.2
104	5.4	1.8 14.6	306.4 17.2	56.7	31.5	20.5	11.0	2.0	3.0	-1.9	5.3
105	5.4	1.9 14.5	312.0 16.1	57.8	30.4	19.8	10.6	1.9	2.9	-1.5	5.4
106	5.4	2.0 14.5	317.4 15.3	58.8	29.4	19.1	10.3	1.8	2.8	-1.2	5.4

107	5.4	2.1	322.6	59.7	28.4	18.5	10.0	1.8	2.7	-0.9	5.5
		14.4	14.6								
108	5.4	2.2	327.6	60.7	27.6	17.9	9.7	1.7	2.6	-0.6	5.5
		14.4	14.0								
109	5.4	2.3	332.5	61.6	26.8	17.4	9.4	1.6	2.5	-0.4	5.6
		14.3	13.6								
110	5.4	2.4	337.3	62.5	26.0	16.9	9.1	1.6	2.4	-0.2	5.7
		14.3	13.2								
111	5.5	1.4	285.3	51.9	37.0	24.1	13.0	2.5	3.5	-3.7	5.3
		14.8	30.6								
112	5.5	1.5	291.9	53.1	35.4	23.0	12.4	2.4	3.3	-3.1	5.3
		14.7	24.1								
113	5.5	1.6	298.3	54.2	33.9	22.0	11.9	2.2	3.2	-2.6	5.3
		14.6	20.7								
114	5.5	1.7	304.4	55.3	32.6	21.2	11.4	2.1	3.1	-2.2	5.3
		14.6	18.6								
115	5.5	1.8	310.2	56.4	31.3	20.4	11.0	2.0	2.9	-1.8	5.3
		14.5	17.1								
116	5.5	1.9	315.9	57.4	30.2	19.6	10.6	1.9	2.8	-1.4	5.3
		14.5	16.1								
117	5.5	2.0	321.3	58.4	29.2	19.0	10.2	1.8	2.7	-1.1	5.3
		14.4	15.2								
118	5.5	2.1	326.6	59.4	28.3	18.4	9.9	1.7	2.6	-0.8	5.4
		14.4	14.6								
119	5.5	2.2	331.7	60.3	27.4	17.8	9.6	1.6	2.5	-0.6	5.5
		14.3	14.0								
120	5.5	2.3	336.6	61.2	26.6	17.3	9.3	1.6	2.4	-0.4	5.6
		14.3	13.6								
121	5.5	2.4	341.4	62.1	25.9	16.8	9.1	1.5	2.3	-0.1	5.7
		14.3	13.2								
122	5.6	1.4	288.7	51.6	36.8	23.9	12.9	2.5	3.4	-3.6	5.2
		14.8	30.5								
123	5.6	1.5	295.4	52.8	35.2	22.9	12.3	2.3	3.3	-3.0	5.2
		14.7	24.0								
124	5.6	1.6	301.9	53.9	33.7	21.9	11.8	2.2	3.1	-2.5	5.2
		14.6	20.7								
125	5.6	1.7	308.0	55.0	32.4	21.0	11.3	2.0	3.0	-2.1	5.2
		14.5	18.6								
126	5.6	1.8	314.0	56.1	31.1	20.2	10.9	1.9	2.9	-1.7	5.2
		14.5	17.1								
127	5.6	1.9	319.7	57.1	30.0	19.5	10.5	1.8	2.8	-1.4	5.2
		14.4	16.0								
128	5.6	2.0	325.2	58.1	29.0	18.9	10.2	1.7	2.6	-1.0	5.3
		14.4	15.2								
129	5.6	2.1	330.5	59.0	28.1	18.3	9.8	1.7	2.5	-0.8	5.3
		14.3	14.5								

130	5.6	2.2	335.7	59.9	27.2	17.7	9.5	1.6	2.4	-0.5	5.4	14.3	14.0
131	5.6	2.3	340.7	60.8	26.5	17.2	9.3	1.5	2.3	-0.3	5.5	14.3	13.5
132	5.6	2.4	345.6	61.7	25.7	16.7	9.0	1.5	2.3	-0.1	5.6	14.2	13.1
133	5.7	1.4	292.2	51.3	36.6	23.8	12.8	2.4	3.4	-3.4	5.2	14.7	30.5
134	5.7	1.5	299.0	52.4	35.0	22.7	12.2	2.2	3.2	-2.9	5.2	14.6	24.0
135	5.7	1.6	305.5	53.6	33.5	21.8	11.7	2.1	3.1	-2.4	5.1	14.6	20.6
136	5.7	1.7	311.7	54.7	32.2	20.9	11.3	2.0	2.9	-2.0	5.1	14.5	18.5
137	5.7	1.8	317.7	55.7	31.0	20.1	10.8	1.9	2.8	-1.6	5.1	14.4	17.0
138	5.7	1.9	323.5	56.7	29.9	19.4	10.5	1.8	2.7	-1.3	5.2	14.4	16.0
139	5.7	2.0	329.0	57.7	28.9	18.8	10.1	1.7	2.6	-1.0	5.2	14.3	15.1
140	5.7	2.1	334.4	58.7	27.9	18.2	9.8	1.6	2.5	-0.7	5.3	14.3	14.5
141	5.7	2.2	339.7	59.6	27.1	17.6	9.5	1.6	2.4	-0.5	5.3	14.3	13.9
142	5.7	2.3	344.7	60.5	26.3	17.1	9.2	1.5	2.3	-0.3	5.5	14.2	13.5
143	5.7	2.4	349.7	61.3	25.6	16.6	8.9	1.4	2.2	-0.1	5.6	14.2	13.1
144	5.8	1.4	295.6	51.0	36.4	23.7	12.7	2.3	3.3	-3.3	5.1	14.7	30.4
145	5.8	1.5	302.4	52.1	34.8	22.6	12.2	2.2	3.2	-2.8	5.1	14.6	24.0
146	5.8	1.6	309.0	53.3	33.3	21.6	11.7	2.0	3.0	-2.3	5.1	14.5	20.6
147	5.8	1.7	315.3	54.4	32.0	20.8	11.2	1.9	2.9	-1.9	5.1	14.5	18.5
148	5.8	1.8	321.4	55.4	30.8	20.0	10.8	1.8	2.8	-1.5	5.1	14.4	17.0
149	5.8	1.9	327.2	56.4	29.7	19.3	10.4	1.7	2.6	-1.2	5.1	14.3	15.9
150	5.8	2.0	332.9	57.4	28.7	18.7	10.0	1.6	2.5	-0.9	5.1	14.3	15.1
151	5.8	2.1	338.3	58.3	27.8	18.1	9.7	1.6	2.4	-0.7	5.2	14.2	14.4
152	5.8	2.2	343.6	59.2	26.9	17.5	9.4	1.5	2.3	-0.4	5.3	14.2	13.9
153	5.8	2.3	348.8	60.1	26.1	17.0	9.2	1.5	2.2	-0.2	5.4	14.2	13.5
154	5.8	2.4	353.7	61.0	25.4	16.5	8.9	1.4	2.1	0.0	5.6	14.1	13.1

C.3: OPTIMAP FOR SEA STATE 8

Given: Storage Capacity, S_c=2Mbbl; Sea State 8⇒(H_s, 11.5m; T_z, 11.6s).

Please enter the sea state number: 8

Please enter the maximum allowable green water exceedance level: 2
Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
295.6	51.0	36.4	23.7	[m]

Table C. 3: Principal Dimensions, Natural Periods and Most Probable Responses of 154, 2Mbbl Capacity FPSOs evaluated for Sea State 8

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.5	1.4	249.6	55.5	39.6	25.7	13.9	6.2	6.6	-0.6	8.4	15.3	31.1
2	4.5	1.5	255.4	56.7	37.8	24.6	13.2	5.9	6.4	0.1	8.6	15.2	24.6
3	4.5	1.6	260.9	58.0	36.2	23.6	12.7	5.7	6.2	0.6	8.7	15.1	21.3
4	4.5	1.7	266.2	59.2	34.8	22.6	12.2	5.4	6.0	1.2	8.8	15.1	19.1
5	4.5	1.8	271.4	60.3	33.5	21.8	11.7	5.2	5.9	1.6	8.9	15.0	17.6
6	4.5	1.9	276.3	61.4	32.3	21.0	11.3	5.0	5.7	2.1	9.0	15.0	16.5
7	4.5	2.0	281.1	62.5	31.2	20.3	10.9	4.8	5.5	2.4	9.1	14.9	15.7
8	4.5	2.1	285.7	63.5	30.2	19.6	10.6	4.7	5.4	2.8	9.2	14.9	15.0
9	4.5	2.2	290.1	64.5	29.3	19.0	10.3	4.5	5.2	3.1	9.4	14.8	14.4
10	4.5	2.3	294.5	65.4	28.5	18.5	10.0	4.4	5.1	3.4	9.5	14.8	14.0

11	4.5	2.4 14.8	298.7 13.6	66.4	27.7	18.0	9.7	4.2	5.0	3.6	9.7
12	4.6	1.4 15.3	253.2 31.0	55.1	39.3	25.6	13.8	6.0	6.5	-0.4	8.4
13	4.6	1.5 15.2	259.1 24.6	56.3	37.6	24.4	13.1	5.8	6.3	0.3	8.5
14	4.6	1.6 15.1	264.8 21.2	57.6	36.0	23.4	12.6	5.5	6.2	0.9	8.7
15	4.6	1.7 15.0	270.2 19.1	58.7	34.5	22.5	12.1	5.3	6.0	1.4	8.8
16	4.6	1.8 15.0	275.4 17.6	59.9	33.3	21.6	11.6	5.1	5.8	1.8	8.9
17	4.6	1.9 14.9	280.4 16.5	61.0	32.1	20.9	11.2	4.9	5.6	2.3	9.0
18	4.6	2.0 14.9	285.2 15.6	62.0	31.0	20.2	10.9	4.7	5.5	2.6	9.0
19	4.6	2.1 14.8	289.9 14.9	63.0	30.0	19.5	10.5	4.5	5.3	3.0	9.2
20	4.6	2.2 14.8	294.4 14.4	64.0	29.1	18.9	10.2	4.4	5.1	3.3	9.3
21	4.6	2.3 14.7	298.8 13.9	65.0	28.2	18.4	9.9	4.2	5.0	3.5	9.4
22	4.6	2.4 14.7	303.1 13.6	65.9	27.5	17.8	9.6	4.1	4.9	3.8	9.5
23	4.7	1.4 15.2	256.9 30.9	54.7	39.0	25.4	13.7	5.9	6.5	-0.2	8.4
24	4.7	1.5 15.1	262.9 24.5	55.9	37.3	24.2	13.1	5.6	6.3	0.5	8.5
25	4.7	1.6 15.0	268.6 21.1	57.1	35.7	23.2	12.5	5.4	6.1	1.1	8.6
26	4.7	1.7 15.0	274.1 19.0	58.3	34.3	22.3	12.0	5.2	5.9	1.6	8.7
27	4.7	1.8 14.9	279.3 17.5	59.4	33.0	21.5	11.6	4.9	5.7	2.0	8.8
28	4.7	1.9 14.8	284.4 16.4	60.5	31.9	20.7	11.1	4.8	5.5	2.4	8.9
29	4.7	2.0 14.8	289.3 15.6	61.6	30.8	20.0	10.8	4.6	5.4	2.8	9.0
30	4.7	2.1 14.8	294.1 14.9	62.6	29.8	19.4	10.4	4.4	5.2	3.1	9.0

31	4.7	2.2 14.7	298.7 14.4	63.5	28.9	18.8	10.1	4.3	5.1	3.4	9.1
32	4.7	2.3 14.7	303.1 13.9	64.5	28.0	18.2	9.8	4.1	4.9	3.7	9.3
33	4.7	2.4 14.7	307.5 13.5	65.4	27.3	17.7	9.5	4.0	4.8	4.0	9.4
34	4.8	1.4 15.2	260.5 30.9	54.3	38.8	25.2	13.6	5.8	6.4	0.1	8.4
35	4.8	1.5 15.1	266.6 24.5	55.5	37.0	24.1	13.0	5.5	6.2	0.7	8.5
36	4.8	1.6 15.0	272.4 21.1	56.7	35.5	23.1	12.4	5.3	6.0	1.3	8.6
37	4.8	1.7 14.9	277.9 19.0	57.9	34.1	22.1	11.9	5.0	5.8	1.8	8.7
38	4.8	1.8 14.9	283.3 17.5	59.0	32.8	21.3	11.5	4.8	5.6	2.2	8.7
39	4.8	1.9 14.8	288.4 16.4	60.1	31.6	20.6	11.1	4.6	5.5	2.6	8.8
40	4.8	2.0 14.7	293.4 15.5	61.1	30.6	19.9	10.7	4.4	5.3	3.0	8.9
41	4.8	2.1 14.7	298.2 14.9	62.1	29.6	19.2	10.4	4.3	5.1	3.3	8.9
42	4.8	2.2 14.7	302.9 14.3	63.1	28.7	18.6	10.0	4.1	5.0	3.6	9.0
43	4.8	2.3 14.6	307.4 13.8	64.0	27.8	18.1	9.7	4.0	4.8	3.8	9.1
44	4.8	2.4 14.6	311.8 13.5	65.0	27.1	17.6	9.5	3.9	4.7	4.1	9.2
45	4.9	1.4 15.1 6.1	264.1 30.8 46 0.9	53.9 4.9 8.5	38.5 1.5 15.0	25.0 270.3 24.4	13.5 55.2	5.6 36.8	6.3 23.9	0.3 12.9	8.4 5.4
47	4.9	1.6 14.9	276.2 21.0	56.4	35.2	22.9	12.3	5.1	5.9	1.5	8.5
48	4.9	1.7 14.9	281.8 18.9	57.5	33.8	22.0	11.8	4.9	5.7	2.0	8.6
49	4.9	1.8 14.8	287.2 17.4	58.6	32.6	21.2	11.4	4.7	5.5	2.4	8.6
50	4.9	1.9 14.7	292.4 16.3	59.7	31.4	20.4	11.0	4.5	5.4	2.8	8.7
51	4.9	2.0 14.7	297.5 15.5	60.7	30.4	19.7	10.6	4.3	5.2	3.1	8.7
52	4.9	2.1 14.7	302.4 14.8	61.7	29.4	19.1	10.3	4.2	5.0	3.4	8.8
53	4.9	2.2 14.6	307.1 14.3	62.7	28.5	18.5	10.0	4.0	4.9	3.7	8.9

54	4.9	2.3 14.6	311.7 13.8	63.6	27.7	18.0	9.7	3.9	4.7	4.0	9.0
55	4.9	2.4 14.6	316.1 13.4	64.5	26.9	17.5	9.4	3.8	4.6	4.2	9.1
56	5.0	1.4 15.1	267.7 30.8	53.5	38.2	24.9	13.4	5.5	6.3	0.5	8.4
57	5.0	1.5 15.0	273.9 24.4	54.8	36.5	23.7	12.8	5.2	6.1	1.1	8.4
58	5.0	1.6 14.9	279.9 21.0	56.0	35.0	22.7	12.2	5.0	5.8	1.7	8.5
59	5.0	1.7 14.8	285.6 18.8	57.1	33.6	21.8	11.8	4.8	5.6	2.1	8.5
60	5.0	1.8 14.7	291.1 17.4	58.2	32.3	21.0	11.3	4.6	5.5	2.6	8.5
61	5.0	1.9 14.7	296.4 16.3	59.3	31.2	20.3	10.9	4.4	5.3	2.9	8.6
62	5.0	2.0 14.6	301.5 15.4	60.3	30.2	19.6	10.6	4.2	5.1	3.3	8.6
63	5.0	2.1 14.6	306.5 14.8	61.3	29.2	19.0	10.2	4.0	4.9	3.6	8.7
64	5.0	2.2 14.6	311.2 14.2	62.2	28.3	18.4	9.9	3.9	4.8	3.8	8.8
65	5.0	2.3 14.5	315.9 13.8	63.2	27.5	17.9	9.6	3.8	4.6	4.1	8.8
66	5.0	2.4 14.5	320.4 13.4	64.1	26.7	17.4	9.3	3.7	4.5	4.3	8.9
67	5.1	1.4 15.0	271.3 30.7	53.2	38.0	24.7	13.3	5.4	6.2	0.7	8.3
68	5.1	1.5 14.9	277.6 24.3	54.4	36.3	23.6	12.7	5.1	6.0	1.3	8.4
69	5.1	1.6 14.8	283.6 20.9	55.6	34.8	22.6	12.2	4.9	5.8	1.8	8.4
70	5.1	1.7 14.8	289.4 18.8	56.7	33.4	21.7	11.7	4.6	5.6	2.3	8.4
71	5.1	1.8 14.7	295.0 17.3	57.8	32.1	20.9	11.2	4.4	5.4	2.7	8.4
72	5.1	1.9 14.6	300.3 16.2	58.9	31.0	20.1	10.8	4.3	5.2	3.1	8.5
73	5.1	2.0 14.6	305.5 15.4	59.9	30.0	19.5	10.5	4.1	5.0	3.4	8.5

74	5.1	2.1 14.6	310.5 14.7	60.9	29.0	18.8	10.1	3.9	4.8	3.7	8.6
75	5.1	2.2 14.5	315.4 14.2	61.8	28.1	18.3	9.8	3.8	4.7	4.0	8.6
76	5.1	2.3 14.5	320.1 13.7	62.8	27.3	17.7	9.6	3.7	4.5	4.2	8.7
77	5.1	2.4 14.5	324.7 13.3	63.7	26.5	17.2	9.3	3.5	4.4	4.4	8.8
78	5.2	1.4 15.0	274.8 30.7	52.8	37.7	24.5	13.2	5.3	6.1	0.9	8.3
79	5.2	1.5 14.9	281.2 24.2	54.1	36.1	23.4	12.6	5.0	5.9	1.5	8.3
80	5.2	1.6 14.8	287.3 20.9	55.3	34.5	22.4	12.1	4.7	5.7	2.0	8.3
81	5.2	1.7 14.7	293.2 18.7	56.4	33.2	21.6	11.6	4.5	5.5	2.4	8.3
82	5.2	1.8 14.7	298.8 17.3	57.5	31.9	20.8	11.2	4.3	5.3	2.8	8.3
83	5.2	1.9 14.6	304.3 16.2	58.5	30.8	20.0	10.8	4.1	5.1	3.2	8.4
84	5.2	2.0 14.6	309.5 15.3	59.5	29.8	19.3	10.4	4.0	4.9	3.5	8.4
85	5.2	2.1 14.5	314.6 14.7	60.5	28.8	18.7	10.1	3.8	4.7	3.8	8.4
86	5.2	2.2 14.5 4.4	319.5 14.1 87 4.3	61.4 5.2 8.6	27.9 2.3 14.4	18.2 324.3 13.7	9.8 62.4	3.7 27.1	4.6 17.6	4.1 9.5	8.5 3.6
88	5.2	2.4 14.4	328.9 13.3	63.2	26.4	17.1	9.2	3.5	4.3	4.5	8.7
89	5.3	1.4 14.9	278.3 30.7	52.5	37.5	24.4	13.1	5.1	6.0	1.0	8.2
90	5.3	1.5 14.8	284.8 24.2	53.7	35.8	23.3	12.5	4.9	5.8	1.6	8.3
91	5.3	1.6 14.7	291.0 20.8	54.9	34.3	22.3	12.0	4.6	5.6	2.1	8.2
92	5.3	1.7 14.7	296.9 18.7	56.0	33.0	21.4	11.5	4.4	5.4	2.6	8.2
93	5.3	1.8 14.6	302.6 17.2	57.1	31.7	20.6	11.1	4.2	5.2	3.0	8.2
94	5.3	1.9 14.6	308.1 16.1	58.1	30.6	19.9	10.7	4.0	5.0	3.3	8.2
95	5.3	2.0 14.5	313.5 15.3	59.1	29.6	19.2	10.4	3.9	4.8	3.6	8.2
96	5.3	2.1 14.5	318.6 14.6	60.1	28.6	18.6	10.0	3.7	4.7	3.9	8.3

97	5.3	2.2 14.4	323.6 14.1	61.1	27.8	18.0	9.7	3.6	4.5	4.2	8.3
98	5.3	2.3 14.4	328.4 13.6	62.0	26.9	17.5	9.4	3.5	4.3	4.4	8.4
99	5.3	2.4 14.4	333.1 13.3	62.8	26.2	17.0	9.2	3.4	4.2	4.6	8.5
100	5.4	1.4 14.9	281.8 30.6	52.2	37.3	24.2	13.0	5.0	6.0	1.2	8.2
101	5.4	1.5 14.8	288.4 24.1	53.4	35.6	23.1	12.5	4.7	5.7	1.8	8.2
102	5.4	1.6 14.7	294.6 20.8	54.6	34.1	22.2	11.9	4.5	5.5	2.3	8.2
103	5.4	1.7 14.6	300.7 18.7	55.7	32.8	21.3	11.5	4.3	5.3	2.7	8.1
104	5.4	1.8 14.6	306.4 17.2	56.7	31.5	20.5	11.0	4.1	5.1	3.1	8.1
105	5.4	1.9 14.5	312.0 16.1	57.8	30.4	19.8	10.6	3.9	4.9	3.4	8.1
106	5.4	2.0 14.5	317.4 15.3	58.8	29.4	19.1	10.3	3.8	4.7	3.7	8.1
107	5.4	2.1 14.4	322.6 14.6	59.7	28.4	18.5	10.0	3.6	4.6	4.0	8.2
108	5.4	2.2 14.4	327.6 14.0	60.7	27.6	17.9	9.7	3.5	4.4	4.2	8.2
109	5.4	2.3 14.3	332.5 13.6	61.6	26.8	17.4	9.4	3.4	4.3	4.5	8.3
110	5.4	2.4 14.3	337.3 13.2	62.5	26.0	16.9	9.1	3.3	4.1	4.7	8.4
111	5.5	1.4 14.8	285.3 30.6	51.9	37.0	24.1	13.0	4.9	5.9	1.4	8.1
112	5.5	1.5 14.7	291.9 24.1	53.1	35.4	23.0	12.4	4.6	5.6	1.9	8.1
113	5.5	1.6 14.6	298.3 20.7	54.2	33.9	22.0	11.9	4.4	5.4	2.4	8.1
114	5.5	1.7 14.6	304.4 18.6	55.3	32.6	21.2	11.4	4.2	5.2	2.8	8.0
115	5.5	1.8 14.5	310.2 17.1	56.4	31.3	20.4	11.0	4.0	5.0	3.2	8.0
116	5.5	1.9 14.5	315.9 16.1	57.4	30.2	19.6	10.6	3.8	4.8	3.5	8.0

117	5.5	2.0 14.4	321.3 15.2	58.4	29.2	19.0	10.2	3.7	4.6	3.8	8.0
118	5.5	2.1 14.4	326.6 14.6	59.4	28.3	18.4	9.9	3.5	4.5	4.1	8.0
119	5.5	2.2 14.3	331.7 14.0	60.3	27.4	17.8	9.6	3.4	4.3	4.3	8.1
120	5.5	2.3 14.3	336.6 13.6	61.2	26.6	17.3	9.3	3.3	4.2	4.5	8.2
121	5.5	2.4 14.3	341.4 13.2	62.1	25.9	16.8	9.1	3.2	4.0	4.7	8.3
122	5.6	1.4 14.8	288.7 30.5	51.6	36.8	23.9	12.9	4.8	5.8	1.5	8.0
123	5.6	1.5 14.7	295.4 24.0	52.8	35.2	22.9	12.3	4.5	5.5	2.1	8.0
124	5.6	1.6 14.6	301.9 20.7	53.9	33.7	21.9	11.8	4.3	5.3	2.5	7.9
125	5.6	1.7 14.5	308.0 18.6	55.0	32.4	21.0	11.3	4.1	5.1	2.9	7.9
126	5.6	1.8 14.5	314.0 17.1	56.1	31.1	20.2	10.9	3.9	4.9	3.3	7.9
127	5.6	1.9 14.4 4.5	319.7 16.0 128 3.9	57.1 5.6 7.9	30.0 2.0 14.4	19.5 325.2 15.2	10.5 58.1	3.7 29.0	4.7 18.9	3.6 10.2	7.9 3.6
129	5.6	2.1 14.3	330.5 14.5	59.0	28.1	18.3	9.8	3.4	4.4	4.1	7.9
130	5.6	2.2 14.3	335.7 14.0	59.9	27.2	17.7	9.5	3.3	4.2	4.4	8.0
131	5.6	2.3 14.3	340.7 13.5	60.8	26.5	17.2	9.3	3.2	4.1	4.6	8.1
132	5.6	2.4 14.2	345.6 13.1	61.7	25.7	16.7	9.0	3.1	3.9	4.8	8.2
133	5.7	1.4 14.7	292.2 30.5	51.3	36.6	23.8	12.8	4.6	5.7	1.6	8.0
134	5.7	1.5 14.6	299.0 24.0	52.4	35.0	22.7	12.2	4.4	5.5	2.2	7.9
135	5.7	1.6 14.6	305.5 20.6	53.6	33.5	21.8	11.7	4.2	5.2	2.6	7.8
136	5.7	1.7 14.5	311.7 18.5	54.7	32.2	20.9	11.3	4.0	5.0	3.0	7.8
137	5.7	1.8 14.4	317.7 17.0	55.7	31.0	20.1	10.8	3.8	4.8	3.4	7.8
138	5.7	1.9 14.4	323.5 16.0	56.7	29.9	19.4	10.5	3.6	4.6	3.7	7.7
139	5.7	2.0 14.3	329.0 15.1	57.7	28.9	18.8	10.1	3.5	4.4	4.0	7.8

140	5.7	2.1	334.4	58.7	27.9	18.2	9.8	3.4	4.3	4.2	7.8	14.3	14.5
141	5.7	2.2	339.7	59.6	27.1	17.6	9.5	3.3	4.1	4.4	7.9	14.3	13.9
142	5.7	2.3	344.7	60.5	26.3	17.1	9.2	3.2	4.0	4.6	8.0	14.2	13.5
143	5.7	2.4	349.7	61.3	25.6	16.6	8.9	3.1	3.8	4.8	8.2	14.2	13.1
144	5.8	1.4	295.6	51.0	36.4	23.7	12.7	4.5	5.6	1.8	7.9	14.7	30.4
145	5.8	1.5	302.4	52.1	34.8	22.6	12.2	4.3	5.4	2.3	7.8	14.6	24.0
146	5.8	1.6	309.0	53.3	33.3	21.6	11.7	4.1	5.1	2.7	7.7	14.5	20.6
147	5.8	1.7	315.3	54.4	32.0	20.8	11.2	3.9	4.9	3.1	7.7	14.5	18.5
148	5.8	1.8	321.4	55.4	30.8	20.0	10.8	3.7	4.7	3.5	7.6	14.4	17.0
149	5.8	1.9	327.2	56.4	29.7	19.3	10.4	3.5	4.5	3.8	7.6	14.3	15.9
150	5.8	2.0	332.9	57.4	28.7	18.7	10.0	3.4	4.3	4.0	7.6	14.3	15.1
151	5.8	2.1	338.3	58.3	27.8	18.1	9.7	3.3	4.2	4.3	7.7	14.2	14.4
152	5.8	2.2	343.6	59.2	26.9	17.5	9.4	3.2	4.0	4.5	7.8	14.2	13.9
153	5.8	2.3	348.8	60.1	26.1	17.0	9.2	3.1	3.9	4.7	7.9	14.2	13.5
154	5.8	2.4	353.7	61.0	25.4	16.5	8.9	3.0	3.7	4.8	8.1	14.1	13.1

C.4: OPTIMAP FOR SEA STATE 9

Given: Storage Capacity, S_c=2Mbbl; Sea State 9⇒(H_s, 15m; T_z, 14.2s).

Please enter the sea state number: 9

Please enter the maximum allowable green water exceedance level: 2

Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
253.2	55.1	39.3	25.6	[m]

Table C. 4: Principal Dimensions, Natural Periods and Most Probable Responses of 154, 2Mbbl Capacity FPSOs evaluated for Sea State 9

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	[s]	[s]
1	4.5	1.4	249.6	55.5	39.6	25.7	13.9	10.4	8.9	1.7	10.1	15.3	31.1
2	4.5	1.5	255.4	56.7	37.8	24.6	13.2	10.1	8.7	2.4	10.3	15.2	24.6
3	4.5	1.6	260.9	58.0	36.2	23.6	12.7	9.8	8.4	2.9	10.4	15.1	21.3
4	4.5	1.7	266.2	59.2	34.8	22.6	12.2	9.5	8.2	3.4	10.6	15.1	19.1
5	4.5	1.8	271.4	60.3	33.5	21.8	11.7	9.3	8.0	3.9	10.7	15.0	17.6
6	4.5	1.9	276.3	61.4	32.3	21.0	11.3	9.0	7.8	4.3	10.8	15.0	16.5
7	4.5	2.0	281.1	62.5	31.2	20.3	10.9	8.8	7.6	4.7	10.9	14.9	15.7
8	4.5	2.1	285.7	63.5	30.2	19.6	10.6	8.6	7.4	5.0	11.0	14.9	15.0
9	4.5	2.2	290.1	64.5	29.3	19.0	10.3	8.5	7.2	5.4	11.1	14.8	14.4
10	4.5	2.3	294.5	65.4	28.5	18.5	10.0	8.3	7.1	5.7	11.2	14.8	14.0
11	4.5	2.4	298.7	66.4	27.7	18.0	9.7	8.1	6.9	5.9	11.4	14.8	13.6
12	4.6	1.4	253.2	55.1	39.3	25.6	13.8	10.3	8.8	2.0	10.1	15.3	31.0
13	4.6	1.5	259.1	56.3	37.6	24.4	13.1	9.9	8.6	2.6	10.3	15.2	24.6
14	4.6	1.6	264.8	57.6	36.0	23.4	12.6	9.6	8.3	3.2	10.4	15.1	21.2
15	4.6	1.7	270.2	58.7	34.5	22.5	12.1	9.4	8.1	3.7	10.5	15.0	19.1
16	4.6	1.8	275.4	59.9	33.3	21.6	11.6	9.1	7.9	4.1	10.6	15.0	17.6
17	4.6	1.9	280.4	61.0	32.1	20.9	11.2	8.9	7.7	4.5	10.7	14.9	16.5
18	4.6	2.0	285.2	62.0	31.0	20.2	10.9	8.7	7.5	4.9	10.8	14.9	15.6
19	4.6	2.1	289.9	63.0	30.0	19.5	10.5	8.5	7.3	5.2	10.9	14.8	14.9
20	4.6	2.2	294.4	64.0	29.1	18.9	10.2	8.3	7.1	5.6	11.0	14.8	14.4

$T_{n3,5}$ T_{n4}

21	4.6	2.3 14.7	298.8 13.9	65.0	28.2	18.4	9.9	8.1	7.0	5.9	11.1
22	4.6	2.4 14.7	303.1 13.6	65.9	27.5	17.8	9.6	8.0	6.8	6.1	11.2
23	4.7	1.4 15.2	256.9 30.9	54.7	39.0	25.4	13.7	10.1	8.7	2.2	10.1
24	4.7	1.5 15.1	262.9 24.5	55.9	37.3	24.2	13.1	9.8	8.5	2.8	10.2
25	4.7	1.6 15.0	268.6 21.1	57.1	35.7	23.2	12.5	9.5	8.2	3.4	10.3
26	4.7	1.7 15.0	274.1 19.0	58.3	34.3	22.3	12.0	9.2	8.0	3.9	10.4
27	4.7	1.8 14.9	279.3 17.5	59.4	33.0	21.5	11.6	9.0	7.8	4.3	10.5
28	4.7	1.9 14.8	284.4 16.4	60.5	31.9	20.7	11.1	8.7	7.6	4.7	10.6
29	4.7	2.0 14.8	289.3 15.6	61.6	30.8	20.0	10.8	8.5	7.4	5.1	10.7
30	4.7	2.1 14.8	294.1 14.9	62.6	29.8	19.4	10.4	8.3	7.2	5.4	10.7
31	4.7	2.2 14.7	298.7 14.4	63.5	28.9	18.8	10.1	8.1	7.0	5.7	10.8
32	4.7	2.3 14.7	303.1 13.9	64.5	28.0	18.2	9.8	8.0	6.9	6.0	10.9
33	4.7	2.4 14.7	307.5 13.5	65.4	27.3	17.7	9.5	7.8	6.7	6.3	11.0
34	4.8	1.4 15.2	260.5 30.9	54.3	38.8	25.2	13.6	9.9	8.6	2.4	10.1
35	4.8	1.5 15.1	266.6 24.5	55.5	37.0	24.1	13.0	9.6	8.4	3.1	10.2
36	4.8	1.6 15.0	272.4 21.1	56.7	35.5	23.1	12.4	9.3	8.1	3.6	10.3
37	4.8	1.7 14.9	277.9 19.0	57.9	34.1	22.1	11.9	9.1	7.9	4.1	10.3
38	4.8	1.8 14.9	283.3 17.5	59.0	32.8	21.3	11.5	8.8	7.7	4.5	10.4
39	4.8	1.9 14.8	288.4 16.4	60.1	31.6	20.6	11.1	8.6	7.5	4.9	10.5
40	4.8	2.0 14.7	293.4 15.5	61.1	30.6	19.9	10.7	8.4	7.3	5.3	10.5

41	4.8	2.1 14.7	298.2 14.9	62.1	29.6	19.2	10.4	8.2	7.1	5.6	10.6
42	4.8	2.2 14.7	302.9 14.3	63.1	28.7	18.6	10.0	8.0	6.9	5.9	10.7
43	4.8	2.3 14.6	307.4 13.8	64.0	27.8	18.1	9.7	7.8	6.7	6.2	10.8
44	4.8	2.4 14.6	311.8 13.5	65.0	27.1	17.6	9.5	7.7	6.6	6.5	10.9
45	4.9	1.4 15.1	264.1 30.8	53.9	38.5	25.0	13.5	9.8	8.5	2.7	10.1
46	4.9	1.5 15.0	270.3 24.4	55.2	36.8	23.9	12.9	9.5	8.3	3.3	10.1
47	4.9	1.6 14.9	276.2 21.0	56.4	35.2	22.9	12.3	9.2	8.0	3.8	10.2
48	4.9	1.7 14.9	281.8 18.9	57.5	33.8	22.0	11.8	8.9	7.8	4.3	10.3
49	4.9	1.8 14.8	287.2 17.4	58.6	32.6	21.2	11.4	8.7	7.6	4.7	10.3
50	4.9	1.9 14.7	292.4 16.3	59.7	31.4	20.4	11.0	8.4	7.4	5.1	10.4
51	4.9	2.0 14.7	297.5 15.5	60.7	30.4	19.7	10.6	8.2	7.2	5.5	10.4
52	4.9	2.1 14.7	302.4 14.8	61.7	29.4	19.1	10.3	8.0	7.0	5.8	10.5
53	4.9	2.2 14.6	307.1 14.3	62.7	28.5	18.5	10.0	7.9	6.8	6.1	10.5
54	4.9	2.3 14.6	311.7 13.8	63.6	27.7	18.0	9.7	7.7	6.6	6.4	10.6
55	4.9	2.4 14.6	316.1 13.4	64.5	26.9	17.5	9.4	7.6	6.5	6.6	10.7
56	5.0	1.4 15.1	267.7 30.8	53.5	38.2	24.9	13.4	9.6	8.4	2.9	10.0
57	5.0	1.5 15.0	273.9 24.4	54.8	36.5	23.7	12.8	9.3	8.2	3.5	10.1
58	5.0	1.6 14.9	279.9 21.0	56.0	35.0	22.7	12.2	9.0	7.9	4.0	10.1
59	5.0	1.7 14.8	285.6 18.8	57.1	33.6	21.8	11.8	8.7	7.7	4.5	10.2
60	5.0	1.8 14.7	291.1 17.4	58.2	32.3	21.0	11.3	8.5	7.5	4.9	10.2
61	5.0	1.9 14.7 7.0	296.4 16.3 62 5.6	59.3 5.0 10.3	31.2 2.0 14.6	20.3 301.5 15.4	10.9 60.3	8.3 30.2	7.2 19.6	5.3 10.6	10.2 8.1
63	5.0	2.1 14.6	306.5 14.8	61.3	29.2	19.0	10.2	7.9	6.9	5.9	10.3

64	5.0	2.2 14.6	311.2 14.2	62.2	28.3	18.4	9.9	7.7	6.7	6.2	10.4
65	5.0	2.3 14.5	315.9 13.8	63.2	27.5	17.9	9.6	7.6	6.5	6.5	10.4
66	5.0	2.4 14.5	320.4 13.4	64.1	26.7	17.4	9.3	7.4	6.4	6.8	10.5
67	5.1	1.4 15.0	271.3 30.7	53.2	38.0	24.7	13.3	9.5	8.3	3.1	10.0
68	5.1	1.5 14.9	277.6 24.3	54.4	36.3	23.6	12.7	9.1	8.1	3.7	10.0
69	5.1	1.6 14.8	283.6 20.9	55.6	34.8	22.6	12.2	8.9	7.8	4.2	10.0
70	5.1	1.7 14.8	289.4 18.8	56.7	33.4	21.7	11.7	8.6	7.6	4.7	10.1
71	5.1	1.8 14.7	295.0 17.3	57.8	32.1	20.9	11.2	8.4	7.3	5.1	10.1
72	5.1	1.9 14.6	300.3 16.2	58.9	31.0	20.1	10.8	8.1	7.1	5.4	10.1
73	5.1	2.0 14.6	305.5 15.4	59.9	30.0	19.5	10.5	8.0	6.9	5.8	10.1
74	5.1	2.1 14.6	310.5 14.7	60.9	29.0	18.8	10.1	7.8	6.7	6.1	10.1
75	5.1	2.2 14.5	315.4 14.2	61.8	28.1	18.3	9.8	7.6	6.6	6.4	10.2
76	5.1	2.3 14.5	320.1 13.7	62.8	27.3	17.7	9.6	7.4	6.4	6.6	10.3
77	5.1	2.4 14.5	324.7 13.3	63.7	26.5	17.2	9.3	7.3	6.2	6.9	10.3
78	5.2	1.4 15.0	274.8 30.7	52.8	37.7	24.5	13.2	9.3	8.2	3.3	9.9
79	5.2	1.5 14.9	281.2 24.2	54.1	36.1	23.4	12.6	9.0	8.0	3.9	9.9
80	5.2	1.6 14.8	287.3 20.9	55.3	34.5	22.4	12.1	8.7	7.7	4.4	9.9
81	5.2	1.7 14.7	293.2 18.7	56.4	33.2	21.6	11.6	8.5	7.5	4.8	9.9
82	5.2	1.8 14.7	298.8 17.3	57.5	31.9	20.8	11.2	8.2	7.2	5.2	9.9
83	5.2	1.9 14.6	304.3 16.2	58.5	30.8	20.0	10.8	8.0	7.0	5.6	9.9

84	5.2	2.0	309.5	59.5	29.8	19.3	10.4	7.8	6.8	5.9	10.0
		14.6	15.3								
85	5.2	2.1	314.6	60.5	28.8	18.7	10.1	7.6	6.6	6.2	10.0
		14.5	14.7								
86	5.2	2.2	319.5	61.4	27.9	18.2	9.8	7.5	6.5	6.5	10.0
		14.5	14.1								
87	5.2	2.3	324.3	62.4	27.1	17.6	9.5	7.3	6.3	6.8	10.1
		14.4	13.7								
88	5.2	2.4	328.9	63.2	26.4	17.1	9.2	7.2	6.1	7.0	10.2
		14.4	13.3								
89	5.3	1.4	278.3	52.5	37.5	24.4	13.1	9.2	8.1	3.5	9.8
		14.9	30.7								
90	5.3	1.5	284.8	53.7	35.8	23.3	12.5	8.9	7.9	4.0	9.8
		14.8	24.2								
91	5.3	1.6	291.0	54.9	34.3	22.3	12.0	8.6	7.6	4.5	9.8
		14.7	20.8								
92	5.3	1.7	296.9	56.0	33.0	21.4	11.5	8.3	7.4	5.0	9.8
		14.7	18.7								
93	5.3	1.8	302.6	57.1	31.7	20.6	11.1	8.1	7.1	5.4	9.8
		14.6	17.2								
94	5.3	1.9	308.1	58.1	30.6	19.9	10.7	7.9	6.9	5.7	9.8
		14.6	16.1								
95	5.3	2.0	313.5	59.1	29.6	19.2	10.4	7.7	6.7	6.1	9.8
		14.5	15.3								
96	5.3	2.1	318.6	60.1	28.6	18.6	10.0	7.5	6.5	6.4	9.8
		14.5	14.6								
97	5.3	2.2	323.6	61.1	27.8	18.0	9.7	7.4	6.3	6.6	9.9
		14.4	14.1								
98	5.3	2.3	328.4	62.0	26.9	17.5	9.4	7.2	6.2	6.9	9.9
		14.4	13.6								
99	5.3	2.4	333.1	62.8	26.2	17.0	9.2	7.1	6.0	7.1	10.0
		14.4	13.3								
100	5.4	1.4	281.8	52.2	37.3	24.2	13.0	9.0	8.0	3.6	9.7
		14.9	30.6								
101	5.4	1.5	288.4	53.4	35.6	23.1	12.5	8.7	7.8	4.2	9.7
		14.8	24.1								
102	5.4	1.6	294.6	54.6	34.1	22.2	11.9	8.4	7.5	4.7	9.7
		14.7	20.8 103	5.4	1.7	300.7	55.7	32.8	21.3	11.5	8.2
		7.2	5.1	9.7	14.6	18.7					
104	5.4	1.8	306.4	56.7	31.5	20.5	11.0	8.0	7.0	5.5	9.7
		14.6	17.2								
105	5.4	1.9	312.0	57.8	30.4	19.8	10.6	7.8	6.8	5.9	9.6
		14.5	16.1								
106	5.4	2.0	317.4	58.8	29.4	19.1	10.3	7.6	6.6	6.2	9.6
		14.5	15.3								

107	5.4	2.1 14.4	322.6 14.6	59.7	28.4	18.5	10.0	7.4	6.4	6.5	9.7
108	5.4	2.2 14.4	327.6 14.0	60.7	27.6	17.9	9.7	7.2	6.2	6.7	9.7
109	5.4	2.3 14.3	332.5 13.6	61.6	26.8	17.4	9.4	7.1	6.1	7.0	9.8
110	5.4	2.4 14.3	337.3 13.2	62.5	26.0	16.9	9.1	6.9	5.9	7.2	9.9
111	5.5	1.4 14.8	285.3 30.6	51.9	37.0	24.1	13.0	8.9	7.9	3.8	9.7
112	5.5	1.5 14.7	291.9 24.1	53.1	35.4	23.0	12.4	8.6	7.6	4.4	9.6
113	5.5	1.6 14.6	298.3 20.7	54.2	33.9	22.0	11.9	8.3	7.4	4.8	9.6
114	5.5	1.7 14.6	304.4 18.6	55.3	32.6	21.2	11.4	8.1	7.1	5.3	9.5
115	5.5	1.8 14.5	310.2 17.1	56.4	31.3	20.4	11.0	7.8	6.9	5.6	9.5
116	5.5	1.9 14.5	315.9 16.1	57.4	30.2	19.6	10.6	7.6	6.7	6.0	9.5
117	5.5	2.0 14.4	321.3 15.2	58.4	29.2	19.0	10.2	7.4	6.5	6.3	9.5
118	5.5	2.1 14.4	326.6 14.6	59.4	28.3	18.4	9.9	7.3	6.3	6.6	9.5
119	5.5	2.2 14.3	331.7 14.0	60.3	27.4	17.8	9.6	7.1	6.1	6.8	9.6
120	5.5	2.3 14.3	336.6 13.6	61.2	26.6	17.3	9.3	7.0	6.0	7.1	9.6
121	5.5	2.4 14.3	341.4 13.2	62.1	25.9	16.8	9.1	6.8	5.8	7.3	9.7
122	5.6	1.4 14.8	288.7 30.5	51.6	36.8	23.9	12.9	8.7	7.8	4.0	9.6
123	5.6	1.5 14.7	295.4 24.0	52.8	35.2	22.9	12.3	8.4	7.5	4.5	9.5
124	5.6	1.6 14.6	301.9 20.7	53.9	33.7	21.9	11.8	8.2	7.3	5.0	9.5
125	5.6	1.7 14.5	308.0 18.6	55.0	32.4	21.0	11.3	7.9	7.0	5.4	9.4
126	5.6	1.8 14.5	314.0 17.1	56.1	31.1	20.2	10.9	7.7	6.8	5.8	9.4

127	5.6	1.9 14.4	319.7 16.0	57.1	30.0	19.5	10.5	7.5	6.6	6.1	9.3
128	5.6	2.0 14.4	325.2 15.2	58.1	29.0	18.9	10.2	7.3	6.4	6.4	9.3
129	5.6	2.1 14.3	330.5 14.5	59.0	28.1	18.3	9.8	7.2	6.2	6.7	9.4
130	5.6	2.2 14.3	335.7 14.0	59.9	27.2	17.7	9.5	7.0	6.0	6.9	9.4
131	5.6	2.3 14.3	340.7 13.5	60.8	26.5	17.2	9.3	6.9	5.9	7.2	9.5
132	5.6	2.4 14.2	345.6 13.1	61.7	25.7	16.7	9.0	6.7	5.7	7.4	9.6
133	5.7	1.4 14.7	292.2 30.5	51.3	36.6	23.8	12.8	8.6	7.7	4.1	9.5
134	5.7	1.5 14.6	299.0 24.0	52.4	35.0	22.7	12.2	8.3	7.4	4.6	9.4
135	5.7	1.6 14.6	305.5 20.6	53.6	33.5	21.8	11.7	8.0	7.2	5.1	9.3
136	5.7	1.7 14.5	311.7 18.5	54.7	32.2	20.9	11.3	7.8	6.9	5.5	9.3
137	5.7	1.8 14.4	317.7 17.0	55.7	31.0	20.1	10.8	7.6	6.7	5.9	9.2
138	5.7	1.9 14.4	323.5 16.0	56.7	29.9	19.4	10.5	7.4	6.5	6.2	9.2
139	5.7	2.0 14.3	329.0 15.1	57.7	28.9	18.8	10.1	7.2	6.3	6.5	9.2
140	5.7	2.1 14.3	334.4 14.5	58.7	27.9	18.2	9.8	7.1	6.1	6.8	9.2
141	5.7	2.2 14.3	339.7 13.9	59.6	27.1	17.6	9.5	6.9	5.9	7.0	9.3
142	5.7	2.3 14.2	344.7 13.5	60.5	26.3	17.1	9.2	6.8	5.7	7.2	9.4
143	5.7	2.4 14.2 7.6	349.7 13.1 144 4.3	61.3 5.8 9.4	25.6 1.4 14.7	16.6 295.6 30.4	8.9 51.0	6.6 36.4	5.6 23.7	7.5 12.7	9.6 8.5
145	5.8	1.5 14.6	302.4 24.0	52.1	34.8	22.6	12.2	8.2	7.3	4.8	9.3
146	5.8	1.6 14.5	309.0 20.6	53.3	33.3	21.6	11.7	7.9	7.1	5.2	9.2
147	5.8	1.7 14.5	315.3 18.5	54.4	32.0	20.8	11.2	7.7	6.8	5.6	9.1
148	5.8	1.8 14.4	321.4 17.0	55.4	30.8	20.0	10.8	7.5	6.6	6.0	9.1
149	5.8	1.9 14.3	327.2 15.9	56.4	29.7	19.3	10.4	7.3	6.4	6.3	9.1

150	5.8	2.0 14.3	332.9 15.1	57.4	28.7	18.7	10.0	7.1	6.2	6.6	9.1
151	5.8	2.1 14.2	338.3 14.4	58.3	27.8	18.1	9.7	7.0	6.0	6.8	9.1
152	5.8	2.2 14.2	343.6 13.9	59.2	26.9	17.5	9.4	6.8	5.8	7.1	9.2
153	5.8	2.3 14.2	348.8 13.5	60.1	26.1	17.0	9.2	6.7	5.6	7.3	9.3
154	5.8	2.4 14.1	353.7 13.1	61.0	25.4	16.5	8.9	6.5	5.5	7.5	9.5

C.5: OPTIMAP FOR 119.022KT FPSOS, SEA STATE 6

S_c=649260 bbl; Sea State 6⇒(H_s, 5m; T_z, 8.8s).

Please enter the sea state number: 6

Please enter the maximum allowable green water exceedance level: 2

Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
243.1	41.9	17.5	11.4	[m]

Table C. 5: Principal Dimensions, Natural Periods and Most Probable Responses of 154, 649260 bbl Capacity FPSOs evaluated for Sea State 6

No	$\frac{L}{B}$	$\frac{B}{D_m}$	L [m]	B [m]	D_m [m]	D [m]	F_B [m]	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]	$T_{n3,5}$ [s]	T_{n4} [s]
1	4.5	1.4	171.5	38.1	27.2	17.7	9.5	2.2	3.7	-3.8	1.2	12.7	29.2
2	4.5	1.5	175.5	39.0	26.0	16.9	9.1	2.1	3.6	-3.4	1.2	12.6	22.0
3	4.5	1.6	179.3	39.8	24.9	16.2	8.7	2.0	3.5	-3.0	1.2	12.6	18.6
4	4.5	1.7	183.0	40.7	23.9	15.5	8.4	1.9	3.4	-2.6	1.2	12.5	16.5
5	4.5	1.8	186.5	41.4	23.0	15.0	8.1	1.8	3.3	-2.3	1.2	12.4	15.1
6	4.5	1.9	189.9	42.2	22.2	14.4	7.8	1.7	3.2	-2.0	1.3	12.4	14.1
7	4.5	2.0	193.2	42.9	21.5	14.0	7.5	1.7	3.1	-1.7	1.3	12.4	13.3
8	4.5	2.1	196.3	43.6	20.8	13.5	7.3	1.6	3.0	-1.5	1.3	12.3	12.7
9	4.5	2.2	199.4	44.3	20.1	13.1	7.0	1.5	3.0	-1.3	1.3	12.3	12.2
10	4.5	2.3	202.4	45.0	19.6	12.7	6.8	1.5	2.9	-1.1	1.4	12.3	11.8
11	4.5	2.4	205.3	45.6	19.0	12.4	6.7	1.4	2.8	-0.9	1.4	12.2	11.5
12	4.6	1.4	174.0	37.8	27.0	17.6	9.5	2.1	3.7	-3.7	1.2	12.7	29.2
13	4.6	1.5	178.1	38.7	25.8	16.8	9.0	2.0	3.6	-3.2	1.2	12.6	22.0
14	4.6	1.6	182.0	39.6	24.7	16.1	8.7	1.9	3.5	-2.8	1.2	12.5	18.5
15	4.6	1.7	185.7	40.4	23.7	15.4	8.3	1.8	3.4	-2.5	1.2	12.5	16.5
16	4.6	1.8	189.3	41.1	22.9	14.9	8.0	1.8	3.3	-2.2	1.2	12.4	15.1
17	4.6	1.9	192.7	41.9	22.0	14.3	7.7	1.7	3.2	-1.9	1.3	12.4	14.1
18	4.6	2.0	196.0	42.6	21.3	13.8	7.5	1.6	3.1	-1.6	1.3	12.3	13.3
19	4.6	2.1	199.2	43.3	20.6	13.4	7.2	1.5	3.0	-1.4	1.3	12.3	12.7
20	4.6	2.2	202.3	44.0	20.0	13.0	7.0	1.5	2.9	-1.2	1.3	12.2	12.2

21	4.6	2.3 12.2	205.4 11.8	44.6	19.4	12.6	6.8	1.4	2.8	-1.0	1.4
22	4.6	2.4 12.2	208.3 11.4	45.3	18.9	12.3	6.6	1.4	2.7	-0.8	1.4
23	4.7	1.4 12.6	176.6 29.2	37.6	26.8	17.4	9.4	2.1	3.7	-3.6	1.2
24	4.7	1.5 12.5	180.7 21.9	38.4	25.6	16.7	9.0	2.0	3.6	-3.1	1.2
25	4.7	1.6 12.5	184.6 18.5	39.3	24.5	16.0	8.6	1.9	3.5	-2.7	1.2
26	4.7	1.7 12.4	188.4 16.4	40.1	23.6	15.3	8.3	1.8	3.4	-2.4	1.2
27	4.7	1.8 12.4	192.0 15.0	40.8	22.7	14.8	7.9	1.7	3.2	-2.1	1.2
28	4.7	1.9 12.3	195.5 14.0	41.6	21.9	14.2	7.7	1.6	3.1	-1.8	1.3
29	4.7	2.0 12.3	198.9 13.2	42.3	21.2	13.8	7.4	1.5	3.0	-1.5	1.3
30	4.7	2.1 12.2	202.1 12.6	43.0	20.5	13.3	7.2	1.5	2.9	-1.3	1.3
31	4.7	2.2 12.2	205.3 12.1	43.7	19.9	12.9	6.9	1.4	2.9	-1.1	1.3
32	4.7	2.3 12.2	208.3 11.7	44.3	19.3	12.5	6.7	1.4	2.8	-0.9	1.3
33	4.7	2.4 12.1	211.3 11.4	45.0	18.7	12.2	6.6	1.3	2.7	-0.7	1.4
34	4.8	1.4 12.6	179.1 29.2	37.3	26.6	17.3	9.3	2.0	3.6	-3.5	1.2
35	4.8	1.5 12.5	183.2 21.9	38.2	25.4	16.5	8.9	1.9	3.5	-3.0	1.2
36	4.8	1.6 12.4	187.2 18.5	39.0	24.4	15.8	8.5	1.8	3.4	-2.6	1.2
37	4.8	1.7 12.4	191.0 16.4	39.8	23.4	15.2	8.2	1.7	3.3	-2.3	1.2
38	4.8	1.8 12.3	194.7 15.0	40.6	22.5	14.6	7.9	1.6	3.2	-2.0	1.2
39	4.8	1.9 12.3	198.2 14.0	41.3	21.7	14.1	7.6	1.6	3.1	-1.7	1.2
40	4.8	2.0 12.2	201.7 13.2	42.0	21.0	13.7	7.4	1.5	3.0	-1.4	1.3

41	4.8	2.1 12.2	205.0 12.6	42.7	20.3	13.2	7.1	1.4	2.9	-1.2	1.3

							1.4				
							1.3				
42	4.8	2.2	208.2	43.4	19.7	12.8	6.9	2.8	-1.0	1.3	12.2
		12.1									
43	4.8	2.3	211.3	44.0	19.1	12.4	6.7	2.7	-0.8	1.3	12.1
		11.7									
44	4.8	2.4	214.3	44.6	18.6	12.1	6.5	1.3	2.6	-0.6	1.3
		12.1	11.3								
45	4.9	1.4	181.5	37.0	26.5	17.2	9.3	2.0	3.6	-3.3	1.2
		12.5	29.2								
46	4.9	1.5	185.8	37.9	25.3	16.4	8.8	1.9	3.5	-2.9	1.2
		12.4	21.9								
47	4.9	1.6	189.8	38.7	24.2	15.7	8.5	1.8	3.4	-2.5	1.2
		12.4	18.4								
48	4.9	1.7	193.7	39.5	23.2	15.1	8.1	1.7	3.3	-2.2	1.2
		12.3	16.3								
49	4.9	1.8	197.4	40.3	22.4	14.5	7.8	1.6	3.2	-1.9	1.2
		12.3	14.9								
50	4.9	1.9	201.0	41.0	21.6	14.0	7.6	1.5	3.0	-1.6	1.2
		12.2	13.9								
51	4.9	2.0	204.5	41.7	20.9	13.6	7.3	1.4	2.9	-1.4	1.2
		12.2	13.2								
52	4.9	2.1	207.8	42.4	20.2	13.1	7.1	1.4	2.8	-1.1	1.3
		12.1	12.6								
53	4.9	2.2	211.1	43.1	19.6	12.7	6.9	1.3	2.8	-0.9	1.3
		12.1	12.1								
54	4.9	2.3	214.2	43.7	19.0	12.4	6.7	1.3	2.7	-0.7	1.3
		12.1	11.7								
55	4.9	2.4	217.3	44.3	18.5	12.0	6.5	1.2	2.6	-0.6	1.3
		12.1	11.3								
56	5.0	1.4	184.0	36.8	26.3	17.1	9.2	1.9	3.6	-3.2	1.2
		12.5	29.2								
57	5.0	1.5	188.3	37.7	25.1	16.3	8.8	1.8	3.5	-2.8	1.2
		12.4	21.8								

1.4

1.3

58	5.0	1.6 12.3	192.4 18.4	38.5	24.0	15.6	8.4	1.7	3.3	-2.4	1.2
59	5.0	1.7 12.3	196.3 16.3	39.3	23.1	15.0	8.1	1.6	3.2	-2.1	1.2
60	5.0	1.8 12.2	200.1 14.9	40.0	22.2	14.4	7.8	1.5	3.1	-1.8	1.2
61	5.0	1.9 12.2	203.7 13.9	40.7	21.4	13.9	7.5	1.5	3.0	-1.5	1.2
62	5.0	2.0 12.1	207.2 13.1	41.4	20.7	13.5	7.3	1.4	2.9	-1.3	1.2
63	5.0	2.1 12.1	210.6 12.5	42.1	20.1	13.0	7.0	1.3	2.8	-1.1	1.2
64	5.0	2.2 12.1	213.9 12.0	42.8	19.4	12.6	6.8	1.3	2.7	-0.9	1.3
65	5.0	2.3 12.0	217.1 11.6	43.4	18.9	12.3	6.6	1.2	2.6	-0.7	1.3
66	5.0	2.4 12.0	220.2 11.3	44.0	18.4	11.9	6.4	1.2	2.5	-0.5	1.3
67	5.1	1.4 12.4	186.4 29.2	36.6	26.1	17.0	9.1	1.9	3.5	-3.1	1.2
68	5.1	1.5 12.4	190.8 21.8	37.4	24.9	16.2	8.7	1.8	3.4	-2.7	1.2
69	5.1	1.6 12.3	194.9 18.3	38.2	23.9	15.5	8.4	1.7	3.3	-2.3	1.2
70	5.1	1.7 12.2	198.9 16.3	39.0	22.9	14.9	8.0	1.6	3.2	-2.0	1.2
71	5.1	1.8 12.2	202.7 14.9	39.8	22.1	14.4	7.7	1.5	3.1	-1.7	1.2
72	5.1	1.9 12.1	206.4 13.9	40.5	21.3	13.8	7.5	1.4	2.9	-1.4	1.2
73	5.1	2.0 12.1	210.0 13.1	41.2	20.6	13.4	7.2	1.3	2.8	-1.2	1.2
74	5.1	2.1 12.1	213.4 12.5	41.8	19.9	13.0	7.0	1.3	2.7	-1.0	1.2

							1.4				
							1.3				
75	5.1	2.2	216.8	42.5	19.3	12.6	6.8	1.2	2.6	-0.8	1.2
		12.0	12.0								
76	5.1	2.3	220.0	43.1	18.8	12.2	6.6	1.2	2.5	-0.6	1.3
		12.0	11.6								
77	5.1	2.4	223.1	43.8	18.2	11.8	6.4	1.1	2.5	-0.5	1.3
		12.0	11.2								
78	5.2	1.4	188.9	36.3	25.9	16.9	9.1	1.8	3.5	-3.0	1.2
		12.4	29.2								
79	5.2	1.5	193.3	37.2	24.8	16.1	8.7	1.7	3.4	-2.6	1.2
		12.3	21.8								
80	5.2	1.6	197.5	38.0	23.7	15.4	8.3	1.6	3.2	-2.2	1.2
		12.3	18.3								
81	5.2	1.7	201.5	38.7	22.8	14.8	8.0	1.5	3.1	-1.9	1.2
		12.2	16.2								
82	5.2	1.8	205.4	39.5	21.9	14.3	7.7	1.4	3.0	-1.6	1.2
		12.1	14.8 83	5.2	1.9	209.1	40.2	21.2	13.8	7.4	2.9
		-1.4	1.2	12.1	13.8						
84	5.2	2.0	212.7	40.9	20.5	13.3	7.2	2.8	-1.1	1.2	12.1
		13.1									
85	5.2	2.1	216.2	41.6	19.8	12.9	6.9	1.2	2.7	-0.9	1.2
		12.0	12.4								
86	5.2	2.2	219.6	42.2	19.2	12.5	6.7	1.2	2.6	-0.7	1.2
		12.0	12.0								
87	5.2	2.3	222.9	42.9	18.6	12.1	6.5	1.1	2.5	-0.6	1.3
		12.0	11.6								
88	5.2	2.4	226.0	43.5	18.1	11.8	6.3	1.1	2.4	-0.4	1.3
		11.9	11.2								
89	5.3	1.4	191.3	36.1	25.8	16.8	9.0	1.8	3.5	-2.9	1.2
		12.4	29.2								
90	5.3	1.5	195.7	36.9	24.6	16.0	8.6	1.7	3.3	-2.5	1.2
		12.3	21.7								

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91	5.3	1.6 12.2	200.0 18.3	37.7	23.6	15.3	8.3	1.6	3.2	-2.1	1.2
92	5.3	1.7 12.2	204.1 16.2	38.5	22.6	14.7	7.9	1.5	3.1	-1.8	1.2
93	5.3	1.8 12.1	208.0 14.8	39.2	21.8	14.2	7.6	1.4	2.9	-1.5	1.2
94	5.3	1.9 12.1	211.8 13.8	40.0	21.0	13.7	7.4	1.3	2.8	-1.3	1.2
95	5.3	2.0 12.0	215.4 13.0	40.6	20.3	13.2	7.1	1.3	2.7	-1.1	1.2
96	5.3	2.1 12.0	219.0 12.4	41.3	19.7	12.8	6.9	1.2	2.6	-0.9	1.2
97	5.3	2.2 12.0	222.4 11.9	42.0	19.1	12.4	6.7	1.2	2.5	-0.7	1.2
98	5.3	2.3 11.9	225.7 11.5	42.6	18.5	12.0	6.5	1.1	2.4	-0.5	1.2
99	5.3	2.4 11.9	228.9 11.2	43.2	18.0	11.7	6.3	1.1	2.3	-0.4	1.3
100	5.4	1.4 12.3	193.7 29.2	35.9	25.6	16.7	9.0	1.7	3.4	-2.8	1.1
101	5.4	1.5 12.2	198.2 21.7	36.7	24.5	15.9	8.6	1.6	3.3	-2.4	1.1
102	5.4	1.6 12.2	202.5 18.2	37.5	23.4	15.2	8.2	1.5	3.1	-2.1	1.2
103	5.4	1.7 12.1	206.6 16.2	38.3	22.5	14.6	7.9	1.4	3.0	-1.8	1.2
104	5.4	1.8 12.1	210.6 14.8	39.0	21.7	14.1	7.6	1.4	2.9	-1.5	1.2
105	5.4	1.9 12.0	214.4 13.8	39.7	20.9	13.6	7.3	1.3	2.8	-1.2	1.2
106	5.4	2.0 12.0	218.1 13.0	40.4	20.2	13.1	7.1	1.2	2.7	-1.0	1.2
107	5.4	2.1 12.0	221.7 12.4	41.1	19.6	12.7	6.8	1.2	2.6	-0.8	1.2

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108	5.4	2.2 11.9	225.2 11.9	41.7	19.0	12.3	6.6	1.1	2.5	-0.6	1.2
109	5.4	2.3 11.9	228.5 11.5	42.3	18.4	12.0	6.4	1.1	2.4	-0.5	1.2
110	5.4	2.4 11.9	231.8 11.1	42.9	17.9	11.6	6.3	1.0	2.3	-0.3	1.2
111	5.5	1.4 12.3	196.1 29.2	35.6	25.5	16.6	8.9	1.7	3.4	-2.7	1.1
112	5.5	1.5 12.2	200.6 21.7	36.5	24.3	15.8	8.5	1.6	3.2	-2.3	1.1
113	5.5	1.6 12.1	205.0 18.2	37.3	23.3	15.1	8.2	1.5	3.1	-2.0	1.1
114	5.5	1.7 12.1	209.2 16.1	38.0	22.4	14.5	7.8	1.4	3.0	-1.7	1.1
115	5.5	1.8 12.0	213.2 14.7	38.8	21.5	14.0	7.5	1.3	2.8	-1.4	1.1
116	5.5	1.9 12.0	217.1 13.7	39.5	20.8	13.5	7.3	1.2	2.7	-1.2	1.1
117	5.5	2.0 12.0	220.8 13.0	40.1	20.1	13.0	7.0	1.2	2.6	-1.0	1.2
118	5.5	2.1 11.9	224.4 12.3	40.8	19.4	12.6	6.8	1.1	2.5	-0.8	1.2
119	5.5	2.2 11.9	227.9 11.9	41.4	18.8	12.2	6.6	1.1	2.4	-0.6	1.2
120	5.5	2.3 11.9	231.3 11.5	42.1	18.3	11.9	6.4	1.0	2.3	-0.4	1.2
121	5.5	2.4 11.8	234.7 11.1	42.7	17.8	11.6	6.2	1.0	2.2	-0.3	1.2
122	5.6	1.4 12.3	198.4 29.2	35.4	25.3	16.5	8.9	1.6	3.3	-2.6	1.1

							1.4				
							1.3				
123	5.6	1.5	203.1	36.3	24.2	15.7	8.5	1.5	3.2	-2.3	1.1
		12.2	21.6 124	5.6	1.6	207.5	37.0	23.2	15.1	8.1	3.0
		-1.9	1.1	12.1	18.2						
125	5.6	1.7	211.7	37.8	22.2	14.5	7.8	2.9	-1.6	1.1	12.0
		16.1									
126	5.6	1.8	215.8	38.5	21.4	13.9	7.5	1.3	2.8	-1.4	1.1
		12.0	14.7								
127	5.6	1.9	219.7	39.2	20.6	13.4	7.2	1.2	2.7	-1.1	1.1
		12.0	13.7								
128	5.6	2.0	223.5	39.9	20.0	13.0	7.0	1.1	2.6	-0.9	1.1
		11.9	12.9								
129	5.6	2.1	227.2	40.6	19.3	12.6	6.8	1.1	2.4	-0.7	1.2
		11.9	12.3								
130	5.6	2.2	230.7	41.2	18.7	12.2	6.6	1.1	2.4	-0.6	1.2
		11.8	11.8								
131	5.6	2.3	234.1	41.8	18.2	11.8	6.4	1.0	2.3	-0.4	1.2
		11.8	11.4								
132	5.6	2.4	237.5	42.4	17.7	11.5	6.2	1.0	2.2	-0.3	1.2
		11.8	11.1								
133	5.7	1.4	200.8	35.2	25.2	16.4	8.8	1.6	3.3	-2.6	1.1
		12.2	29.3								
134	5.7	1.5	205.5	36.0	24.0	15.6	8.4	1.5	3.1	-2.2	1.1
		12.1	21.6								
135	5.7	1.6	209.9	36.8	23.0	15.0	8.1	1.4	3.0	-1.9	1.1
		12.1	18.1								
136	5.7	1.7	214.2	37.6	22.1	14.4	7.7	1.3	2.8	-1.6	1.1
		12.0	16.1								
137	5.7	1.8	218.3	38.3	21.3	13.8	7.4	1.2	2.7	-1.3	1.1
		12.0	14.7								
138	5.7	1.9	222.3	39.0	20.5	13.3	7.2	1.2	2.6	-1.1	1.1
		11.9	13.7								
139	5.7	2.0	226.1	39.7	19.8	12.9	6.9	1.1	2.5	-0.9	1.1
		11.9	12.9								
140	5.7	2.1	229.8	40.3	19.2	12.5	6.7	1.1	2.4	-0.7	1.1
		11.8	12.3								

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141	5.7	2.2	233.4	41.0	18.6	12.1	6.5	1.0	2.3	-0.5	1.2	11.8	11.8
142	5.7	2.3	236.9	41.6	18.1	11.7	6.3	1.0	2.2	-0.4	1.2	11.8	11.4
143	5.7	2.4	240.3	42.2	17.6	11.4	6.1	1.0	2.1	-0.2	1.2	11.8	11.1
144	5.8	1.4	203.1	35.0	25.0	16.3	8.8	1.5	3.2	-2.5	1.1	12.2	29.3
145	5.8	1.5	207.9	35.8	23.9	15.5	8.4	1.4	3.1	-2.1	1.1	12.1	21.6
146	5.8	1.6	212.4	36.6	22.9	14.9	8.0	1.3	2.9	-1.8	1.1	12.0	18.1
147	5.8	1.7	216.7	37.4	22.0	14.3	7.7	1.3	2.8	-1.5	1.1	12.0	16.0
148	5.8	1.8	220.9	38.1	21.2	13.8	7.4	1.2	2.7	-1.3	1.1	11.9	14.6
149	5.8	1.9	224.9	38.8	20.4	13.3	7.1	1.1	2.5	-1.0	1.1	11.9	13.6
150	5.8	2.0	228.8	39.4	19.7	12.8	6.9	1.1	2.4	-0.8	1.1	11.8	12.9
151	5.8	2.1	232.5	40.1	19.1	12.4	6.7	1.0	2.3	-0.7	1.1	11.8	12.3
152	5.8	2.2	236.2	40.7	18.5	12.0	6.5	1.0	2.2	-0.5	1.1	11.8	11.8
153	5.8	2.3	239.7	41.3	18.0	11.7	6.3	1.0	2.1	-0.3	1.2	11.8	11.4
154	5.8	2.4	243.1	41.9	17.5	11.4	6.1	0.9	2.1	-0.2	1.2	11.7	11.0

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C.6: OPTIMAP FOR 119.022KT FPSOS, SEA STATE 7

S_c=649260 bbl; Sea State 7⇒(H_s, 7.5m; T_z, 10.7s).
Please enter the sea state number: 7

Please enter the maximum allowable green water exceedance level: 2
Optimal Principal Dimensions for up to 2m permissible green water exceedance level:

Length	Beam	Depth	Draught	
228.8	39.4	19.7	12.8	[m]

Please enter the maximum allowable green water exceedance level: 1
Optimal Principal Dimensions for up to 1m permissible green water exceedance level:

Length	Beam	Depth	Draught	
209.9	36.8	23.0	15.0	[m]

Table C. 6: Principal Dimensions, Natural Periods and Most Probable Responses of 154, 649260 bbl Capacity FPSOs evaluated for Sea State 7

L	*B*	L	B	D_m	D	F_B	η_3	η_5	E	BM [GN	$T_{n3,5}$	T_{n4}

No	$\overline{B}$	$\overline{D_m}$	[m]	[m]	[m]	[m]	[m]	[m]	[deg]	[m]	m]	[s]	[s]
1	4.5	1.4	171.5	38.1	27.2	17.7	9.5	4.7	6.5	-1.2	1.7	12.7	29.2
2	4.5	1.5	175.5	39	26	16.9	9.1	4.5	6.4	-0.7	1.8	12.6	22
3	4.5	1.6	179.3	39.8	24.9	16.2	8.7	4.3	6.2	-0.3	1.8	12.6	18.6
4	4.5	1.7	183	40.7	23.9	15.5	8.4	4.2	6	0	1.8	12.5	16.5
5	4.5	1.8	186.5	41.4	23	15	8.1	4.1	5.8	0.4	1.8	12.4	15.1
6	4.5	1.9	189.9	42.2	22.2	14.4	7.8	3.9	5.7	0.6	1.9	12.4	14.1
7	4.5	2	193.2	42.9	21.5	14	7.5	3.8	5.5	0.9	1.9	12.4	13.3
8	4.5	2.1	196.3	43.6	20.8	13.5	7.3	3.7	5.4	1.1	1.9	12.3	12.7
9	4.5	2.2	199.4	44.3	20.1	13.1	7	3.6	5.2	1.4	1.9	12.3	12.2
10	4.5	2.3	202.4	45	19.6	12.7	6.8	3.5	5.1	1.6	1.9	12.3	11.8
11	4.5	2.4	205.3	45.6	19	12.4	6.7	3.4	5	1.7	2	12.2	11.5
12	4.6	1.4	174	37.8	27	17.6	9.5	4.6	6.5	-1	1.7	12.7	29.2
13	4.6	1.5	178.1	38.7	25.8	16.8	9	4.4	6.3	-0.6	1.8	12.6	22
14	4.6	1.6	182	39.6	24.7	16.1	8.7	4.3	6.1	-0.2	1.8	12.5	18.5
15	4.6	1.7	185.7	40.4	23.7	15.4	8.3	4.1	5.9	0.2	1.8	12.5	16.5
16	4.6	1.8	189.3	41.1	22.9	14.9	8	4	5.8	0.5	1.8	12.4	15.1
17	4.6	1.9	192.7	41.9	22	14.3	7.7	3.8	5.6	0.8	1.8	12.4	14.1
18	4.6	2	196	42.6	21.3	13.8	7.5	3.7	5.4	1	1.9	12.3	13.3

19	4.6	2.1 12.3	199.2 12.7	43.3	20.6	13.4	7.2	3.6	5.3	1.3	1.9
20	4.6	2.2 12.2	202.3 12.2	44	20	13	7	3.5	5.2	1.5	1.9
21	4.6	2.3 12.2	205.4 11.8	44.6	19.4	12.6	6.8	3.4	5	1.7	1.9
22	4.6	2.4 12.2	208.3 11.4	45.3	18.9	12.3	6.6	3.3	4.9	1.8	1.9
23	4.7	1.4 12.6	176.6 29.2	37.6	26.8	17.4	9.4	4.5	6.4	-0.9	1.7
24	4.7	1.5 12.5	180.7 21.9	38.4	25.6	16.7	9	4.3	6.2	-0.4	1.8
25	4.7	1.6 12.5	184.6 18.5	39.3	24.5	16	8.6	4.2	6	0	1.8
26	4.7	1.7 12.4	188.4 16.4	40.1	23.6	15.3	8.3	4	5.8	0.3	1.8
27	4.7	1.8 12.4	192 15	40.8	22.7	14.8	7.9	3.9	5.7	0.6	1.8
28	4.7	1.9 12.3	195.5 14	41.6	21.9	14.2	7.7	3.8	5.5	0.9	1.8
29	4.7	2 12.3	198.9 13.2	42.3	21.2	13.8	7.4	3.6	5.4	1.1	1.8
30	4.7	2.1 12.2	202.1 12.6	43	20.5	13.3	7.2	3.5	5.2	1.4	1.8
31	4.7	2.2 12.2	205.3 12.1	43.7	19.9	12.9	6.9	3.4	5.1	1.6	1.9
32	4.7	2.3 12.2	208.3 11.7	44.3	19.3	12.5	6.7	3.4	4.9	1.8	1.9
33	4.7	2.4 12.1	211.3 11.4	45	18.7	12.2	6.6	3.3	4.8	1.9	1.9
34	4.8	1.4 12.6	179.1 29.2	37.3	26.6	17.3	9.3	4.4	6.3	-0.7	1.7

35	4.8	1.5 12.5	183.2 21.9	38.2	25.4	16.5	8.9	4.2	6.1	-0.3	1.8
36	4.8	1.6 12.4	187.2 18.5	39	24.4	15.8	8.5	4.1	6	0.1	1.8
37	4.8	1.7 12.4	191 16.4	39.8	23.4	15.2	8.2	3.9	5.8	0.4	1.8
38	4.8	1.8 12.3	194.7 15	40.6	22.5	14.6	7.9	3.8	5.6	0.7	1.8
39	4.8	1.9 12.3	198.2 14	41.3	21.7	14.1	7.6	3.7	5.4	1	1.8
40	4.8	2 12.2	201.7 13.2	42	21	13.7	7.4	3.6	5.3	1.2	1.8
41	4.8	2.1 12.2	205 12.6	42.7	20.3	13.2	7.1	3.5	5.1	1.5	1.8
42	4.8	2.2 12.2	208.2 12.1	43.4	19.7	12.8	6.9	3.4	5	1.7	1.8
43	4.8	2.3 12.1	211.3 11.7	44	19.1	12.4	6.7	3.3	4.9	1.9	1.8
44	4.8	2.4 12.1	214.3 11.3	44.6	18.6	12.1	6.5	3.2	4.7	2	1.9
45	4.9	1.4 12.5	181.5 29.2	37	26.5	17.2	9.3	4.3	6.3	-0.6	1.7
46	4.9	1.5 12.4	185.8 21.9	37.9	25.3	16.4	8.8	4.2	6.1	-0.2	1.7
47	4.9	1.6 12.4 5.7	189.8 18.4 48 0.5	38.7 4.9 1.8	24.2 1.7 12.3	15.7 193.7 16.3	8.5 39.5	4 23.2	5.9 15.1	0.2 8.1	1.8 3.9
49	4.9	1.8 12.3	197.4 14.9	40.3	22.4	14.5	7.8	3.7	5.5	0.8	1.8
50	4.9	1.9 12.2	201 13.9	41	21.6	14	7.6	3.6	5.3	1.1	1.8
51	4.9	2 12.2	204.5 13.2	41.7	20.9	13.6	7.3	3.5	5.2	1.4	1.8

52	4.9	2.1 12.1	207.8 12.6	42.4	20.2	13.1	7.1	3.4	5	1.6	1.8
53	4.9	2.2 12.1	211.1 12.1	43.1	19.6	12.7	6.9	3.3	4.9	1.8	1.8
54	4.9	2.3 12.1	214.2 11.7	43.7	19	12.4	6.7	3.2	4.8	2	1.8
55	4.9	2.4 12.1	217.3 11.3	44.3	18.5	12	6.5	3.1	4.6	2.1	1.8
56	5	1.4 12.5	184 29.2	36.8	26.3	17.1	9.2	4.3	6.2	-0.5	1.7
57	5	1.5 12.4	188.3 21.8	37.7	25.1	16.3	8.8	4.1	6	0	1.7
58	5	1.6 12.3	192.4 18.4	38.5	24	15.6	8.4	3.9	5.8	0.3	1.7
59	5	1.7 12.3	196.3 16.3	39.3	23.1	15	8.1	3.8	5.6	0.7	1.7
60	5	1.8 12.2	200.1 14.9	40	22.2	14.4	7.8	3.6	5.4	0.9	1.7
61	5	1.9 12.2	203.7 13.9	40.7	21.4	13.9	7.5	3.5	5.3	1.2	1.8
62	5	2 12.1	207.2 13.1	41.4	20.7	13.5	7.3	3.4	5.1	1.4	1.8
63	5	2.1 12.1	210.6 12.5	42.1	20.1	13	7	3.3	5	1.7	1.8
64	5	2.2 12.1	213.9 12	42.8	19.4	12.6	6.8	3.2	4.8	1.9	1.8
65	5	2.3 12	217.1 11.6	43.4	18.9	12.3	6.6	3.1	4.7	2	1.8
66	5	2.4 12	220.2 11.3	44	18.4	11.9	6.4	3.1	4.6	2.2	1.8
67	5.1	1.4 12.4	186.4 29.2	36.6	26.1	17	9.1	4.2	6.1	-0.3	1.7

68	5.1	1.5 12.4	190.8 21.8	37.4	24.9	16.2	8.7	4	5.9	0.1	1.7
69	5.1	1.6 12.3	194.9 18.3	38.2	23.9	15.5	8.4	3.8	5.7	0.4	1.7
70	5.1	1.7 12.2	198.9 16.3	39	22.9	14.9	8	3.7	5.5	0.8	1.7
71	5.1	1.8 12.2	202.7 14.9	39.8	22.1	14.4	7.7	3.6	5.3	1	1.7
72	5.1	1.9 12.1	206.4 13.9	40.5	21.3	13.8	7.5	3.4	5.2	1.3	1.7
73	5.1	2 12.1	210 13.1	41.2	20.6	13.4	7.2	3.3	5	1.5	1.7
74	5.1	2.1 12.1	213.4 12.5	41.8	19.9	13	7	3.2	4.9	1.7	1.7
75	5.1	2.2 12	216.8 12	42.5	19.3	12.6	6.8	3.1	4.7	1.9	1.7
76	5.1	2.3 12	220 11.6	43.1	18.8	12.2	6.6	3.1	4.6	2.1	1.8
77	5.1	2.4 12	223.1 11.2	43.8	18.2	11.8	6.4	3	4.5	2.3	1.8
78	5.2	1.4 12.4	188.9 29.2	36.3	25.9	16.9	9.1	4.1	6	-0.2	1.7
79	5.2	1.5 12.3	193.3 21.8	37.2	24.8	16.1	8.7	3.9	5.8	0.2	1.7
80	5.2	1.6 12.3	197.5 18.3	38	23.7	15.4	8.3	3.8	5.6	0.6	1.7
81	5.2	1.7 12.2	201.5 16.2	38.7	22.8	14.8	8	3.6	5.4	0.9	1.7
82	5.2	1.8 12.1	205.4 14.8	39.5	21.9	14.3	7.7	3.5	5.3	1.1	1.7
83	5.2	1.9 12.1	209.1 13.8	40.2	21.2	13.8	7.4	3.4	5.1	1.4	1.7

84	5.2	2 12.1	212.7 13.1	40.9	20.5	13.3	7.2	3.3	4.9	1.6	1.7
85	5.2	2.1 12	216.2 12.4	41.6	19.8	12.9	6.9	3.2	4.8	1.8	1.7
86	5.2	2.2 12	219.6 12	42.2	19.2	12.5	6.7	3.1	4.6	2	1.7
87	5.2	2.3 12	222.9 11.6	42.9	18.6	12.1	6.5	3	4.5	2.2	1.7
88	5.2	2.4 11.9 6	226 11.2 89 -0.1	43.5 5.3 1.7	18.1 1.4 12.4	11.8 191.3 29.2	6.3 36.1	2.9 25.8	4.4 16.8	2.3 9	1.7 4
90	5.3	1.5 12.3	195.7 21.7	36.9	24.6	16	8.6	3.8	5.8	0.3	1.7
91	5.3	1.6 12.2	200 18.3	37.7	23.6	15.3	8.3	3.7	5.5	0.6	1.7
92	5.3	1.7 12.2	204.1 16.2	38.5	22.6	14.7	7.9	3.5	5.4	1	1.7
93	5.3	1.8 12.1	208 14.8	39.2	21.8	14.2	7.6	3.4	5.2	1.2	1.7
94	5.3	1.9 12.1	211.8 13.8	40	21	13.7	7.4	3.3	5	1.5	1.7
95	5.3	2 12	215.4 13	40.6	20.3	13.2	7.1	3.2	4.8	1.7	1.7
96	5.3	2.1 12	219 12.4	41.3	19.7	12.8	6.9	3.1	4.7	1.9	1.7
97	5.3	2.2 12	222.4 11.9	42	19.1	12.4	6.7	3	4.5	2.1	1.7
98	5.3	2.3 11.9	225.7 11.5	42.6	18.5	12	6.5	2.9	4.4	2.2	1.7
99	5.3	2.4 11.9	228.9 11.2	43.2	18	11.7	6.3	2.9	4.3	2.4	1.7
100	5.4	1.4 12.3	193.7 29.2	35.9	25.6	16.7	9	3.9	5.9	0	1.7

101	5.4	1.5 12.2	198.2 21.7	36.7	24.5	15.9	8.6	3.8	5.7	0.4	1.7
102	5.4	1.6 12.2	202.5 18.2	37.5	23.4	15.2	8.2	3.6	5.5	0.7	1.7
103	5.4	1.7 12.1	206.6 16.2	38.3	22.5	14.6	7.9	3.5	5.3	1	1.7
104	5.4	1.8 12.1	210.6 14.8	39	21.7	14.1	7.6	3.3	5.1	1.3	1.7
105	5.4	1.9 12	214.4 13.8	39.7	20.9	13.6	7.3	3.2	4.9	1.6	1.6
106	5.4	2 12	218.1 13	40.4	20.2	13.1	7.1	3.1	4.8	1.8	1.6
107	5.4	2.1 12	221.7 12.4	41.1	19.6	12.7	6.8	3	4.6	2	1.6
108	5.4	2.2 11.9	225.2 11.9	41.7	19	12.3	6.6	3	4.5	2.1	1.7
109	5.4	2.3 11.9	228.5 11.5	42.3	18.4	12	6.4	2.9	4.3	2.3	1.7
110	5.4	2.4 11.9	231.8 11.1	42.9	17.9	11.6	6.3	2.8	4.2	2.5	1.7
111	5.5	1.4 12.3	196.1 29.2	35.6	25.5	16.6	8.9	3.8	5.8	0.1	1.7
112	5.5	1.5 12.2	200.6 21.7	36.5	24.3	15.8	8.5	3.7	5.6	0.5	1.7
113	5.5	1.6 12.1	205 18.2	37.3	23.3	15.1	8.2	3.5	5.4	0.8	1.6
114	5.5	1.7 12.1	209.2 16.1	38	22.4	14.5	7.8	3.4	5.2	1.1	1.6
115	5.5	1.8 12	213.2 14.7	38.8	21.5	14	7.5	3.3	5	1.4	1.6
116	5.5	1.9 12	217.1 13.7	39.5	20.8	13.5	7.3	3.2	4.8	1.6	1.6

117	5.5	2	220.8	40.1	20.1	13	7	3.1	4.7	1.8	1.6	12	13
118	5.5	2.1	224.4	40.8	19.4	12.6	6.8	3	4.5	2	1.6	11.9	12.3
119	5.5	2.2	227.9	41.4	18.8	12.2	6.6	2.9	4.4	2.2	1.6	11.9	11.9
120	5.5	2.3	231.3	42.1	18.3	11.9	6.4	2.8	4.2	2.4	1.6	11.9	11.5
121	5.5	2.4	234.7	42.7	17.8	11.6	6.2	2.8	4.1	2.5	1.7	11.8	11.1
122	5.6	1.4	198.4	35.4	25.3	16.5	8.9	3.8	5.7	0.2	1.6	12.3	29.2
123	5.6	1.5	203.1	36.3	24.2	15.7	8.5	3.6	5.5	0.6	1.6	12.2	21.6
124	5.6	1.6	207.5	37	23.2	15.1	8.1	3.5	5.3	0.9	1.6	12.1	18.2
125	5.6	1.7	211.7	37.8	22.2	14.5	7.8	3.3	5.1	1.2	1.6	12	16.1
126	5.6	1.8	215.8	38.5	21.4	13.9	7.5	3.2	4.9	1.5	1.6	12	14.7
127	5.6	1.9	219.7	39.2	20.6	13.4	7.2	3.1	4.7	1.7	1.6	12	13.7
128	5.6	2	223.5	39.9	20	13	7	3	4.6	1.9	1.6	11.9	12.9
129	5.6	2.1	227.2	40.6	19.3	12.6	6.8	2.9	4.4	2.1	1.6	11.9	12.3
130	5.6	2.2	230.7	41.2	18.7	12.2	6.6	2.8	4.3	2.2	1.6	11.8	11.8
131	5.6	2.3	234.1	41.8	18.2	11.8	6.4	2.8	4.2	2.4	1.6	11.8	11.4
132	5.6	2.4	237.5	42.4	17.7	11.5	6.2	2.7	4	2.5	1.6	11.8	11.1
133	5.7	1.4	200.8	35.2	25.2	16.4	8.8	3.7	5.6	0.3	1.6	12.2	29.3
134	5.7	1.5	205.5	36	24	15.6	8.4	3.5	5.4	0.7	1.6	12.1	21.6
135	5.7	1.6	209.9	36.8	23	15	8.1	3.4	5.2	1	1.6	12.1	18.1

136	5.7	1.7	214.2	37.6	22.1	14.4	7.7	3.3	5	1.3	1.6	12	16.1
137	5.7	1.8	218.3	38.3	21.3	13.8	7.4	3.1	4.8	1.5	1.6	12	14.7
138	5.7	1.9	222.3	39	20.5	13.3	7.2	3	4.6	1.7	1.6	11.9	13.7
139	5.7	2	226.1	39.7	19.8	12.9	6.9	2.9	4.5	1.9	1.6	11.9	12.9
140	5.7	2.1	229.8	40.3	19.2	12.5	6.7	2.9	4.3	2.1	1.6	11.8	12.3
141	5.7	2.2	233.4	41	18.6	12.1	6.5	2.8	4.2	2.3	1.6	11.8	11.8
142	5.7	2.3	236.9	41.6	18.1	11.7	6.3	2.7	4.1	2.4	1.6	11.8	11.4
143	5.7	2.4	240.3	42.2	17.6	11.4	6.1	2.7	3.9	2.6	1.6	11.8	11.1
144	5.8	1.4	203.1	35	25	16.3	8.8	3.6	5.6	0.4	1.6	12.2	29.3
145	5.8	1.5	207.9	35.8	23.9	15.5	8.4	3.5	5.3	0.7	1.6	12.1	21.6
146	5.8	1.6	212.4	36.6	22.9	14.9	8	3.3	5.1	1.1	1.6	12	18.1
147	5.8	1.7	216.7	37.4	22	14.3	7.7	3.2	4.9	1.3	1.6	12	16
148	5.8	1.8	220.9	38.1	21.2	13.8	7.4	3.1	4.7	1.6	1.6	11.9	14.6
149	5.8	1.9	224.9	38.8	20.4	13.3	7.1	3	4.6	1.8	1.5	11.9	13.6
150	5.8	2	228.8	39.4	19.7	12.8	6.9	2.9	4.4	2	1.5	11.8	12.9
151	5.8	2.1	232.5	40.1	19.1	12.4	6.7	2.8	4.2	2.2	1.6	11.8	12.3
152	5.8	2.2	236.2	40.7	18.5	12	6.5	2.7	4.1	2.3	1.6	11.8	11.8
153	5.8	2.3	239.7	41.3	18	11.7	6.3	2.7	4	2.5	1.6	11.8	11.4
154	5.8	2.4	243.1	41.9	17.5	11.4	6.1	2.6	3.9	2.6	1.6	11.7	11

C.7: EFFECTS OF DIFFERENT EXTREME SEA STATES ON THE OPTIMAL DIMENSIONS OF 393.36KTON FPSO

Table C. 7: Effects of Different Extreme Sea States on 393.36kTon FPSO (with Length 348.75m, Breadth 60.13m, and Draught 18.30m)

Extreme Sea State	η_3 [m]	η_5 [deg]	E [m]	BM [GNm]
(a) H_s 16.5m, T_z 17.5s	10.14	6.00	6.91	10.24
(b) H_s 16.5m, T_z 15s	8.19	6.33	9.69	10.68
(c) H_s 16.5m, T_z 12.2s	5.17	5.94	12.04	11.74
(d) H_s 13.49m, T_z 11s	3.01	4.31	8.46	10.08
(e) H_s 11.15m, T_z 10s	1.68	2.95	5.14	8.54

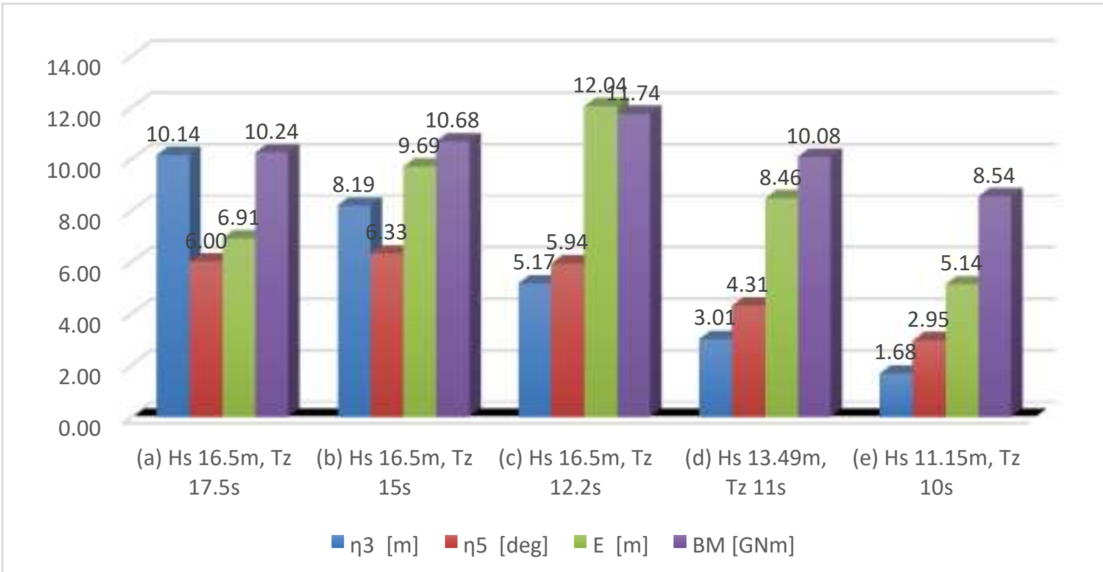


Figure C. 1: Effects of Different Extreme Sea States on 393.36kTon FPSO (with Length 348.75m, Breadth 60.13m, and Draught 18.30m)

Table C. 8: Optimal Dimensions of 393.36kT FPSO required to curb the effects of green water in different extreme sea states

H_s	T_z	L [m]	B	D_m	D	L/B	B/D_m
[m]		348.75		[s] [m]	[m]	[m]	

16.50 17.50 60.13 26.14 18.30 5.80 2.30

16.50 15.00 292.16 51.26 36.61 25.63 5.70 1.40 16.50 12.20

249.56 55.46 39.61 27.73 4.50 1.40 13.49 11.00 309.02 53.28

33.30 23.31 5.80 1.60

11.15 10.00 353.73 60.99 25.41 17.79 5.80 2.40

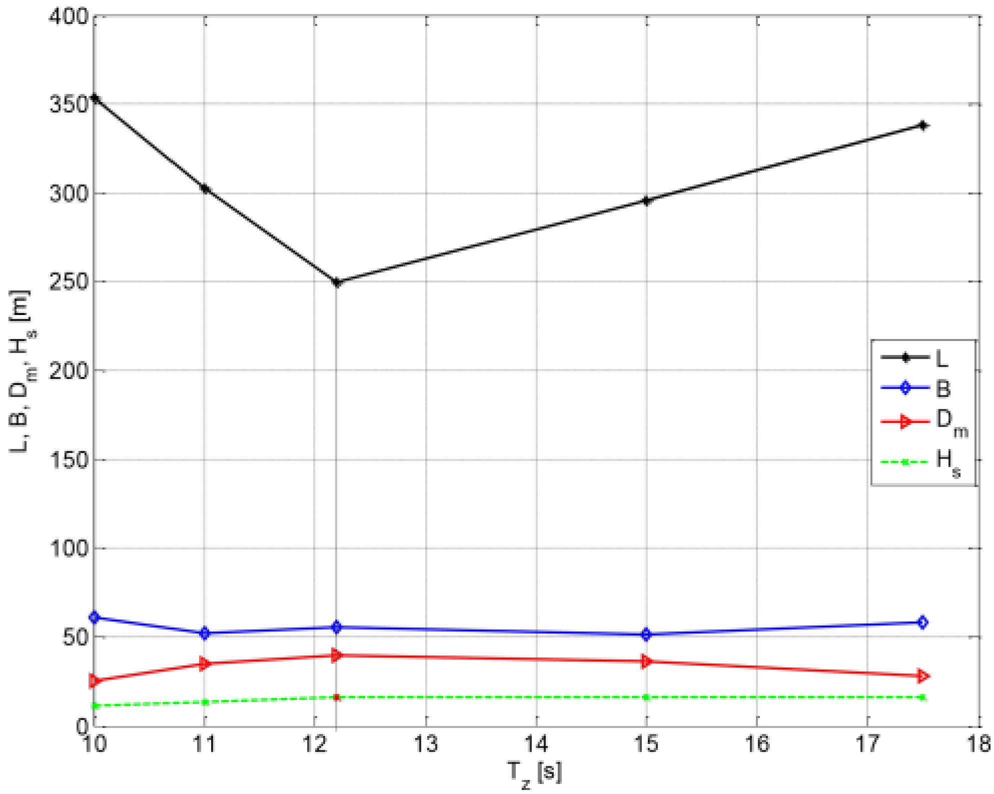
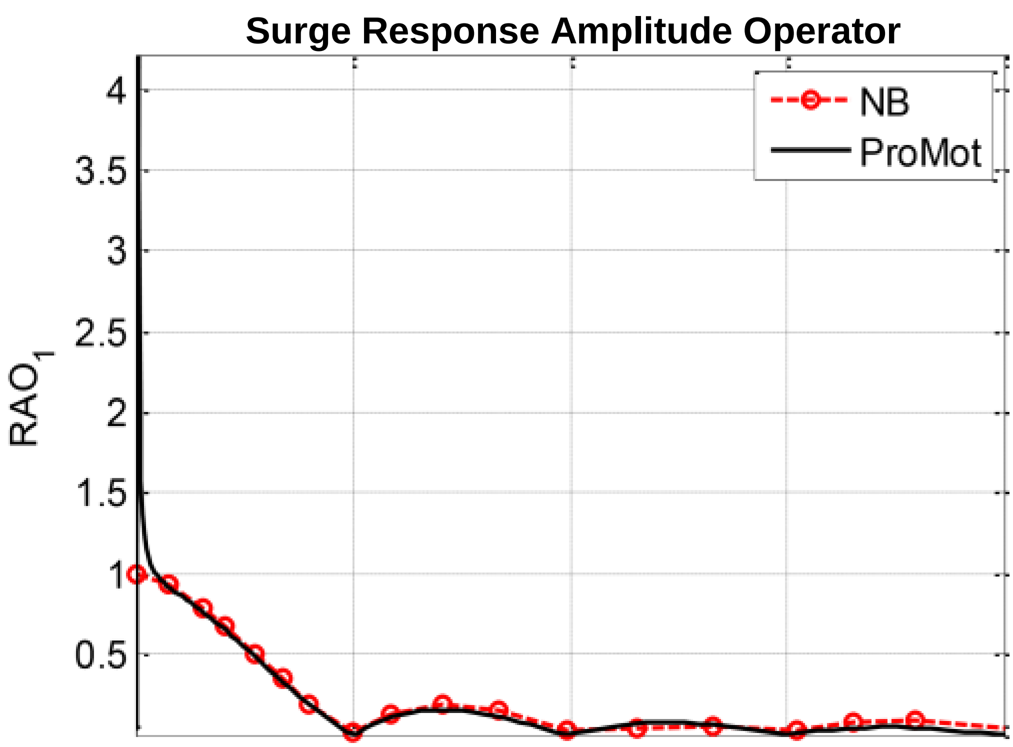


Figure C. 2: Effect of Extreme Sea States on the Optimal Dimensions of 393.36kT FPSO (required to curb the effects of green water; for permissible freeboard exceedance of 7m)

APPENDIX D: COMPARISON OF RAOS AND WAVE BENDING MOMENT RESULTS



0 1 2 3 4

L/□

Figure D. 1: Comparison of Surge RAOs obtained from my programme for motion analysis (ProMot) with that given by Barltrop (1998). Vessel Dimensions: Length, L, 250m; Beam, B, 40m; Draught, D, 12m

Heave Response Amplitude Operator

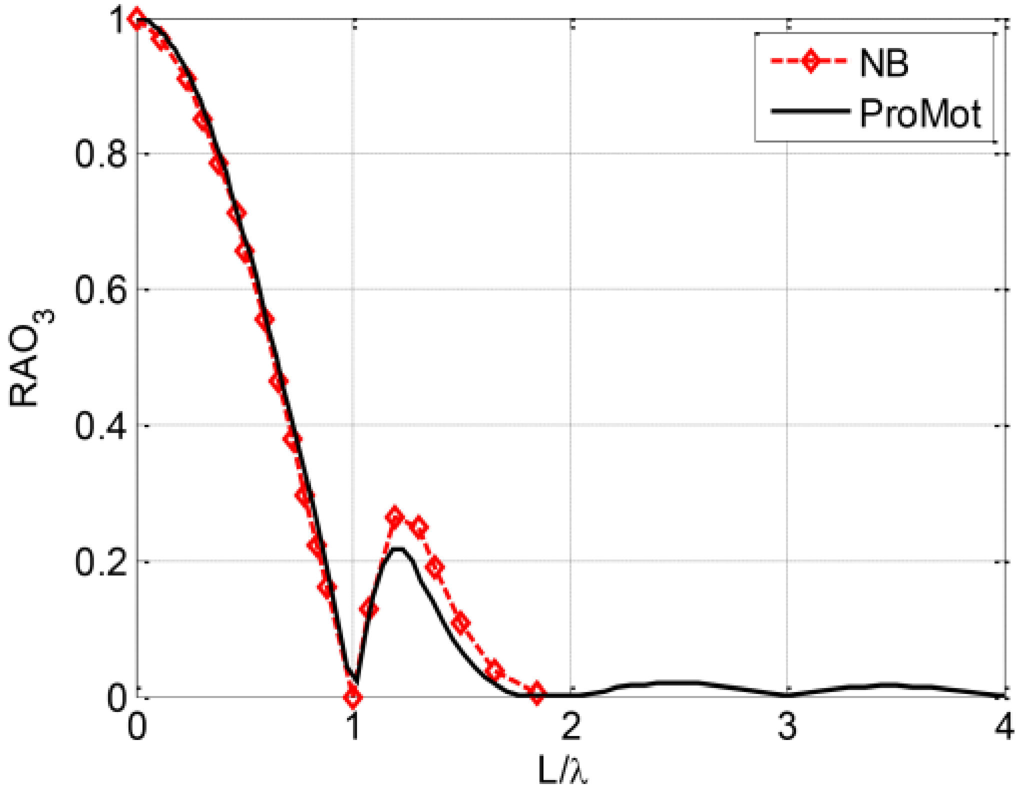


Figure D. 2: Comparison of Heave RAOs obtained from my programme for motion analysis (ProMot) with that given by Barltrop (1998). Vessel Dimensions: Length, L, 250m; Beam, B, 40m; Draught, D, 12m.

Pitch RAO

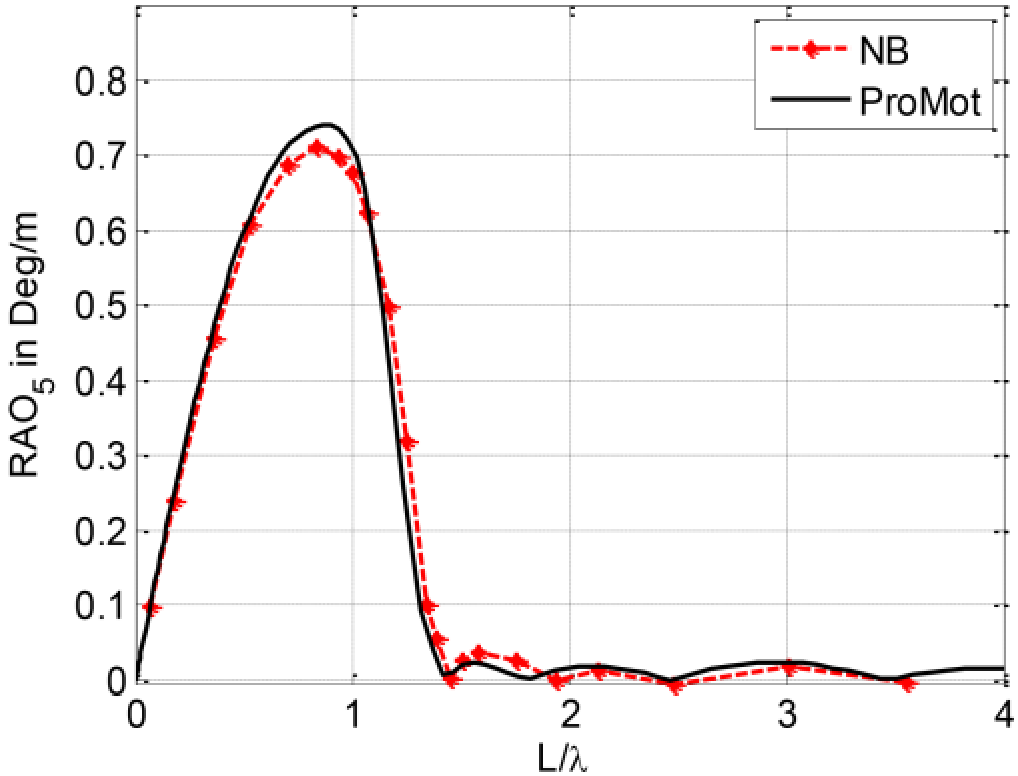


Figure D. 3: Comparison of Pitch RAOs obtained from my programme for motion analysis (ProMot) with that given by Barltrop (1998). Vessel Dimensions: Length, L, 250m; Beam, B, 40m; Draught, D, 12m.

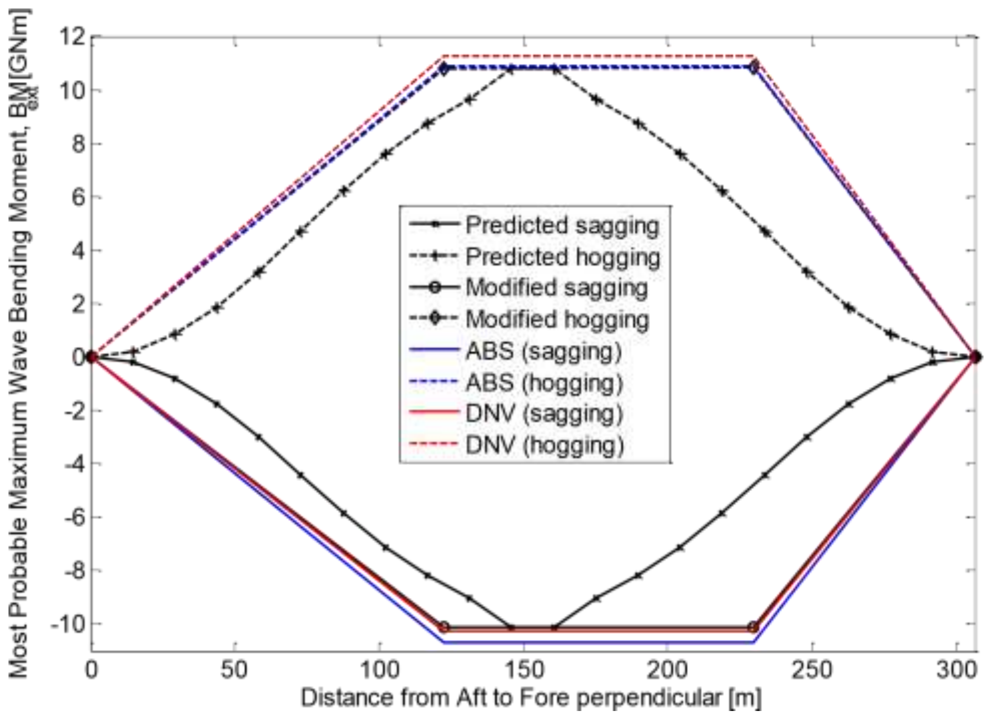


Figure D. 4: Some Predicted Extreme Wave bending Moment Distribution showing both Sagging and Hogging moments

Table D. 1: Predicted Extreme (Design) Values of Wave Bending Moments for the 100 Year Return Period storm of the North Sea

	BM (ABS)	BM	BM (DNV)	(Predicted)
Sagging [GNm]	10.105	10.701	10.256	
Hogging [GNm]	10.610	10.872	11.282	

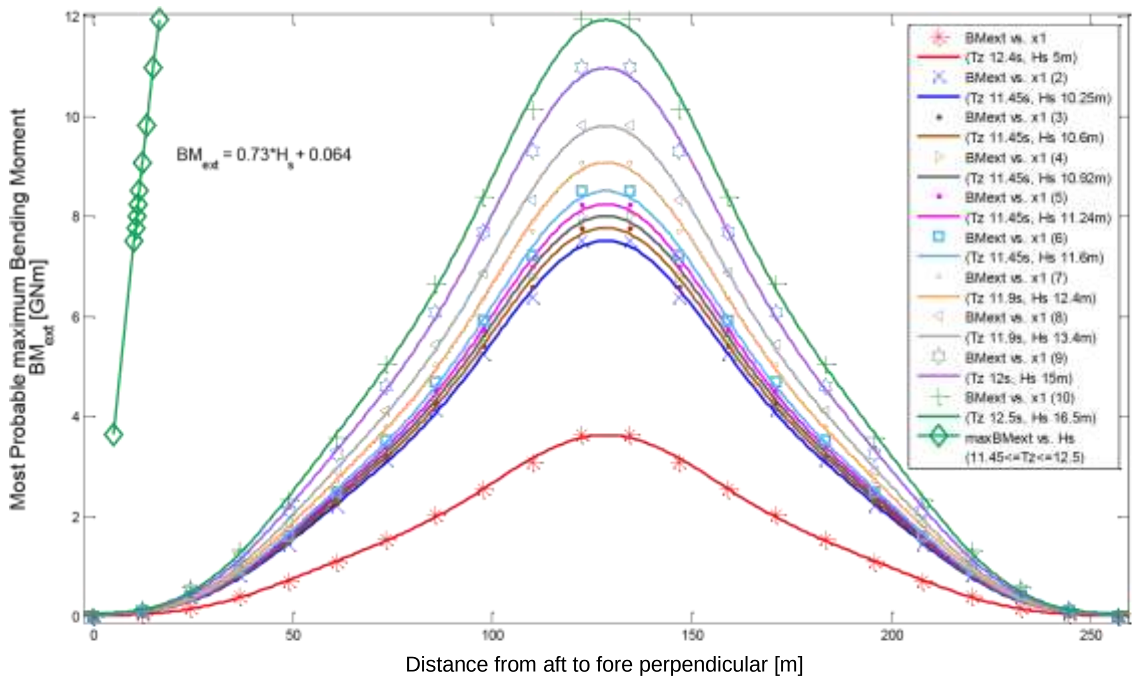


Figure D. 5: Most Probable Maximum Bending Moment Distribution for different Significant Wave Heights (or Sea States). Vessel Dimensions: L=256.9m; B=54.7m; D_m=39.0m; D=25.4m)

APPENDIX E: WAVE DATA

Table E. 1: World Meteorological Organization Sea State Codes

Sea State Code	Significant Wave Height Range [m]	Significant Wave Height Mean [m]	Description
0	0	0	Calm (glassy)
1	0.0-0.1	0.05	Calm (ripple)
2	0.1-0.5	0.3	Smooth wavelet
3	0.5-1.25	0.875	Slight
4	1.25-2.5	1.875	Moderate
5	2.5-4.0	3.25	Rough
6	4.0-6.0	5	Very Rough
7	6.0-9.0	7.5	High
8	9.0-14.0	11.5	Very High
9	>14.0	>14.0	Huge or Phenomenal

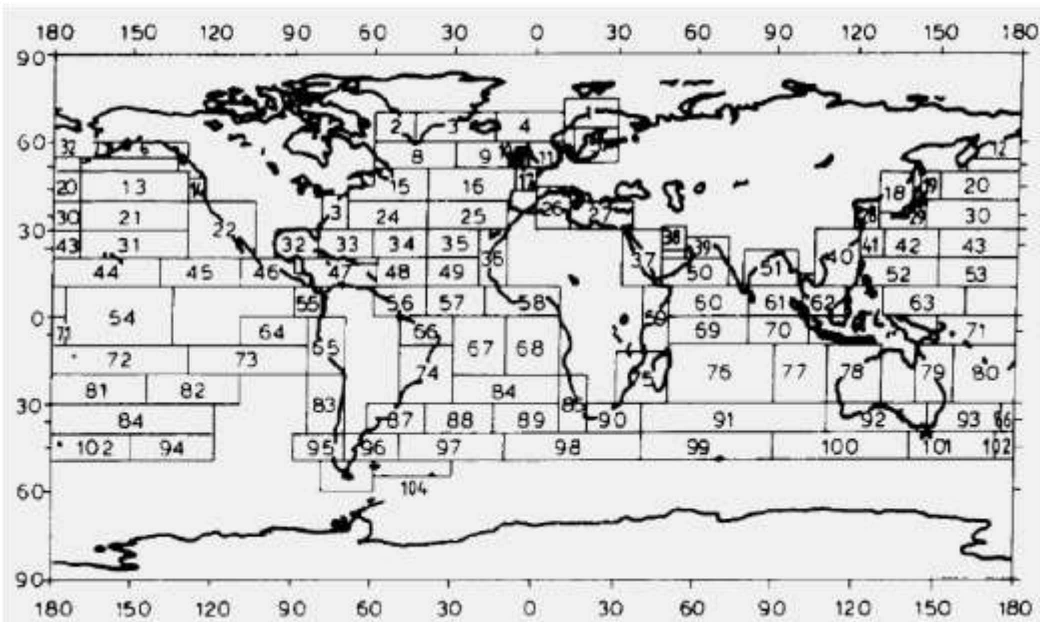


Figure E. 1: Definition of the extent of the North Atlantic

Source: http://www.bmt.org, http://www.geomar.de

Table E. 2: Probability of Sea States in the North Atlantic described as occurrence per 100000 observations: Derived from BMT's Global Wave Statistics

H_s/T_z	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	Sum
0.5	0.0	0.0	1.3	133.7	865.6	1,186.0	634.2	186.3	36.9	5.6	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	3,050
1.5	0.0	0.0	0.0	29.3	986.0	4,976.0	7,738.0	5,569.7	2,375.7	703.5	160.7	30.5	5.1	0.8	0.1	0.0	0.0	0.0	22,575
2.5	0.0	0.0	0.0	2.2	197.5	2,158.8	6,230.0	7,449.5	4,860.4	2,066.0	644.5	160.2	33.7	6.3	1.1	0.2	0.0	0.0	23,810
3.5	0.0	0.0	0.0	0.2	34.9	695.5	3,226.5	5,675.0	5,099.1	2,838.0	1,114.1	337.7	84.3	18.2	3.5	0.6	0.1	0.0	19,128
4.5	0.0	0.0	0.0	0.0	6.0	196.1	1,354.3	3,288.5	3,857.5	2,685.5	1,275.2	455.1	130.9	31.9	6.9	1.3	0.2	0.0	13,289
5.5	0.0	0.0	0.0	0.0	1.0	51.0	498.4	1,602.9	2,372.7	2,008.3	1,126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8,328
6.5	0.0	0.0	0.0	0.0	0.2	12.6	167.0	690.3	1,257.9	1,268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4,806
7.5	0.0	0.0	0.0	0.0	0.0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2,586
8.5	0.0	0.0	0.0	0.0	0.0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1,309
9.5	0.0	0.0	0.0	0.0	0.0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0.0	0.0	0.0	0.0	0.0	0.0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0.0	51
13.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0.0	21
14.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0.0	0.0	8
15.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0.0	0.0	3
16.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	1
Sum	0	0	1	165	2,091	9,280	19,922	24,879	20,870	12,898	6,245	2,479	837	247	66	16	3	1	100,000

Source: (IACS, 2001)

Table E. 3: Annual Sea States in the North Atlantic

Sea state number	Significant wave height (m)		Sustained wind speed(1) (knots)		Probability of sea states (%)	Modal wave period (sec)	
	Range	Mean	Range	Mean		Range(2)	Most probable(3)
0.1	0.0–0.1	0.05	0–6	3.0	1.30	–	–
2	0.1–0.5	0.3	7–10	8.5	6.40	5.1–14.9	6.3
3	0.5–1.25	0.88	11–16	13.5	15.50	5.3–16.1	7.5
4	1.25–2.5	1.88	17–21	19.0	31.60	6.1–17.2	8.8
5	2.5–4.0	3.25	22–27	24.5	20.94	7.7–17.8	9.7
6	4.0–6.0	5.0	28–47	37.5	15.03	10.0–18.7	12.4
7	6.0–9.0	7.5	48–55	51.5	7.60	11.7–19.8	15.0
8	9.0–14.0	11.5	56–63	59.5	1.56	14.5–21.5	16.4
>8	>14.0	>14.0	>63	>63	0.07	16.4–22.5	20.0

Source: (Lee et al., 1985)

Table E. 4: Characteristics of 100-Year Return Period Storms at Various Ocean Regions

Property		Gulf of Mexico	North Sea	West Africa	Brazil	Timor Sea
Wind speed (knots)		80	83	42	60	80
Current speed (knots)		2.1	2.8	1.7	3.2	4.2
Wave	H_s(m)	12.2	16.5	2.7	7.6	9.8
	H_{max}(m)	22.8	30.8	5.1	14.2	18.2
	T_z(s)	14.0	17.5	7.6	14.3	12.4
Swell	H_s(m)	–	–	3.7	–	–
	H_{max}(m)	–	–	6.8	–	–
	T_z(s)	–	–	13.9	–	–

Notes: H_s=significant wave height; H_{max}=maximum wave height;
T_z=period. This data is indicative of metocean conditions for usual areas of operations of ship-shaped offshore installations.

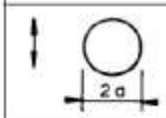
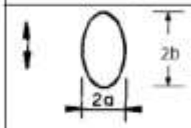
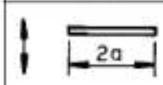
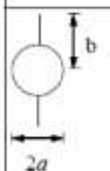
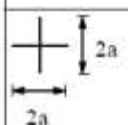
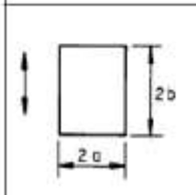
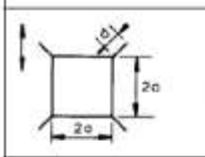
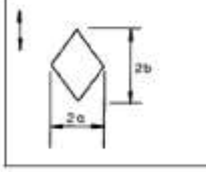
Table E. 5: Extremes of Environmental Phenomena at Various Ocean Regions

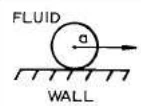
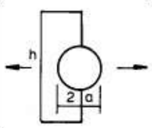
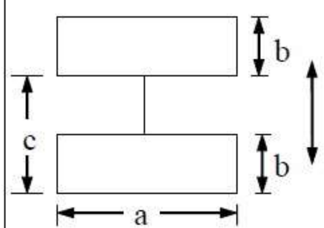
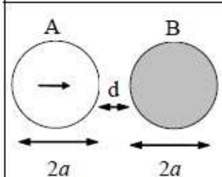
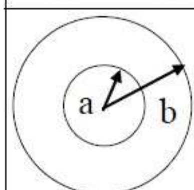
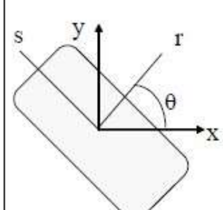
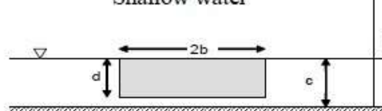
Item	Gulf of Mexico	Southern North Sea	Northern North Sea	Canadian Georges Bank	N.W. Australia	Beaufort Sea	Newfoundland	Bass Strait
Wave height (m)	22	20	32	25	22	8	30	23
Wind (m/s)	70	40	45	50	70	40	60	50
Current (cm/s)	100	50	50	120	180	75	150	130
Tide (m)	1.5	2	2	2	4	0.5	2	1
Icing	No	No	No	Yes	No	Yes	Yes	No
Fog (%)	5	5–15	2–5	30–40	1	20	30–40	1

Source: (Sharples et al., 1989)

APPENDIX F: ADDED MASS COEFFICIENTS

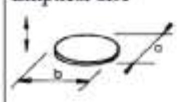
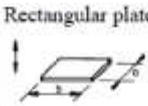
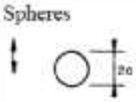
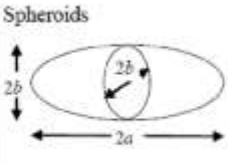
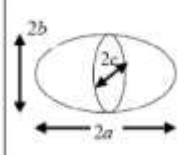
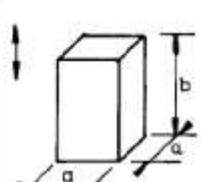
Table F. 1: Analytical added mass coefficient for two-dimensional bodies, i.e. long cylinders in infinite fluid (far from boundaries).

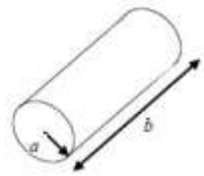
Section through body		*Direction of motion*	C_A	A_R	*Added mass moment of inertia* [(kg/m)*m²]
			1.0	πa^2	0
		Vertical	1.0	πa^2	$\rho \frac{\pi}{8}(b^2 - a^2)^2$
		Horizontal	1.0	πb^2	
		Vertical	1.0	πa^2	$\rho \frac{\pi}{8} a^4$
	Circular cylinder with two fins	Vertical	1.0	πa^2	$\rho a^4(\csc^4\alpha\, f(\alpha) - \pi^2)/2\pi$ where $f(\alpha) = 2\alpha^2 - \alpha \sin 4\alpha$ $+ 0.5 \sin^2 2\alpha$ and $\sin\alpha = 2ab/(a^2 + b^2)$ $\pi/2 < \alpha < \pi$
		Horizontal	$1 - \left(\frac{a}{b}\right)^2 + \left(\frac{a}{b}\right)^4$	πb^2	
		Horizontal or Vertical	1.0	πa^2	$\frac{2}{\pi} \rho a^4$
	$a/b = \infty$ $a/b = 10$ $a/b = 5$ $a/b = 2$ $a/b = 1$ $a/b = 0.5$ $a/b = 0.2$ $a/b = 0.1$	Vertical	1.0 1.14 1.21 1.36 1.51 1.70 1.98 2.23	πa^2	$\beta_1 \rho \pi a^4$ or $\beta_2 \rho \pi b^4$ a/b | β_1 | β_2 0.1 | - | 0.147 0.2 | - | 0.15 0.5 | - | 0.15 1.0 | 0.234 | 0.234 2.0 | 0.15 | - 5.0 | 0.15 | - ∞ | 0.125 | -
	$d/a = 0.05$ $d/a = 0.10$ $d/a = 0.25$	Vertical	1.61 1.72 2.19	πa^2	$\beta \rho \pi a^4$ d/a | β 0.05 | 0.31 0.10 | 0.40 0.10 | 0.69
	$a/b = 2$ $a/b = 1$ $a/b = 0.5$ $a/b = 0.2$	Vertical	0.85 0.76 0.67 0.61	πa^2	0.059 $\rho \pi a^4$ for $a = b$ only

<table>
<tr><th>Section through body</th><th>Direction of motion</th><th>C_A</th><th>A_R</th><th>Added mass moment of inertia [(kg/m)*m]</th></tr>
<tr><td></td><td>Horizontal</td><td>$\frac{\pi^2}{3}-1$</td><td>πa^2</td><td></td></tr>
<tr><td></td><td>Horizontal</td><td>$1+\left(\frac{h}{2a}-\frac{2a}{h}\right)^2$</td><td>$\pi a^2$</td><td></td></tr>
<tr><td></td><td>Vertical</td><td><table>
<tr><th rowspan="2">c/a</th><th colspan="4">b/a</th></tr>
<tr><th>0.1</th><th>0.2</th><th>0.4</th><th>1.0</th></tr>
<tr><td>0.5</td><td>4.7</td><td>2.6</td><td>1.3</td><td>-</td></tr>
<tr><td>1.0</td><td>5.2</td><td>3.2</td><td>1.7</td><td>0.6</td></tr>
<tr><td>1.5</td><td>5.8</td><td>3.7</td><td>2.0</td><td>0.7</td></tr>
<tr><td>2.0</td><td>6.4</td><td>4.0</td><td>2.3</td><td>0.9</td></tr>
<tr><td>3.0</td><td>7.2</td><td>4.6</td><td>2.5</td><td>1.1</td></tr>
<tr><td>4.0</td><td>-</td><td>4.8</td><td>-</td><td>-</td></tr>
</table></td><td>$2ab$</td><td></td></tr>
<tr><td>A moving
B fixed</td><td>Horizontal</td><td>$d/a=\infty$ 1.000
$d/a=1.2$ 1.024
$d/a=0.8$ 1.044
$d/a=0.4$ 1.096
$d/a=0.2$ 1.160
$d/a=0.1$ 1.224</td><td>πa^2</td><td></td></tr>
<tr><td>Cylinder within pipe</td><td></td><td>$\frac{b^2+a^2}{b^2-a^2}$</td><td>πa^2</td><td></td></tr>
<tr><td>Cross section is symmetric about r and s axes</td><td colspan="3">$m_{yy}^a = m_{rr}^a \sin^2\theta + m_{ss}^a \cos^2\theta$
$m_{xx}^a = m_{rr}^a \cos^2\theta + m_{ss}^a \sin^2\theta$
$m_{xy}^a = \frac{1}{2}(m_{rr}^a - m_{ss}^a)\sin 2\theta$</td><td></td></tr>
<tr><td>Shallow water</td><td colspan="2">$\frac{b}{c\varepsilon}-\frac{2}{\pi}\ln 4\varepsilon+\frac{2}{\pi}-\frac{2b}{c}+\varepsilon\frac{b}{c}+\frac{2}{3\pi}\varepsilon^2$
$\frac{d}{c}=1-\varepsilon$ where $\varepsilon \ll 1$</td><td>$2\rho c^2$</td><td></td></tr>
</table>

Added mass per unit length is $A_{ij} = \rho C_A A_R \, [\frac{kg}{m}]$ where A_R $[m^2]$ is the reference area. Source: Hearn (1988)

Table F. 2: Analytical added mass coefficient for three-dimensional bodies, i.e. long cylinders in infinite fluid (far from boundaries).

Body shape		*Direction of motion*	C_A				V_R
Flat plates	Circular disc 	Vertical	$2/\pi$				$\frac{4}{3}\pi a^3$
	Elliptical disc 	Vertical	*b/a*	C_A	*b/a*	C_A	$\frac{\pi}{6}a^2 b$
			∞	1.000	5.0	0.952	
			14.3	0.991	4.0	0.933	
			12.8	0.989	3.0	0.900	
			10.0	0.984	2.0	0.826	
			7.0	0.972	1.5	0.758	
			6.0	0.964	1.0	0.637	
	Rectangular plates 	Vertical	*b/a*	C_A	*b/a*	C_A	$\frac{\pi}{4}a^2 b$
			1.00	0.579	3.17	0.840	
			1.25	0.642	4.00	0.872	
			1.50	0.690	5.00	0.897	
			1.59	0.704	6.25	0.917	
			2.00	0.757	8.00	0.934	
			2.50	0.801	10.00	0.947	
			3.00	0.830	∞	1.000	
	Triangular plates 	Vertical	$\frac{1}{\pi}(\tan\theta)^{3/2}$				$\frac{a^3}{3}$
Bodies of revolution	Spheres 	Any direction	½				$\frac{4}{3}\pi a^3$
	Spheroids 	Lateral or axial	*a/b*	C_A Axial	C_A Lateral		$\frac{4}{3}\pi b^2 a$
			1.0	0.500	0.500		
			1.5	0.304	0.622		
			2.0	0.210	0.704		
			2.5	0.156	0.762		
			4.0	0.082	0.860		
			5.0	0.059	0.894		
			6.0	0.045	0.917		
			7.0	0.036	0.933		
			8.0	0.029	0.945		
Ellipsoid	 Axis $a > b > c$	Axial	$C_A = \frac{\alpha_0}{2-\alpha_0}$ where $\alpha_0 = \varepsilon\delta\int_0^\infty (1+u)^{-3/2}(\varepsilon^2+u)^{-1/2}(\delta^2+u)^{-1/2}du$; $\varepsilon = b/a \quad \delta = c/a$				$\frac{4}{3}\pi abc$
Square prisms		Vertical	*b/a*	C_A			$a^2 b$
			1.0	0.68			
			2.0	0.36			
			3.0	0.24			
			4.0	0.19			
			5.0	0.15			
			6.0	0.13			
			7.0	0.11			
			10.0	0.08			

Body shape		*Direction of motion*	C_A		V_R
			$b/2a$	C_A	
Right circular cylinder		Vertical	1.2 2.5 5.0 9.0 ∞	0.62 0.78 0.90 0.96 1.00	$\pi a^2 b$

Added mass is $A_{ij} = \rho C_A V_R$ $[kg]$ where V_R $[m^3]$ is the reference volume.

Source: Hearn (1988)

APPENDIX G: CATENARY MOORING SYSTEM

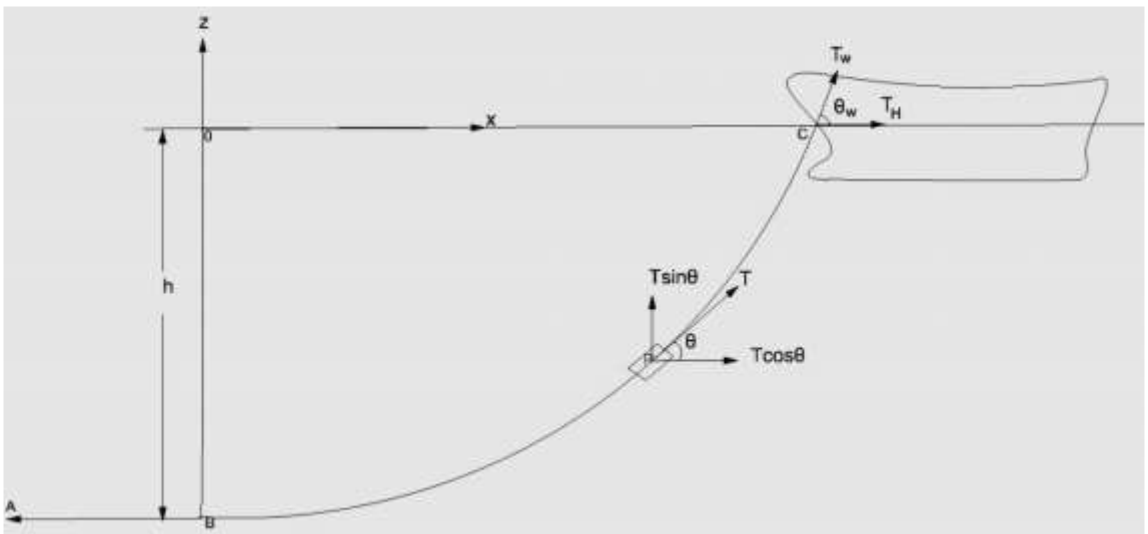


Figure G. 1: Single-point Mooring

$$C_{11} = w\left[cosh^{-1}\left(1+\frac{h}{a}\right) - 2\left(1+\frac{2a}{h}\right)^{-\frac{1}{2}}\right]^{-1} \qquad \text{(G.1)}$$

Therefore, the coefficient of the hydrostatic restoring force is a function of the weight per unit length of the mooring line, the horizontal component of the line tension and the water depth. This is required in the evaluation of surge response of a moored floating structure.

APPENDIX H: LIST OF PUBLICATIONS FROM THIS RESEARCH

[1] **Akandu, E.**, Incecik, A. and Barltrop, N. (2012) 'Design of Floating Production, Storage and Offloading Vessel for Safe Operations in Deep Sea', in *15th International HSE Biennial Conference on the Oil and Gas Industry in Nigeria* Abuja, Nigeria, 5th-7th November, 2012.,

[2] **Akandu, E.**, Incecik, A. and Barltrop, N. (2014) 'The Floating Production, Storage and Offloading Vessel Design for Deep Sea Oil field development', in *5th UK Marine Technology Postgraduate Conference (MTPC) 2014*, Newcastle, United Kingdom, 9th-10th June, 2014,

[3] **Akandu, E.**, Incecik, A. and Barltrop, N. (2014) *The Floating Production, Storage and Offloading Vessel Design for Oil Field Development in Harsh Marine Environment*, translated by Pekanbaru,

Indonesia: International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, OMAse, 7-12.

[4] **Akandu, E.**, Incecik, A. and Barltrop, N. (2014) *The Susceptibility of FPSO Vessel to Green Water in Extreme Wave Environment*, translated by Pekanbaru, Indonesia: International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, OMAse, 82-87.

[5] **Akandu, E.**, Incecik, A. and Barltrop, N. (2014) 'The Susceptibility of FPSO Vessel to Green Water in Extreme Wave Environment', *Journal of Ocean, Mechanical and Aerospace -science and engineering-(JOMAse)*, 14, 1-6.

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