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The Susceptibility of FPSO Vessel to Green Water in Extreme Wave Environment

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ABSTRACT

The Floating Production, Storage and Offloading (FPSO) vessels in harsh environment are often vulnerable to green water. Green water is the unbroken waves which overtop the bow, side or stern part of the deck of the floating offshore structure. It occurs when the relative motion between the vessel and the wave exceeds the freeboard. Green-water occurrence could lead to deck flooding and damage to deck-mounted equipment. It is therefore necessary to consider the vulnerability of the floating vessel to green water in the design stage. The objective 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. In order to achieve this, the effects of extreme environmental loads on the vessel have been evaluated in terms of the maximum responses in heave and pitch modes of motion. Furthermore, an interactive programme, the ProGreen has been designed to optimise the principal particulars based on the response and freeboard exceedance analyses for the required storage capacity of the FPSO. This design technique helps to prevent or reduce the green water occurrence, ensures good performance during operation and increases the level of safety and operability of the vessel even in extreme wave conditions.

KEY WORDS: *FPSO; Principal Dimensions; Green Water; Responses*.

NOMENCLATURE

ProGreen: Programme for Green Water Analysis

B	Breadth, Wave spectral parameter
a_3	Water particle vertical acceleration
T_z	zero up-crossing period
E_i	Freeboard exceedance of each FPSO vessel
ρ	Density of sea water
g	Acceleration due to gravity
RAO_R	Response amplitude operator of the relative motion
Mbbls	Million barrels of oil
z_m	Draught to Depth ratio
Γ	Gamma function

Other symbols are defined in the sections where they are used.

1.0 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, 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 [1]. 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 [2, 3]. 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 [4, 5].

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. 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 (L, B, T, 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 paper.

2.0 THEORETICAL ANALYSIS

2.1 The Principal Dimensions of the FPSO

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. These factors are directly related to (or functions of) cubic number, length-breadth (x_b) and breath-depth (y_d) ratios (as variables in the analyses) respectively. The cubic number is the overall volume of the vessel and it is directly proportional to the required storage capacity. With the knowledge of the oil storage efficiency, the cubic number and the preliminary evaluation of the principal dimensions can be made. The overall volume or the cubic numberC_n is given by:

$$C_n = \mathrm{LBD} = \frac{L^3}{{x_b}^2 \times y_d} = \frac{B^3}{[y_d/x_b]} = \frac{\mathrm{D}^3}{[x_b \times {y_d}^2]^{-1}} = \frac{\nabla}{(T/\mathrm{D})} = \left(\frac{S_c}{C_f \times E_s}\right) \quad (1)$$

From eqn. (1), it follows that:

$$\text{The Length, L} = aC_{nr} \quad (2)$$
$$\text{Breadth, B} = bC_{nr} \quad (3)$$
$$\text{Depth, D} = (\mathrm{ab})^{-1}C_{nr} \quad (4)$$
$$\text{Draught, T} = z_m\mathrm{D} \quad (5)$$

Where: The cubic number, $C_n$in m^3; and the cube root of the cubic number is given by: $C_{nr} = (C_n)^{1/3} = \left(\frac{S_c}{C_f \times E_s}\right)^{1/3}$

$\nabla$is the displacement; and the new dimensionless factors are: $a = [{x_b}^2 \times y_d]^{1/3}$; $b = [y_d/x_b]^{1/3}$; $z_m = \nabla/C_n$

S_c: Required oil storage capacity in barrel (bbl); E_s: Oil storage Efficiency; and Conversion factor, $C_f = 6.28981077; 6.28981077bbl = 1m^3$.

2.2 The Wave Environment

In offshore structural design, it is convenient to describe the wave environment in spectral form. The general form of the wave spectrum model is given by:

$$S(\omega) = A\omega^{-p}\exp(-B\omega^{-q}) \quad (6)$$

The parameters (A, B) of the Spectrum are solved in terms of the significant wave height and the wave period (which are in common use in wave description) for specified values of p and q (For Pierson-Moskowitz spectrum, p=5 and q=4). The nth moment of the spectrum which is very useful in obtaining the wave characteristics is expressed as:

$$m_n = \int_0^\infty \omega^n S(\omega)d\omega = \frac{A}{q}\left[\frac{\Gamma[(p-n-1)/q]}{B^{[(p-n-1)/q]}}\right] \quad (7)$$

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

By substituting the expressions for A and B, the modified version of the wave spectrum is therefore obtained as:

$$S(\omega) = 124\frac{{H_s}^2}{{T_z}^4}\omega^{-5}\exp[-496.1(\omega T_z)^{-4}] \quad (8)$$

The rectangular-shaped floating production, storage and offloading vessel with length L, Beam B and draught T, (which are evaluated based on the required storage capacity as given in eqns. 1-5) is 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.

The equation of motion of this vessel is given by:

$$(M_{jk} + A_{jk})\ddot{\eta}_k + d_{jk}\dot{\eta}_k + C_{jk}\eta_k = F_j \quad (9)$$

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 amplitudes of the wave exciting forces and moments, j and k indicate the directions of fluid forces and the modes of motions; η_k represents responses; $\dot{\eta}_k$ and $\ddot{\eta}_k$ are the velocity and acceleration terms; and ω is the angular frequency of encounter.

2.3 Heave Force and Response

Assuming the vessel has a constant mass density, zero forward speed and moored in deep sea, with a sinusoidal wave propagating along the negative x-axis (head sea),the velocity potential is:

$$\phi = g\frac{\zeta_a}{\omega}e^{kz}\cos(\omega t + kx) \quad (10)$$

The vessel is divided into strips of equal sizes and the force acting on each strip (dF_3) is the sum of the pressure force and the added mass force. These forces are integrated across the length of the vessel to obtain the heave excitation force.

$$dF_3 = pBdx + A_{33}^{(2D)}a_3dx = \left(-\rho\frac{\partial\phi}{\partial t}\right)Bdx + A_{33}^{(2D)}\left(\frac{\partial^2\phi}{\partial z\partial t}\right)dx$$

$$= \zeta_a\left(\rho gB - A_{33}^{(2D)}kg\right)e^{-kT}\sin(\omega t + kx)\,dx$$

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

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

Where $A_{33}^{(2D)}$ is the 2-D added mass in heave, while the amplitude of the heave force is given by:

$$F_{3a} = 2\zeta_a\left[\frac{\rho gB}{k} - A_{33}^{(2D)}g\right]\left(e^{-kT}\right)sin\left(\frac{kL}{2}\right)$$

$$= \rho g\zeta_a\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\left(e^{-kT}\right)\sin\left(\frac{kL}{2}\right) \quad (11)$$

Therefore, the Heave Response Amplitude Operator, RAO_3, defined as the heave amplitude per wave amplitude, is:

$$RAO_3 = \frac{F_{3a}Q_3}{C_{33}\zeta_a}$$

$$RAO_3 = \frac{\rho gQ_3}{C_{33}}\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\left(e^{-kT}\right)\sin\left(\frac{kL}{2}\right) \quad (12)$$

Q_3: Dynamic magnification factor in heave; λ: wavelength; c_v: virtual added mass coefficient in heave; ζ_a: wave amplitude; and wave number, $k = 2\pi/\lambda$.

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

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

Where $A_{33}^{(2D)}$ is the 2-D added mass in heave, while the amplitude of the heave force is given by:

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$$= \rho g\zeta_a\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\left(e^{-kT}\right)\sin\left(\frac{kL}{2}\right) \quad (11)$$

Therefore, the Heave Response Amplitude Operator, RAO_3, defined as the heave amplitude per wave amplitude, is:

$$RAO_3 = \frac{F_{3a}Q_3}{C_{33}\zeta_a} = \frac{\rho gQ_3}{C_{33}}\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\left(e^{-kT}\right)\sin\left(\frac{kL}{2}\right) \quad \ldots \ (12)$$

Q_3: Dynamic magnification factor in heave; λ: wavelength; c_v: virtual added mass coefficient in heave; ζ_a: wave amplitude; and wave number, $k = 2\pi/\lambda$.

2.4Pitching Moment and Response

The amplitude of the pitching moment has also been obtained following similar procedure and it is given by:

$$F_{5a} = \rho g\zeta_a\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\left(e^{-kT}\right)\frac{1}{k}\left[\frac{kL}{2}\cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \quad \ldots \ (13)$$

So, the Pitch Response Amplitude Operator, RAO_5, defined as the pitch response amplitude per wave amplitude, is:

$$RAO_5 = \frac{F_{5a}Q_5}{C_{55}\zeta_a}$$

$$= \frac{\rho gQ_5}{C_{55}}\left[\left(\frac{B\lambda}{\pi}\right) - c_v\pi\left(\frac{B}{2}\right)^2\right]\frac{1}{k}\left[\frac{kL}{2}\cos\left(\frac{kL}{2}\right) - sin\left(\frac{kL}{2}\right)\right] \quad (14)$$

$Q_5$is the dynamic magnification factor in pitch motion.

2.5 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 vesselat 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:

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

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

$$RAO_R = \left\{\left[RAO_3 - cos\left(\frac{kL}{2}\right)\right]^2 + \left[\frac{LRAO_5}{2} + \sin\left(\frac{kL}{2}\right)\right]^2\right\}^{1/2} \quad \ldots \ (15)$$

These 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 draftis required to be greater than thismaximum relative motion ($T > R$) in orderprevent the bow from exiting the water (bow slamming). Furthermore, a minimum freeboard, equivalent to R is needed to avoid green water on the deck.

The most probable maximum amplitude of the relative motion between the wave and the vessel at the bow is:

$$R = 3.72\sqrt{\int_0^\infty (RAO_R)^2 S(\omega)d\omega} \quad (16)$$

2.6 Freeboard Exceedance

The freeboard exceedance is the difference between the most probable relative motion and the freeboard. For each of the vessels being analysed (where i represents each of the vessels), it is given by:

$$E_i = R_i - (D_i - T_i) = R_i - (1 - z_m)(\mathrm{a}_i \mathrm{b}_i)^{-1}\left(\frac{S_c}{C_f \times E_s}\right)^{\frac{1}{3}} \quad (17)$$

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.

3.0 RESULTS AND DISCUSSIONS

To determine the optimal design point, it is necessary to examine the peak of the response amplitudes of motions, and the corresponding freeboard exceedances.

Figures- 1 and 2 show the response amplitude operators for the heave, pitch and relative motions. As the B/D and L/B ratios increase the peaks of the pitching and relative motions shift rightwards (on the graph of RAOs) approaching the critical period. A good example of critical period is the natural period of the vessel. The critical period is defined as the period at which the actual response is maximum (and it occurs when $\frac{L}{\lambda}$ tends to unity).

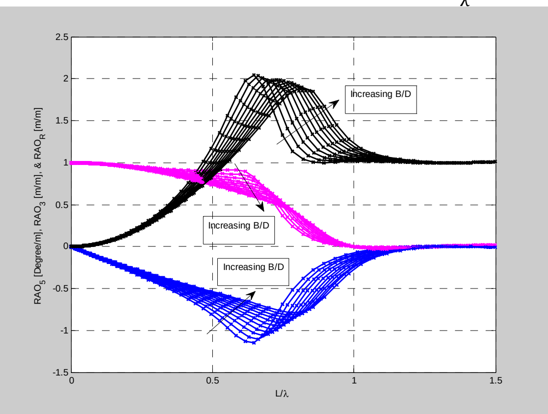

Figure 1: The Heave, Pitch, and Relative Motion Response Amplitude Operators for various B/D Ratios

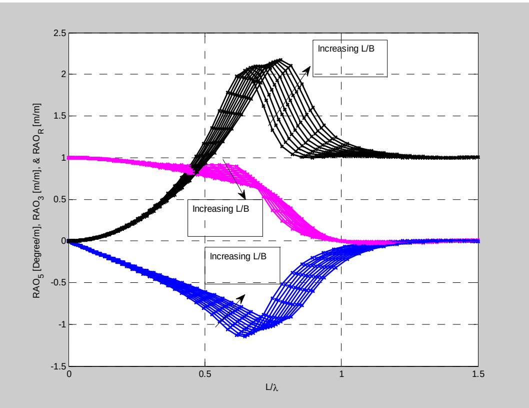

Figure 2: The Heave, Pitch, and Relative Motion Response Amplitude Operators for various L/B Ratios

As the B/D (and hence the "b" of eqn. 17) increases, the peak of the RAO_R decreases. Conversely, as L/B (and hence the "a" of eqn. 17) increases, the peak of the RAO_R also increases. In both cases, the freeboard exceedances increase (see Figs. 4 and 6).

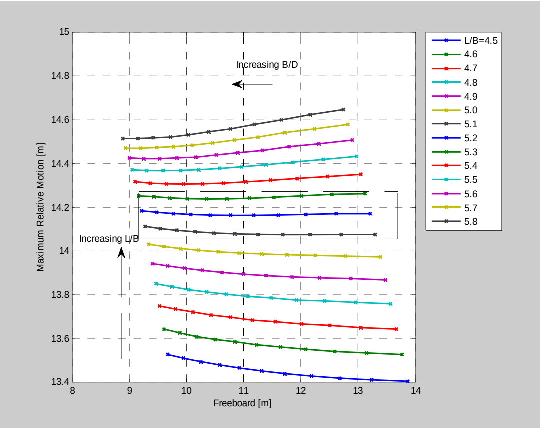

Figure 3: Effects of Freeboard on the Most Probable Maximum Relative Motion for given L/B

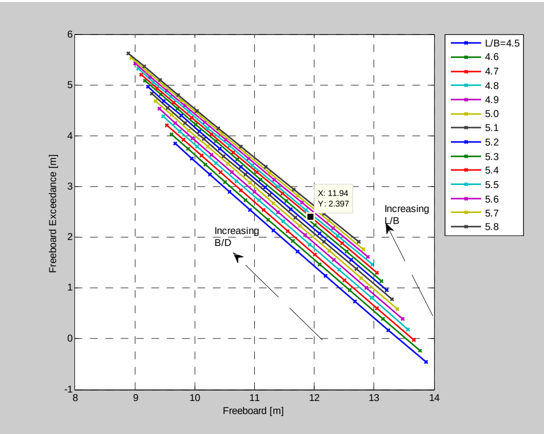

Figure 4: Effects of Freeboard on the Exceedance for given L/B

Figures 3 and 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.

The B/D has greater influence on the freeboard. The freeboard decreases more rapidly with increase in B/D (Figure 3), and slowly with increase in L/B (Figure 5).

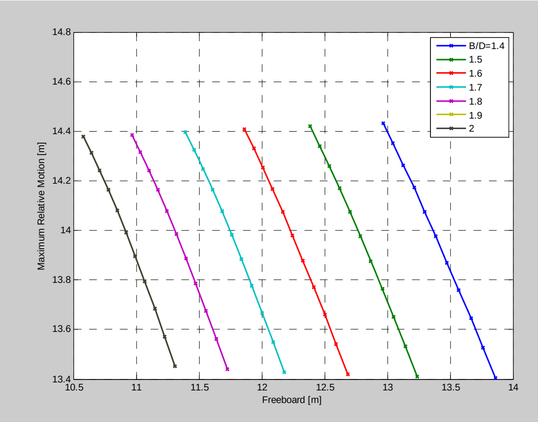

Figure 5: Effects of Freeboard on the Most Probable Maximum Relative Motion for given B/D

Generally, the exceedance is directly proportional to the pitch, heave and relative motions but inversely proportional to the freeboard. So, in order to avoid the vulnerability of the vessel to green water, the exceedance must be less or equal to zero.

$$L_a, B_a, D_a, T_a = L, B, D, T(E_i \leq 0) \quad (18)$$

Where the subscript, 'a' represents "avoidance of green water". The optimal design is obtained when the green water avoidance criterion is met with minimum heave and pitch motions.

$$L_o, B_o, D_o, T_o = L_a, B_a, D_a, T_a(\eta_{3max} \equiv \min(\eta_{3max})) \quad (19)$$

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

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 tables 1 and 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 4 for instance, the FPSO with L/B of 5.4, and B/D 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.

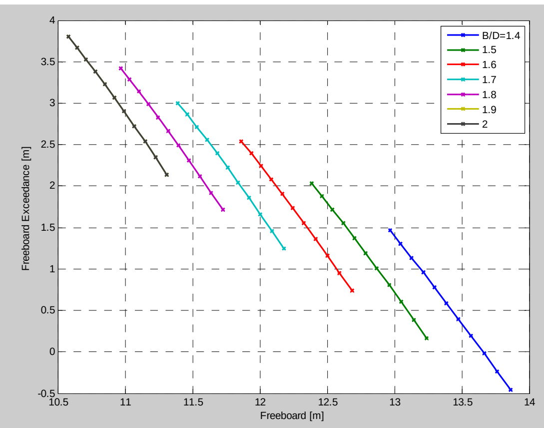

Figure 6: Effects of Freeboard on the Exceedance for given B/D

Table 1: Green Water Susceptibility of 2Mbbl North Sea FPSOs

S/No	L/B	B/D	L	B	D	Freeboard	Constraint	Exeedance
			[m]	[m]	[m]	D-T	D-T-R>0	E=R-(D-T)
1	4.5	1.4	249.5586	55.4575	39.6125	13.8644	0.4608	-0.4608
2	4.5	1.5	255.3643	56.7476	37.8318	13.2411	-0.1701	0.1701
3	4.5	1.6	260.9175	57.9817	36.2385	12.6835	-0.7364	0.7364
4	4.5	1.7	266.2438	59.1653	34.8031	12.1811	-1.2485	1.2485
5	4.5	1.8	271.3651	60.3034	33.5019	11.7257	-1.7147	1.7147
6	4.5	1.9	276.3001	61.4	32.3158	11.3105	-2.1417	2.1417
7	4.5	2	281.0648	62.4588	31.2294	10.9303	-2.5348	2.5348
8	4.5	2.1	285.6733	63.4829	30.23	10.5805	-2.8985	2.8985
9	4.5	2.2	290.1376	64.475	29.3068	10.2574	-3.2367	3.2367
10	4.5	2.3	294.4687	65.4375	28.4511	9.9579	-3.5522	3.5522
11	4.5	2.4	298.6759	66.3724	27.6552	9.6793	-3.8479	3.8479
12	4.6	1.4	253.2422	55.0526	39.3233	13.7632	0.2369	-0.2369
13	4.6	1.5	259.1336	56.3334	37.5556	13.1445	-0.3893	0.3893
14	4.6	1.6	264.7687	57.5584	35.974	12.5909	-0.9511	0.9511
15	4.6	1.7	270.1737	58.7334	34.5491	12.0922	-1.4589	1.4589
16	4.6	1.8	275.3706	59.8632	33.2573	11.6401	-1.9209	1.9209
17	4.6	1.9	280.3784	60.9518	32.0799	11.228	-2.3439	2.3439
18	4.6	2	285.2135	62.0029	31.0015	10.8505	-2.7333	2.7333
19	4.6	2.1	289.8899	63.0195	30.0093	10.5033	-3.0936	3.0936
20	4.6	2.2	294.4202	64.0044	29.0929	10.1825	-3.4284	3.4284
21	4.6	2.3	298.8152	64.9598	28.2434	9.8852	-3.7408	3.7408
22	4.6	2.4	303.0845	65.8879	27.4533	9.6087	-4.0335	4.0335
23	4.7	1.4	256.8992	54.6594	39.0424	13.6649	0.0199	-0.0199
24	4.7	1.5	262.8757	55.931	37.2873	13.0506	-0.6012	0.6012
25	4.7	1.6	268.5922	57.1473	35.717	12.501	-1.1582	1.1582
26	4.7	1.7	274.0752	58.3139	34.3023	12.0058	-1.6614	1.6614
27	4.7	1.8	279.3471	59.4356	33.0198	11.5569	-2.119	2.119
28	4.7	1.9	284.4273	60.5164	31.8508	11.1478	-2.5379	2.5379
29	4.7	2	289.3322	61.56	30.78	10.773	-2.9233	2.9233
30	4.7	2.1	294.0762	62.5694	29.7949	10.4282	-3.2799	3.2799
31	4.7	2.2	298.6718	63.5472	28.8851	10.1098	-3.6112	3.6112
32	4.7	2.3	303.1303	64.4958	28.0417	9.8146	-3.9204	3.9204
33	4.7	2.4	307.4613	65.4173	27.2572	9.54	-4.21	4.21
34	4.8	1.4	260.5303	54.2772	38.7694	13.5693	-0.1901	0.1901
35	4.8	1.5	266.5913	55.5399	37.0266	12.9593	-0.8059	0.8059
36	4.8	1.6	272.3886	56.7476	35.4673	12.4135	-1.3577	1.3577
37	4.8	1.7	277.9491	57.9061	34.0624	11.9218	-1.856	1.856
38	4.8	1.8	283.2956	59.0199	32.7888	11.4761	-2.309	2.309
39	4.8	1.9	288.4475	60.0932	31.628	11.0698	-2.7235	2.7235
40	4.8	2	293.4217	61.1295	30.5648	10.6977	-3.1048	3.1048
41	4.8	2.1	298.2328	62.1318	29.5866	10.3553	-3.4575	3.4575
42	4.8	2.2	302.8934	63.1028	28.6831	10.0391	-3.7852	3.7852
43	4.8	2.3	307.4149	64.0448	27.8456	9.7459	-4.091	4.091
44	4.8	2.4	311.8071	64.9598	27.0666	9.4733	-4.3775	4.3775
102	5.4	1.6	294.6393	54.5628	34.1018	11.9356	-2.3965	2.3965
154	5.8	2.4	353.7343	60.9887	25.4119	8.8942	-5.62	5.62

Table 2: Optimal Design for North Sea FPSO using ProGreen

L_o [m]	B_o [m]	D_o [m]	T_o [m]
256.8992	54.6594	39.0424	25.3776

4.0 CONCLUSIONS

(i) The most probable maximum relative motion is greatly influenced by selected L/B ratio while the freeboard is highly influenced by the B/D ratio.
(ii) The freeboard exceedance increases with both L/B and B/D ratios.

(iii) The optimal design is favoured by larger depths (or lower L/B and B/D ratios) which ensure that there are both sufficient freeboard and disparity from the critical wavelength.
(iv) Theoptimal design of FPSO for oil field development in extreme wave environment such as the North Sea is necessary to avoid green water on deck and its adverse effects.
(v) The optimal dimensions for 2Mbbls of oil storage capacity FPSO are: Length is 3.139 of C_{nr} (or 256.9m); Beam of 66.8% of C_{nr} (or 54.7m); and Depth of not less than 47.7% of C_{nr} (or 25.4m). That is, L/B and B/D ratios of 4.7 and 1.4 respectively.

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