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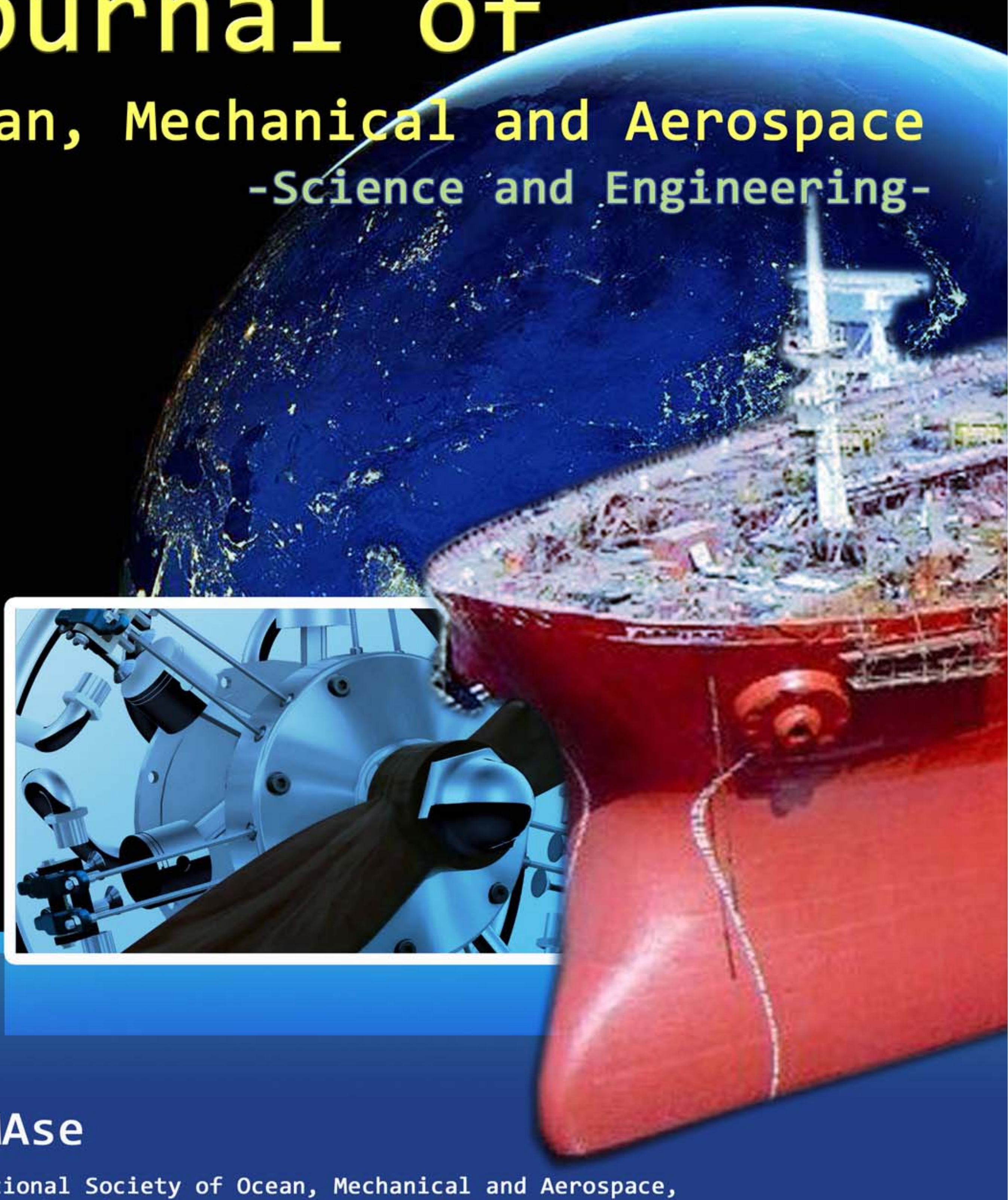

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Slamming Analysis on a 35,000 Ton Class of Drillship

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ABSTRACT

Slamming is a phenomenon that occurs on floating structures. Drillship as floating structures have slamming when moving at a certain speed which resulted in the movement of relative vertical bow that exceeded full of water of the bow. This paper was performed on the drillship 35000 tons with variants of speed is 7 knots, 12 knots, 13 knots and 14 knots. The first stage taken was the design of the drillship structures by using *Maxsurf* in order to get lines plan. After the offset data of drillship has been obtained, modeling followed by *Hydrostar* to get the heave and pitch motion RAO's from head seas. The result of RAO is used to analyze the relative vertical motion of the bow in the form of RAO as well. That result is used to analysis of structural response by multiplying the wave spectra ITTC/ISSC. From these calculations will be known slamming parameters that can generate the probabilities, intensity and pressure of slamming on the drillship 35000 tons. Probabilities, intensities and pressure of slamming, the maximum occures while the drillship moving on 14 knot of speed, ie. each of 0.483 times, 124.451 times/hour and 492,232 kPa at 15 m of significant wave height.

KEY WORDS: *Drillship, RAO, Slamming*

NOMENCLATURE

S_R	Spectrum Respons
RAO	Respon Amplitude Operator
ω	Wave Frequency
$S(\omega)$	Wave Spectrum
Pr	The Relative Probabilities of Upraised The Bow
Z_{br}	Relative Motion of The Bow (m)
T_b	Water Level on The Bow (Position Slamming Reviewed)
V_{br}	Relative Vertical Velocity of The Bow
V_{th}	Threshold Velocity of Slamming
m_{oZbr}	The Area Under The Response of Relative Vertical Offset of The Bow
m_{oVbr}	The Area Under The Response of Relative Vertical Velocity of The Bow
N_{slam}	Intensity of Slamming
Ps	Pressure of Slamming
ρ	Density
k	Slamming Coefficient

1.0 INTRODUCTION

Drillship is a vessel which has function as an offshore exploration drilling in oil and gas operation. It has a capability of drilling at depths of more than 2500 meters. Drillship has more flexibility than other offshore drilling vessel, because it can transit from site to site in short time relatively. In transit condition, drillship usually in high speed and high wave elevation condition. Relativity between drillship motion and wave elevation will give a hydrodynamic impact. It produce the structural response in bow of drillship, usually called slamming [1].

Slamming is a phenomenon due to the head wave excitation which is interacted by ship bow. Slamming will be happened when the water level as impact of head wave excitation more than the draught of the ship and/or the relative velocity of vertical direction has a bigger value than threshold velocity. The safety of structure in operation condition will be affected by slamming condition [2]. As a slender ship, drillship can be got a significant impact on the bow section. The impact will become higher when the speed of drillship is increased gradually [3]. Slamming occurs more frequently especially with huge waves.

Characteristics of the bow motion to review slamming incident is conducted by observing the motion of coupling heave and pitch on the bow. The couple motion is use to get spectra response drillship on the bow by multiplying square of the coupling motion heave RAO and pitch against wave spectrum. For the purposes of analysis, calculation of response spectra use the distribution of water waves infinite ABS 2010 [3], while the wave spectrum used is ITTC/ISSC [2]. Then, the results of spectral response can be used to calculate the characteristic that occur in the drillship slamming with a certain speed.

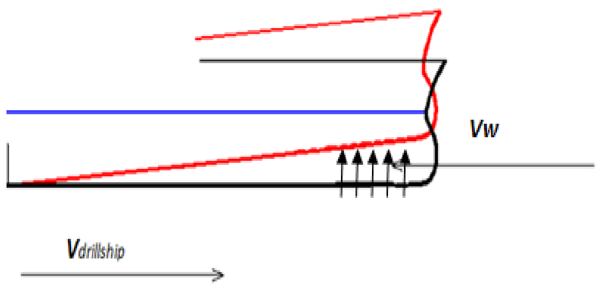

Figure 1: The phenomenon of slamming

Figure 1 illustrates how to slamming incident in this analysis. V_w represents wave velocity, it come from head seas and $V_{drillship}$ symbolizes speed of drillship.

2.0 METHODS OF RESEARCH

The stags which used in this paper are numerical methods which refer to ship motion analysis. Coherently, it will be described in the following sub-subtitle:

2.1 Data Collection

The first primary data for this study is the reference ship, namely the drillship *Oribis One* as made available by Fossli and Hendriks [4]. In this data, new drillship had designed as reported in ref [1]. The general arrangement is exhibited in Figure 1 with principal particulars as presented in Table 1. More details about these data can be seen in the following data. The general arrangement is exhibited in Figure 2 and Figure 3 with principal particulars as presented in Table 1.

Table 1: Principal Dimension of Drillship

Parameter(unit)	Value
Displacement (ton)	35,193.0
Lpp (m)	156.0
B (m)	29.9
H (m)	15.6
T (m)	9.0
LCB to Midship (m)	3.265
LCF to Midship (m)	-7.203
KM_T (m)	13.29
KM_L (m)	222.82
BM_T (m)	8.64
BM_L (m)	218.17

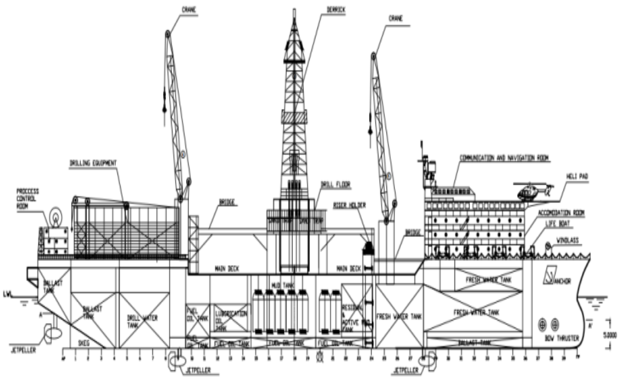

Figure 2: Drillship with a displacement of 35000 tons [1]

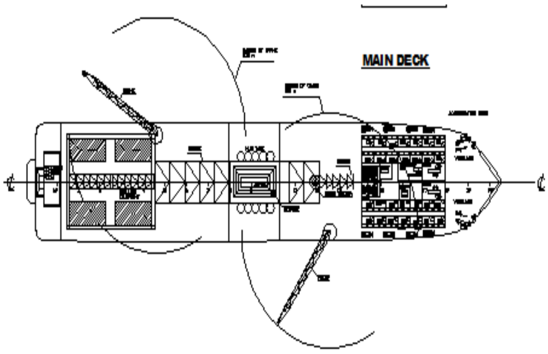

Figure 3: Drillship with a displacement of 35000 tons, top view [1]

The next data is related to the environment regarded as the primary source of excitation. The wave distribution data has been obtained from ABS in 2010 [3], related to the world wave scatter diagram, as contained in Table 2. On the basis of this data, wave spectral analysis is calculated as the increasing of Hs can seen in Figure 4.

	Wave period (s)											
Wave Height (m)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	Sum Over All Periods
0.5	8	260	1344	2149	1349	413	76	10	1	0	0	5610
1.5		55	1223	5349	7569	4788	1698	397	69	9	1	21158
2.5		9	406	3245	7844	7977	4305	1458	351	65	10	25670
3.5		2	113	1332	4599	6488	4716	2092	642	149	28	20161
4.5			30	469	2101	3779	3439	1876	696	192	43	12625
5.5			8	156	858	1867	2030	1307	564	180	46	7016
6.5			2	52	336	856	1077	795	390	140	40	3688
7.5			1	18	132	383	545	452	247	98	30	1906
8.5				6	53	172	272	250	150	65	22	990
9.5				2	22	78	136	137	90	42	15	522
10.5				1	9	37	70	76	53	26	10	282
11.5					4	18	36	42	32	17	7	156
12.5					2	9	19	24	19	11	4	88
13.5					1	4	10	14	12	7	3	51
>14.5					1	5	13	19	19	13	7	77
	8	326	3127	12779	24880	26874	18442	8949	3335	1014	266	100000

Figure 4: Unrestricted worldwide wave data [3]

2.2 Design Model of the 35000 tons Drillship

Drillship design is completed by software which based on panel method and 3D diffraction to get a plan with regard principal lines dimension drillship in accordance with the actual data. Figure 5 is represented lines plan dimension of drillship with the actual data.

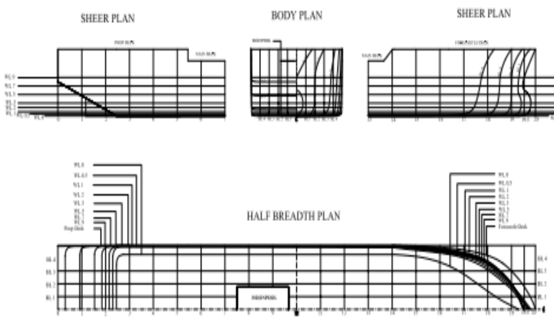

Figure 5: Lines plan of drillship [5]

Validation was performed to compare the existing hydrostatic with hydrostatic results in numerical models of drillship. Tolerance on this validation is less than 5%. Table 2 shows the results of validation model with the data existing hydrostatic. These results will be used for further analysis.

Table 2: Validation of model with the data

Parameter	Data	Hydrostar	Difference (%)
Displacement (ton)	35,193.0	35,421.7	0.65
Lpp (m)	156.0	156.0	0.00
B (m)	29.9	29.9	0.00
H (m)	15.6	15.6	0.00
T (m)	9.0	9.0	0.00
LCB to Midship (m)	3.265	3.270	0.15
LCF to Midship (m)	-7.203	-7.164	0.54
KM_T (m)	13.29	13.33	0.30
KM_L (m)	222.82	223.21	0.17
BM_T (m)	8.64	8.68	0.41
BM_L (m)	218.17	218.55	0.18

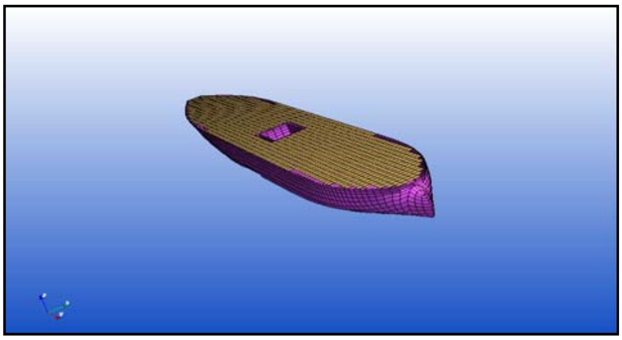

Figure 6: Modelling result with *hydrostar*

Numerical modeling with regard of displacement parameters, water level, the angle of incidence wave, COG coordinates and speed of drillship are computed by using *Hydrostar* software. Figure 6 shown the *Hydrostar* modelling of drillship in SWL condition. The purpose of this modeling is to obtain a model that fits with the data structure. Response Amplitude Operator (RAO) of heave and pitch motions for head seas wave direction had obtained to get the analysis of responses in random waves.

2.3 Motion Analysis

This paper was performed by *Hydrostar* to obtain Response Amplitude Operator (RAO) of heave and pitch motions for head seas wave direction. Results of the analysis of responses are used in the analysis of random waves.

Wave spectrum calculation is used spectra ITTC / ISSC for unrestricted water is required as a condition of the environment in where the drillship operations. Response spectra obtained by multiplying square of the relative vertical RAO bow wave spectrum [2, 6, 7].

$$S_R = [RAO(\omega)]^2 S(\omega) \tag{1}$$

From the response spectra analysis can be searched variants relative velocity response spectra (m_{0Vbr}) and response of the drillship movement (m_{0Zbr}) to calculate slamming criteria.

2.4 Calculation of Slamming

The probabilities of slamming are obtained by using the equation 2 [6,7]:

$$\Pr\,(Z_{br}>T_{b\ dan}V_{br}>V_{th}) = \text{eks}\left(-\frac{{T_b}^2}{2m_{ozbr}} - \frac{{V_{th}}^2}{2m_{oVbr}}\right) \tag{2}$$

The value of m_{0Zbr} and m_{0Vbr} are generated from calculation in the step of response spectra analysis. The results of the calculation of the probabilities of slamming are used in equation intensity of slamming as equation 3:

$$N_{slam} = \frac{1}{2\pi}\sqrt{\frac{m_{2Zbr}}{m_{0Zbr}}}\,x\exp\left(-\frac{{T_b}^2}{2m_{0Zbr}} - \frac{{V_{th}}^2}{2m_{2Zbr}}\right)1/sec \tag{3}$$

Amount of pressure which occurs at the bow base of the vessel due to slamming can be calculated by considering the relative speed of the vertical bow extreme V_{br}. Relative speed V_{br} extreme vertical direction can be calculated by the equation 4 and the last one slamming pressure can be calculated by equation 5:

$$V_{br} = 2x\ln\left\{\frac{3600xT_0}{2\pi}\exp\left(-\frac{{T_b}^2}{2m_{0Zbr}} - \frac{{V_{th}}^2}{2m_{2Zbr}}\right)\right\}\sqrt{\frac{m_{4Vbr}}{m_{2Vbr}}x\sqrt{m_{2Vbr}}} \tag{4}$$

$$p_s = \rho k \times \ln\left\{\frac{3600\,T_0}{2\pi}\exp\left(-\frac{T_b^2}{2m_{0Zbr}} - \frac{V_{th}^2}{2m_{2Zbr}}\right)\right\}\sqrt{\frac{m_{4Zbr}}{m_{2Zbr}}} \times m_{2Zbr} \tag{5}$$

3.0 RESULTS AND DISCUSSION

3.1 Analysis of behavior motion drillship on transit conditions

This analysis is assisted by *Hydrostar software*, which transit conditions means that the drillship is moving with speeds. In this case, speed variations are 7 knots, 12 knots, 13 knots and 14 knots. For slamming analysis purposes, the coupled motion are heave and pitch motions. Head seas will be reviewed wave direction in this study.

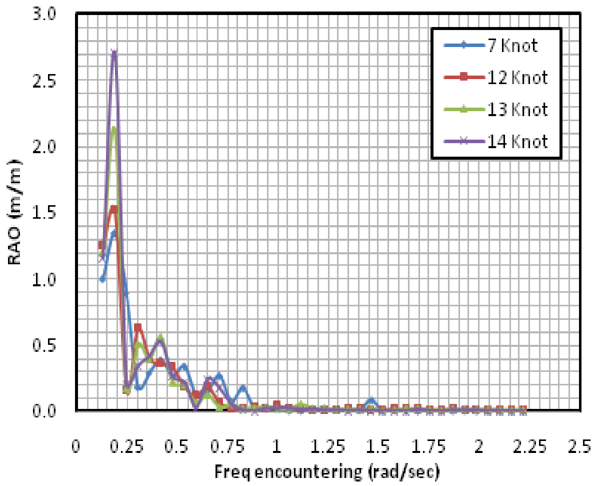

Figure 7: Heave RAO

Figure 7 represented heave RAO motion at the speed of 14 knots, which RAO peak occurs at low frequency 0.187 rad/s is 2.702 m/m. As for the pitch motion mode is shown in Figure 8.

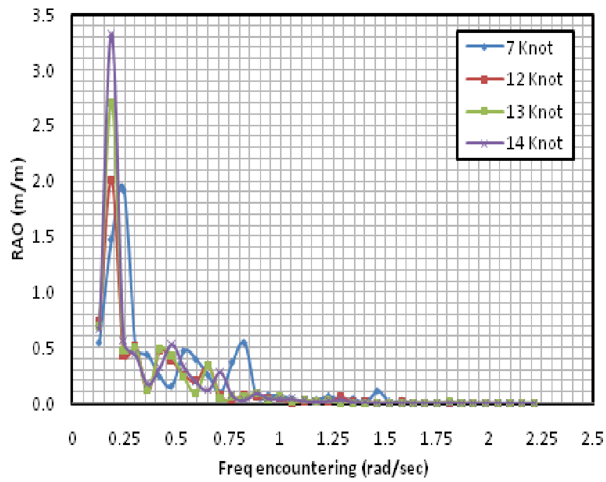

Figure 8: Pitch RAO

Pitch RAO motion reaches the highest point when the drillship has speed of 14 knots. Maximum RAO occurs at low frequency, it is about 0.187 rad/s in 3.33 deg/m.

After RAO of heave and pitch motions are obtained, the next step is calculate the vertical motion of the bow of drillship with point of view within 82.76 m of COG. The vertical relative motion of bow is obtained in the form of RAO as shown in a Figure 9.

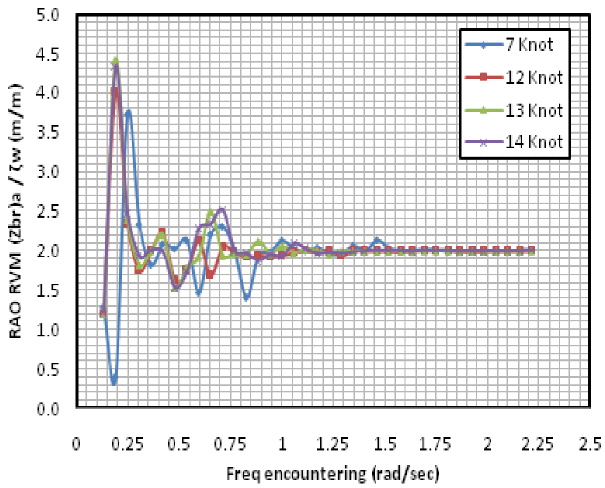

Figure 9: RAO relatively vertical bow

The result of relative vertical bow is combined with wave spectra ITTC/ISSC to get the response with significant wave height variation (Hs) is 3 m, 7 m, 11 m, 13 m and 15 m. Figure 10 illustrates the wave spectra using ITTC/ISSC form and unrestricted world wave data. Figure 11 up to Figure 14 show the response spectra of drillship with speed variation. The speed variation is 7 knot, 12 knot, 13 knot and 14 knot.

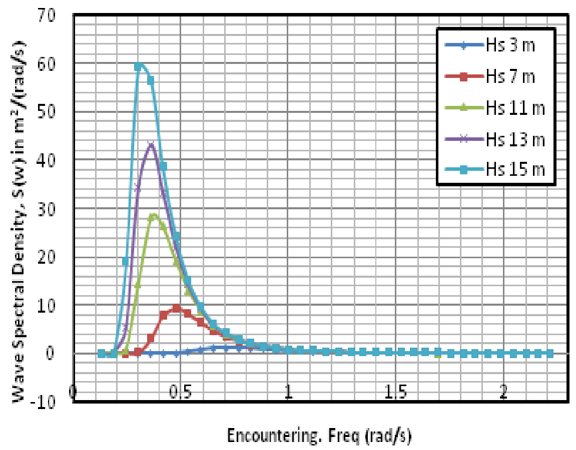

Figure 10: Spectra of ITTC/ISSC

Response spectra is obtained by multiplying square of relative vertical motion on the bow with wave spectra, in order to obtain results in the form of the response spectrum relative velocity spectra variants and vertical direction relative acceleration response spectra of vertical bow. These results are used for the calculation of slamming analysis.

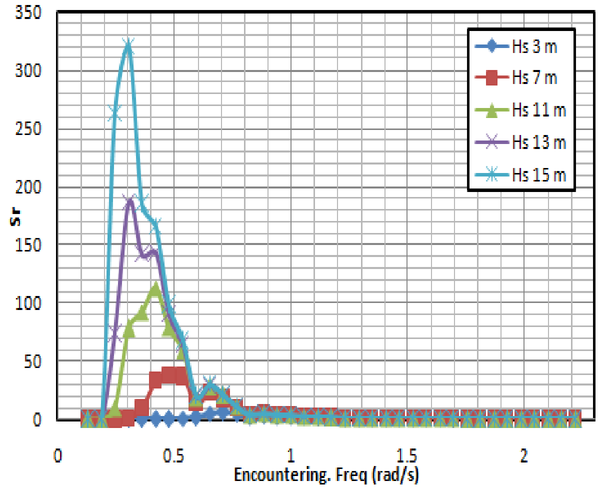

Figure 11: Response spectra of relative vertical motion on bow, 7 knot

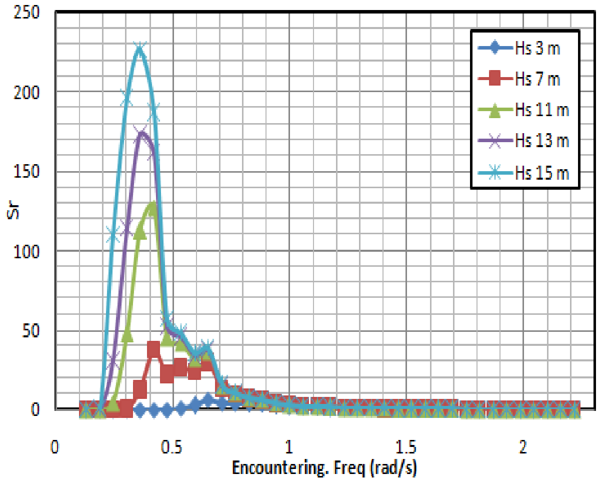

Figure 13: Response spectra of relative vertical motion on bow, 13 knot

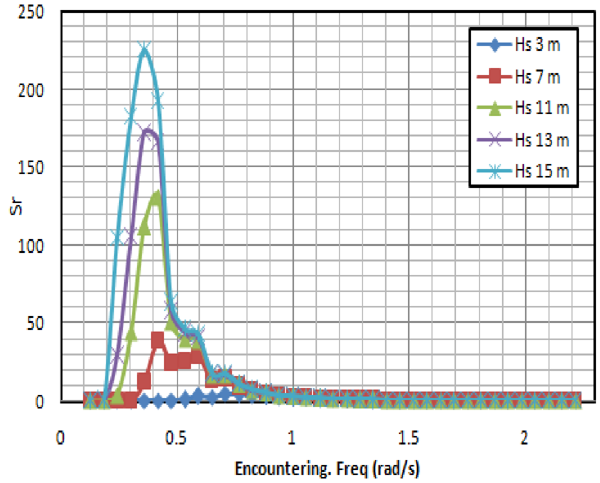

Figure 12: Response spectra of relative vertical motion on bow, 12 knot

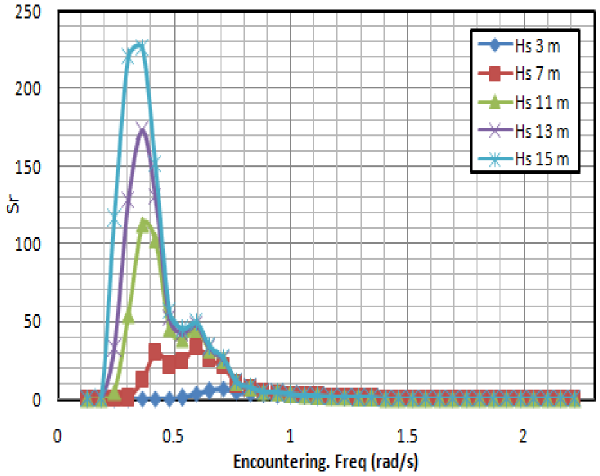

Figure 14: Response spectra of relative vertical motion on bow, 14 knot

Figure 11 illustrates vertical relative response spectra on the condition in speed of 7 knots. Maximum condition occurs at a frequency of 0.303 rad/s which has up to 320.25 (m^2/(rad/s)) at 15 m of Hs. Figure 12 provides vertical relative response spectra on the condition of 14 knots. Maximum condition occurs at a frequency of 0.361 rad/s which has up to 225.668 (m^2/(rad/s)) at 15 m of Hs. In terms of wave energy spectra, area under the curve is more important factor than the height [2].

Figure 13 shows vertical relative response spectra on the condition in speed of 13 knots with Hs variant 3 m, 7 m, 11 m, 13 m and 15 m. Maximum condition occurs at a frequency of 0.361rad/s which has up to 226.38 (m^2/(rad/s)) at 15 m of Hs. Figure 14 illustrates vertical relative motion of the bow on the condition of 14 knots. Maximum occurs at a frequency of 0.361 rad/s which has up to 226.40 m at 15 of Hs.

After getting acquiring the value of the relative response spectra of each speed and wave height. The calculation of slamming, threshold velocity used is V_{th} = 0.5 m/s in accordance with the provisions [8]. The results of calculations for the probabilities, intensities and pressures of slamming can be seen in Table 3.

Table 3: Result of slamming criteria analysis

Speed (Knot)	Hs (m)	Prob. (m)	Intensity (times/hour)	Pressure (kPa)
7	3	0.000	0.001	134.994
	7	0.010	6.799	254.754
	11	0.186	60.148	338.706
	13	0.283	87.112	383.047
	15	0.361	105.990	425.797

Table 3: Result of slamming criteria analysis (continue)

Speed (Knot)	Hs (m)	Prob. (m)	Intensity (times/hour)	Pressure (kPa)
12	3	0.000	0.000	137.712
	7	0.028	10.595	265.658
	11	0.209	71.382	368.889
	13	0.333	98.932	420.918
	15	0.441	118.985	470.459
13	3	0.000	0.000	141.389
	7	0.032	12.256	274.095
	11	0.227	72.978	377.529
	13	0.351	100.307	429.434
	15	0.465	121.940	483.991
14	3	0.000	0.000	143.714
	7	0.034	12.959	278.324
	11	0.247	75.132	386.674
	13	0.372	103.734	439.990
	15	0.483	124.451	492.232

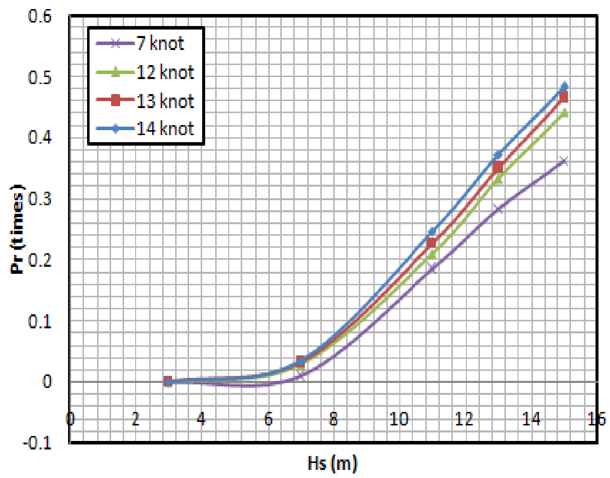

Figure 15: Slamming probability of drillship

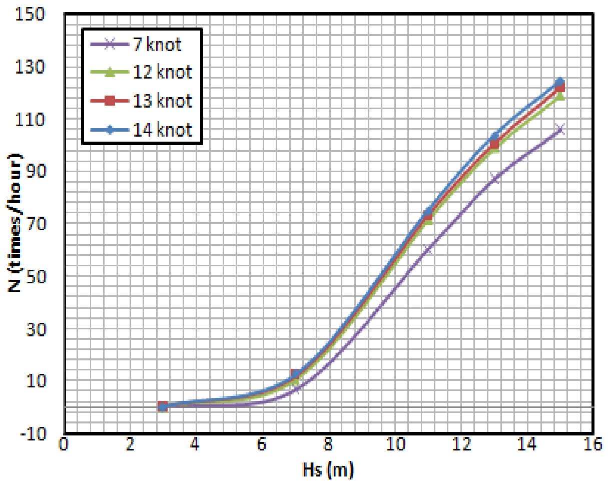

Figure 16: Slamming intensity of drillship

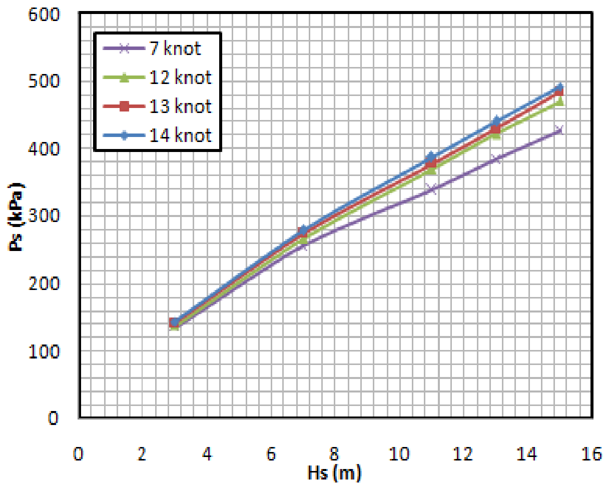

Figure 17: Slamming pressure of drillship

Table 3 describes the slamming criteria on the 35000 tons drillship, it can be seen that the probability of slamming occurs in transit condition with a maximum speed of 7 knots occur on 15 m Hs which is equal to 0.36times. while in transit at speeds of 14 knots, the probability of maximum slamming occurs on 15 m Hs which is equal to 0.483 m. whereas if it is based on the speed of transit, it can be seen that the maximum slamming probability at 14 knot of speed.

Slamming intensity in transit condition with 7 knot speed is occur on 15 meter Hs with 105.99 time/hour. Whereas it is reviewed by maximum speed of drillship with 14 knot, maximum slamming intensity is obtained. It is about 124.451 times/hour.. Meanwhile, by observing the speed of transit, it can be seen that the intensity of the maximum slamming occurs at 14 knot of speed.

Slamming pressure in transit condition with 7 knot speed is occured on 15 meter Hs with 425.797kPa. Whereas it is reviewed by maximum speed of drillship with 14 knot, maximum slamming pressure is obtained. It is about 492.232 kPa. Meanwhile, by observing the speed of transit, it can be seen that the intensity of the maximum slamming occurs at 14 knot of speed.

4.0 CONCLUSION

RAO relatively vertical of bow, the maximum occurs when drillship transit with a speed of 14 knots is 4,232 m/m. By using wave spectra ITTC/ISSC , result obtained the biggest probability of slamming when drillship transit with a speed of 14 knots is 0.483 times at 5 m Hs. Whereas the intensity and slamming pressure, the maximum occurs when drillship transit with a speed of 14 knots which is 124.451 times/hour and 492.232 kPa at 15 m Hs.

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Theoretical Review on Prediction of Motion Response using Diffraction Potential and Morison

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ABSTRACT

This paper reviewed the capability of the proposed diffraction potential theory with Morison Drag term to predict the Round Shape FPSO heave motion response. From both the self-developed programming code and ANSYS AQWA software, it can be observed that the diffraction potential theory is over predicting the Round Shape FPSO heave motion response when the motion is dominated by damping. In this study, Morison equation drag correction method is applied to adjust the motion response predicted by diffraction potential theory. This paper briefly present the procedure to integrate the Morison equation drag term correction method with the diffraction potential theory and then, the proposed numerical method was applied to simulate the Round Shape FPSO heave motion response. From the comparison, it can be concluded that Morison equation drag correction method is able to estimate the FPSO heave response in the damping dominated region and provides more reasonable motion tendency compare to the diffraction potential theory without consider the drag effect in the calculation.

KEY WORDS: *Wave Response, Diffraction Potential, Damping Correction, Morison Theory.*

NOMENCLATURE

$\Phi(x, y, z)$	VelocityPotential in x, y, z directions
$G(P; Q)$	GreenFunction
F_D	Drag Force
R	Horizontal Distance
K	Wave Number

1.0 INTRODUCTION

This paper is targeted to review the accuracy of correction methods applied at the diffraction potential theory in order to evaluate the motion response of offshore floating structure.The diffraction potential theory estimates wave exciting forces on the floating body based on the frequency domain and this method can be considered as an efficient one to study the motion of large size floating structure with acceptable accuracy. The accuracy of the diffraction potential method to predict the structures response was also detailed studied. The good accuracy of this diffraction theory applied to large structures is due to the significant diffraction effect that exists in the large size structure in wave [4].

In this study, the motion response of a selected Round Shape FPSO is simulated by self-developed programming code based on diffraction potential theory with Morison damping correction method. The accuracy of this programming code was checked with the previous semi-submersible experiment result which carried out at the towing tank belong to Universiti Teknologi Malaysia [5].

Besides, the behavior or Round Shape FPSO was also studied by Lamport and Josefsson in year 2008. They were carried a research to study the advantage of round shape FPSO over the traditional ship-shape FPSO [1]. The comparisons were made to compare motion response, mooring system design, constructability and fabrication, operability, safety and costing between both the structures. One of the finding on their study is the motions of their designed structures are similar at any direction of incident wave with little yaw excitation due to mooring and riser asymmetry. Next, Arslan, Pettersen, and Andersson (2011) are also performed a study on fluid flow around the round shape FPSO in side-by-side offloading condition. FLUENT software was used to simulate three dimensional (3D) unsteady cross flow pass a pair of ship sections in close proximity and the behavior of the vortex-shedding around the two bluff bodies [2].Besides, simulation of fluid flow Characteristic around Rounded-Shape FPSO by self-develop programming code based on RANs method also conducted by A. Efi et al.[3].

As presented by Siowet al. [6], their finding found that the diffraction potential theory is less accurate to predict the floating structure heave motion response when the wave frequency is close to the structure's natural frequency. In this situation, the heave response calculated by the diffraction potential theory is significantly higher compared to experimental result due to the low damping represented by the theory [9].

In order to improve the heave motion predict by the diffraction potential theory, Siow et al. tried to increase the damping coefficient by adding viscous damping into the motion equation. In his study, the viscous damping is treated as an extra matrix and can be added into the motion equation separately [6]. Besides,Siow et.al. also tried to integrate the linearized Morison drag equation with diffraction potential theory. The linear Morison drag equation would modify both the damping term and exciting force in the motion equation compared to the viscous damping correction method which only modified the damping term in motion equation. The accuracy of the modification solutions are also checked with the semi-submersible experiment result which was carried out at the towing tank of the UniversitiTeknologi Malaysia [10].

The 6-DOF Round Shape FPSO motion result calculated by this method and the comparison of result between the proposed methods with experiment result was published by Siow et.al in year 2015 [11]. In this paper, thetheoretical numerical calculation result of Round Shape FPSO using Diffraction Potential and Morison was reviewed. The result was compared to the original diffraction potential calculation method and the result obtained from ANSYS Software. Since the diffraction potential theory is only modified to the heave motion equation, hence the discussion in this paper only focused to the heave motion response.

2.0 NUMERICAL CALCULATION

2.1 Diffraction Potential

In this study, the diffraction potential method was used to obtain the wave force act on the Round Shape FPSO also the added mass and damping for all six directions of motions. The regular wave acting on floating bodies can be described by velocity potential. The velocity potential normally written in respective to the flow direction and time as below:

$$\Phi(x,y,z) = Re\left[\phi(x,y,z)e^{iwt}\right] \quad (1)$$

$$\phi(x,y,z) = \frac{g\varsigma_a}{iw}\{\phi_0(x,y,z) + \phi_7(x,y,z)\} + \sum_{j=1}^{6} iwX_j\phi_j(x,y,z) \quad (2)$$

where,

g	: Gravity acceleration
ς_a	: Incident wave amplitude
X_j	: Motions amplitude
ϕ_0	: Incident wave potential
ϕ_7	: Scattering wave potential
ϕ_j	: Radiation wave potential due to motions
j	: Direction of motion

From the above equation, it is shown that total wave potential in the system is contributed by the potential of the incident wave, scattering wave and radiation wave. In addition, the phase and amplitude of both the incident wave and scattering wave areassumed to be the same. However, radiation wave potentials are affected by each type of motions of each single floating body in the system, where the total radiation wave potential from the single body is the summation of the radiation wave generates by each type of body motions such as surge, sway,heave,roll, pitch and yaw,

Also, the wave potential $\emptyset$ must be satisfied with boundary conditions as below:

$$\nabla^2\emptyset = 0 \quad for\ 0 \le z \le h \quad (3)$$

$$\frac{\partial\emptyset}{\partial z} + k\emptyset \quad at\ z = 0 \quad (k = \frac{w^2}{g}) \quad (4)$$

$$\frac{\partial\emptyset}{\partial z} = 0 \quad at\ z = h \quad (5)$$

$$\emptyset \sim \frac{1}{\sqrt{r}}e^{-ik_0 r} \quad should\ be\ 0\ if\ r\ \infty \quad (6)$$

$$\frac{\partial\phi_7}{\partial n} = -\frac{\partial\phi_0}{\partial n}\ on\ the\ body\ boundary \quad (7)$$

2.2 Wave Potential

By considering the wave potential only affected by model surface, S_H, the wave potential at any point can be presented by the following equation:

$$\emptyset(P) = \iint_{S_H}\left\{\frac{\partial\emptyset(Q)}{\partial n_Q}G(P;Q) - \emptyset(Q)\frac{\partial G(P;Q)}{\partial n_Q}\right\}dS(Q) \quad (8)$$

where$P$ =(x, y, z) represents fluid flow pointed at any coordinate and $Q = (\xi,\eta,\varsigma)$ represent any coordinate, (x, y, z) on model surface, S_H. The green function can be applied here to estimate the strength of the wave flow potential. The green function in eq. (8) can be summarized as follow:

$$G(P;Q) = -\frac{1}{4\pi\sqrt{(x-\xi)^2+(y-\eta)^2+(z-\zeta)^2}} + H(x-\xi, y-\eta, z+\zeta) \quad (9)$$

where $H(x-\xi, y-\eta, z+\zeta)$ in eq. (9) represent the effect of free surface and can be solved by second kind of Bessel function.

2.3 Wave Force, Added Mass and Damping

The wave force or moment act on the model to cause the motions of structure can be obtained by integral the diffraction wave potential along the structure surface.

$$E_i = -\iint_{S_H} \phi_D(x,y,z) n_i dS \quad (10)$$

where, ϕ_D is diffraction potential, $\phi_D = \phi_o + \phi_7$

Also, the added mass, A_{ij} and damping, B_{ij} for each motion can be obtained by integral the radiation wave due to each motion along the structure surface.

$$A_{ij} = -\rho \iint_{S_H} Re[\phi_j(x,y,z)] n_i dS \quad (11)$$

$$B_{ij} = -\rho w \iint_{S_H} Im[\phi_j(x,y,z)] n_i dS \quad (12)$$

$n_i$in eq. (10) to eq. (12) is the normal vector for each direction of motion, i = 1~ 6 represent the direction of motion and j = 1~6 represent the six type of motions

2.4 Drag Term of Morison Equation

The linear drag term due to the wave effect on submerge model is calculated using Drag force equation as given by Morison equation:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z - \dot{X}_z| (\dot{\phi}_Z - \dot{X}_z) \quad (13)$$

Where ρ is fluid density, A_{Proj} is projected area in Z direction, C_D is drag coefficient in wave particular motion direction, $\dot{\phi}_Z$ is velocity of particle motion at Z-direction in complex form and $\dot{X}_z$ is structure velocity at Z-direction

In order to simplify the calculation, the calculation is carried out based on the absolute velocity approach. The floating model dominates term is ignored in the calculation because it is assumed that the fluid particular velocity is much higher compared to structure velocity. Expansion of the equation (13) is shown as follows:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| \dot{X}_z - \frac{1}{2}\rho A_{Proj} C_D |\dot{X}_z| \dot{\phi}_Z + \frac{1}{2}\rho A_{Proj} C_D |\dot{X}_z| \dot{X}_z \quad (14)$$

By ignoring all the term consist of $|\dot{X}_z|$, equation (14) can be reduced into following format.

$$F_D = \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D |\dot{\phi}_Z| \dot{X}_z \quad (15)$$

The above equation (15) is still highly nonlinear and this is impossible to combine with the linear analysis based on diffraction potential theory. To able the drag force to join with the diffraction force calculated with diffraction potential theory, the nonlinear drag term is then expanded in Fourier series. By using the Fourier series linearization method, equation (15) can be written in the linear form as follow:

$$F_D = \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z) - \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} \dot{X}_z \quad (16)$$

Where, V_{max} in equation (16) is the magnitude of complex fluid particle velocity in Z direction. From the equation (16), it can summarize that the first term is linearize drag force due to wave and the second term is the viscous damping force due to the drag effect.

According to Christina Sjöbris, the linearize term $\frac{8}{3\pi}V_{max}$ in the equation (16) is the standard result which can be obtained if the work of floating structure performance at resonance is assumed equal between nonlinear and linearized damping term [8].

The linearize drag equation as shown in equation (16) now can be combined with the diffraction term which calculated by diffraction potential theory. The modified motion equation is shown as follows:

$$(m + m_a)\ddot{X}_z + \left(b_p + \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max}\right)\dot{X}_z + kx = F_p + \frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z) \quad (17)$$

Where m is mass, k is restoring force, m_a, b_p, F_p is heave added mass, heave diffraction damping coefficient and heave diffraction force calculated from diffraction potential method respectively. $\frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max}$ is the viscous damping and $\frac{1}{2}\rho A_{Proj} C_D \frac{8}{3\pi} V_{max} (\dot{\phi}_Z)$ is the drag force based on drag term of Morison equation.

2.5 Differentiation of Wave Potential for Morison Drag Force

To obtain the drag force contributed to heave motion, the wave particle velocity at heave direction must be obtained first. This water particle motion is proposed to obtain from the linear wave potential equation. From the theoretical, differential of the wave potential motion in Z-direction will give the speed of water particle motion in the Z-direction.

As mentioned, the drag force in Morison equation is in the function of time; therefore, the time and space dependent wave potential in the complex form should be used here. The wave potential in Euler form as follows:

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz + iKR + i\alpha} \quad (18)$$

The expending for the equation (18) obtained that

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz} \cdot [\cos(KR) + i\sin(KR)] \cdot [\cos\alpha + i\sin\alpha] \quad (19)$$

Rearrange the equation (19), the simplify equation as follows

$$\phi(x,y,z) = \frac{\varsigma g}{w} e^{-Kz} \cdot [\cos(KR + \alpha) + i\sin(KR) + \alpha] \quad (20)$$

Differentiate the equation (20) to the Z-direction, the water particle velocity at Z-direction is shown as follows:

$$\phi_Z(x,y,z) = \frac{\varsigma g}{w}(-K)e^{-Kz} \cdot [\cos(KR + \alpha) + i\sin(KR) + \alpha] \quad (21)$$

Since this numerical model is built for deep water condition, hence it can replace the equation by $Kg = w^2$ and the equation (21) is becoming as follow:

$$\phi_Z(x,y,z) = \varsigma w e^{-Kz} \cdot [\cos(KR+\alpha) + i\sin(KR+\alpha)] \quad (22)$$

In the equations (18) to (22), ς is the wave amplitude, g is the gravity acceleration, w is the wave speed, K is wave number, R is the horizontal distance referring to zero coordinate, α is the time dependent variable.

The horizontal distance, R and the time dependent variable, α can be calculated by the following equation

$$R = Kx\cos\beta + Ky\sin\beta \quad (23)$$

$$\alpha = wt + \epsilon \quad (24)$$

In equation (23) and equation (24), the variable β is wave heading angle, ϵ is the leading phase of the wave particle velocity at the Z-direction and t is time.

To calculate the drag forces by using the Morison equation, equation (22) can be modified by following the assumptions below.

First, since the Morison equation is a two dimensional method, therefore the projected area of the Z-direction is all projected at the bottom of structure.

Second, as mentioned in the previous part, this method applies the absolute velocity method and the heave motion of model is considered very small and can be neglected; therefore, the change of displacement in Z-direction is neglected.

From the first and second assumption, the variable z at equation (22) is no effected by time and it is a constant and equal to the draught of the structure. By ignore the time series term, and thenthe equation (22) can be become as follow:

$$\phi_Z(x,y,z) = \varsigma w e^{-Kz} \cdot [\mathrm{Cos}(KR) + i\,\mathrm{Sin}(KR)] \quad (25)$$

2.6 Determination of Drag Coefficient

Typically the drag coefficient can be identified from experimental results for the more accurate study. In this study, the drag coefficient is determined based on previous empirical data. To able the previous empirical used in this study, the Round Shape FPSO assumed as a vertical cylinder. Second, the laminar flow condition is applied to calculate the drag damping and drag force so it is match with the assumption applied in diffraction potential theory. The drag coefficient applied in the calculation of motion response of Round Shape FPSO as listed in Table 1 and the reference of the dimension used in calculate the drag coefficient is showed in Figure 1.

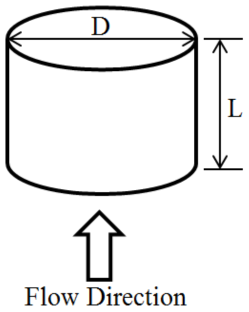

Figure 1: Dimension of Vertical Cylinder and flow direction

Table 1 Drag Coefficient for Cylinder with the flow direction in vertical direction [12]:

Aspect Ratio, AR $Length, L/Diameter, D$	Drag Coefficient, C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

3.0 MODEL PARTICULARS

The objective of this paper is reviewing the heave motion response of new designed Round Shape FPSO estimated by the diffraction potential theory with Morison drag correction method. The designed Round Shape FPSO modelhas the diameter at the draft equal to 1.018meters and draught of 0.2901meters. The model was constructed from wood following the scale of 1:110 (Table 1).

Upon the model complete constructed, inclining test, androll decay test were conducted to identify the hydrostatic particular of the Round Shape FPSO model. The dimension and measured data of the model was summarized as in Table 2.

Table 2: Particular of Round Shape FPSO

Symbol	**Model**
Diameter (m)	1.018
Depth (m)	0.4401
Draught(m)	0.2901
Free board(m)	0.150
Displacement (m^3)	0.2361
Water Plan Area (m^2)	0.8139
KG (m	0.2992
GM (m)	0.069

In this study, the proposed numerical method was applied to execute the heave motion response of Round Shape FPSO. The panel method developed based on diffraction potential theory with Morison damping correction as presented at part 2 in this paper required to generate a number of meshes on the model surface in order to predict the distribution of wave force act on this Round FPSO model. To reduce the execution time, symmetry theory is applied in the calculation and total number of panels generated for execution in each symmetry side is525 (1050 for whole model) for immerse part. The sample of mesh ofRound Shape model used in the numerical calculation is shown in Figure 2.

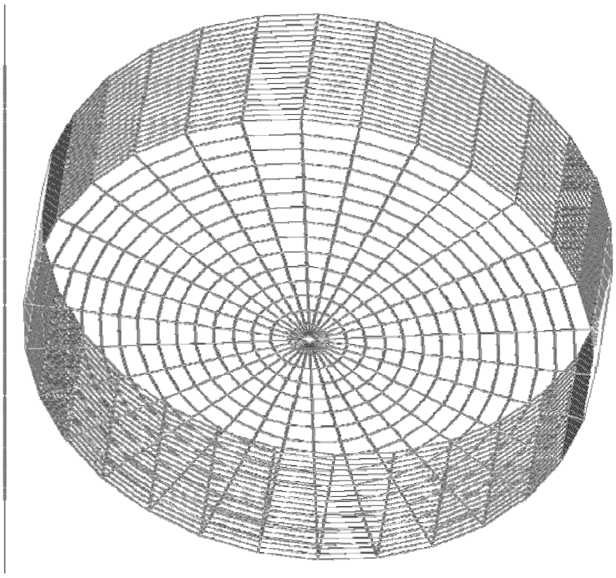

Figure 2: Meshing for Round Shape FPSO model

4.0 ROUND SHAPE FPSO HEAVE RESPONSE

The heave RAO calculated by the diffraction potential theory, the corrected diffraction potential theory by the Morison drag term and ANSYS Diffraction method are presented in Figure 3. From Figure 3, it can be seen that the diffraction potential theory with linearized Morison drag correction is predicted lower heave motion response amplitude compared to the diffraction potential theory without any correction and the ANSYS Diffraction method.

The tendency of the heave response calculated by the diffraction potential theory with and without viscous damping correction is similar between each other. The higher prediction of the heave motion of the Round Shape FPSO by diffraction potential theory is due to the small prediction of the heave damping by this theory alone. In compared to the result calculated by the ANSYS software, the diffraction potential theory without any correction function return the same result as the result predicted by ANSYS software. The observation also proved that the self-developed diffraction potential coding is developed based on the diffraction potential theory correctly. Since the linear potential theory is ignored the viscous effect in the calculation, so both the diffraction potential theory and the ANSYS software would predict the heave response of the Round Shape FPSO with higher amplitude. The maximum response amplitude of the Round Shape FPSO predicted by both the ANSYS and diffraction potential theory is same and has the value of 2.43 at wavelength 3.5 meters.

On the other hand, by involved the drag effect in the calculation, the predicted maximum heave response of the Round Shape FPSO was reduced from 2.43 to 1.74. The peak response amplitude was existed in the same wavelength either the drag effect is included in the calculation. The predicted tendency of the heave response by the diffraction potential theory, diffraction potential theory with Morison drag correction method and ANSYS AQWA software is showed similar between each other. In this calculation, the drag term of the linearized Morison equation has contributed to increase the damping and exciting force in the motion equation as shown in eq. 17. The good prediction of the drag effect by using Morison drag equation in this method was contributed to correct the weakness of the diffraction potential theory when this theory is applied to predict the heave motion of the Round Shape FPSOat damping dominate region. This is because the drag effect becomes significant at damping dominating region while the diffraction potential theory was neglected the drag effect in its prediction hence, causes the predicted motion amplitude become significant higher. By involving the drag effect in the calculation, the peak response predicted by the diffraction potential method would be reduced. Also, by compared to the experiment result, the peak heave motion response of the Round Shape FPSO is closer to the peak heave motion response predicted by experiment method [12].

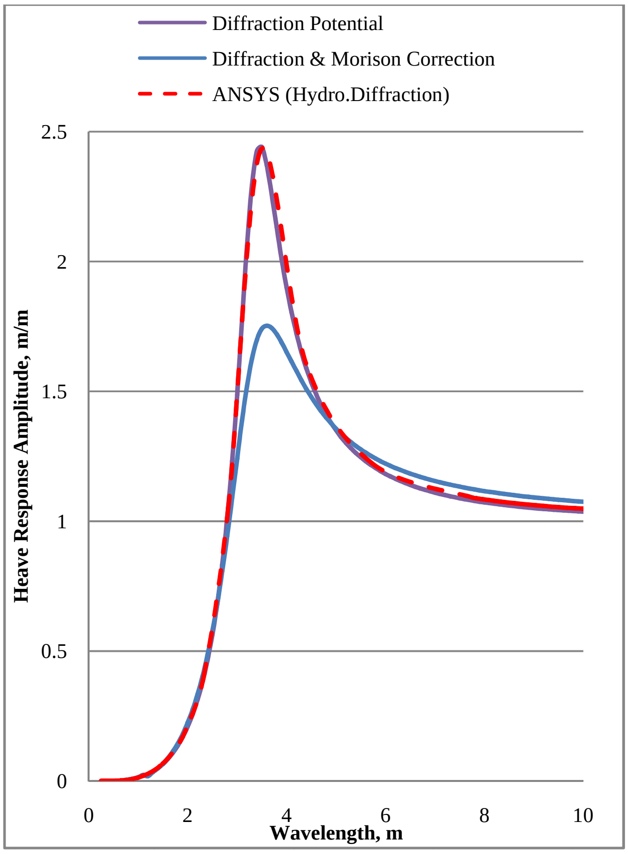

Figure3Heave motion response predicted by Diffraction Potential theory, Diffraction Potential Theory with Morison Drag Correction method and ANSYS AQWA software.

5.0 CONCLUSION

In conclusion, this paper reviewed the tendency of heave motion response predicted by the proposed diffraction potential theory with Morison drag term correction method. In the beginning, the FPSO heave motion response predicted by the self-developed programming was compared to the predicted result by ANSYS AQWA. The comparison showed that the self-developed diffraction potential coding have the same performance as ANSYS AQWA software where both method provided same tendency of result and almost similar response amplitude at any wavelength. After that, the study was focused in compared the effect of the drag effect in the motion response prediction. By involved the Morison drag term in the calculation, the peak heave response predicted by the diffraction potential theory with Morison Drag correction method is lower compared to the diffraction potential theory and ANSYS AQWA. This shown that by involved the drag effect in the calculation would help to avoid the diffraction potential theory predict the FPSO heave motion response with the significant higher magnitude in the damping dominate region.

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In-Place, Seismic and Fatigue Analysis of Offshore Platform for Life Extension

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ABSTRACT

This paper presents reassessment of existing offshore platform in the Ardjuna Field, Northwest of Java, Indonesia. The existing platform of B1C was installed in 1975 and owned by PHE ONWJ. The B1C platform is numerically evaluated for service life extension purposes until the next twenty years. The reassessment analyses focus on in-place analysis, seismic analysis and fatigue analysis. These analyses refer to recommended practice issued by American Petroleum Institute standard. The results indicated that the entire value of unity check for all members fulfill the requirements of API RP 2A - WSD. Analysis of fatigue computation showed that three joints have the fatigue life less than 59 years.

KEY WORDS: *Offshore platform, assessment, fatigue, in-place, seismic*

1.0 INTRODUCTION

The offshore platform or known as the oil and gas drilling offshore structure is one example of offshore structures. The platform is a structure that is equipped with a variety of tools to support the process of oil and gas exploration, ranging from drilling, processing, transportation, extraction of drilling results, and even accommodation for workers.

Start around 1970/1980's, many offshore platforms were built in Indonesian seas. An increasing number of platforms are now reaching their design life. Then the question about how the structural integrity of the platforms can be maintained becomes increasingly important for the platform owners. Basically, an offshore platform structure should be evaluated (assessment) periodically. An assessment to determine structural integrity may be required during the life of a platform.

According to API RP2A [1], an existing platform will require an assessment evaluation if the platform is already beyond the age of design life, the presence of significant damage or deterioration of primary structural component found during inspections and significantly changes from the original design or previous assessment basis.

Many oil companies in Indonesia are planning to extend platforms lifetime that exceed the service design life as part of their program to enhance oil or gas production with minimum investment. One of the platform known as B1C platform, belonging to *Pertamina Hulu Energi* Offshore North West Java (PHE ONWJ) have exceeded it initial service life design (40 years). This platform located offshore in Northwest of Java, Indonesia and it was installed in 1975. Because of its productivity remains high, PHE ONWJ intends to extend the service life until the next twenty years. Thus, a reassessment (reappraisal) is essential in order to evaluate the feasibility of the platform structure, for an extended period of service life until the next twenty years.

The procedure for design and reappraisal of B1C offshore platform for this study is refers to recommended practice issued by American Petroleum Institute (API RP2A). Three analyses are performed to platform structure, which is in-place analysis, seismic analysis and fatigue analysis by combining the operational, self-weight and environmental loads induced on the structure.

2.0 PLATFORM DATA

Based on available data and documents provided by PT. Tripatra Engineers and Constructors, the B1C Platform is located in the Ardjuna Field, Northwest of Java, Indonesian Seas (05^0 54' 53.0" S, 107^0 43' 51.0" E). This platform is located in 131.0 ft water depth and was installed since 1975.

The B1C Platform consist of two level deck structures with Main Deck with top of steel elevation at (+) 43 ft, and Cellar Deck with top of steel elevation at (+) 25 ft. The B1C platform considered in the study is a four legged production platform as shown in Figure 1. Water depth at the location is 131 ft below MSL as shown in Table 1. The platform is designed based on the API recommended criteria for 100-years return period for a wave height of 27.3 ft [6]. The environmental data required to determine the loads to this study is presented in Table 1-5, respectively.

The Jacket Leg structure is 40” diameter (with batter 1:8). All Piles are 36” diameter and penetrated to 165 ft below mud line. For axial pile capacity is recommended to use 2870.0 kips for B1C Platform based on report study by Soilmaklelan (1993). For eartquake source information, Dames dan Moore (2000) reported that the estimation of peak ground acceleration (PGA) for Ductility Level Eartquake (DLE) condition is 2.39 m/s2.

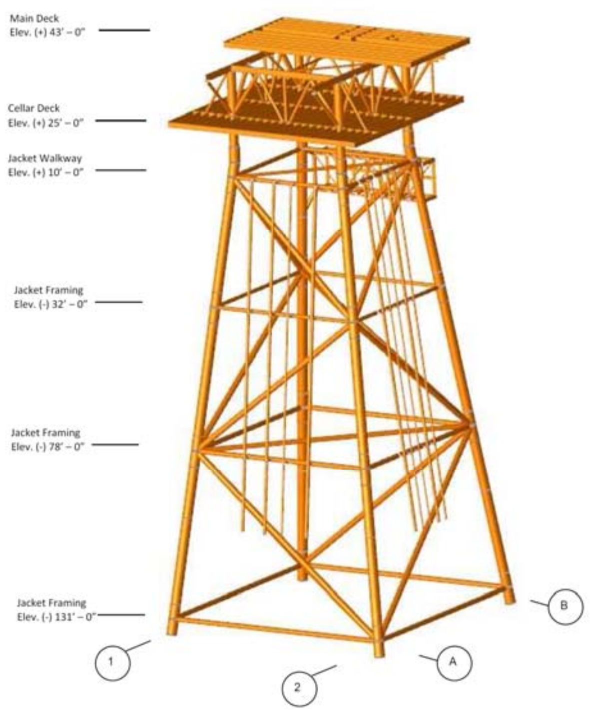

Figure 1: B1C Platform model

Table 1: Water depth

Description	1-year Operating	100-years Storm
Mean Sea Level (MSL)	131,0 ft.	131,0 ft.
Highest Astronomical Tide (HAT)	3,8 ft.	3,8 ft.
Storm Tide (surge)	0,3 ft.	0,5 ft.
Minimum Water Depth (MSL + 1/2 HAT + Storm Tide)	128,8 ft	128,6 ft
Maximum Water Depth (MSL + 1/2 HAT + Storm Tide)	133,2 ft.	133,4 ft.

Table 2: Wind speed

Description	1-year Return Periods	100-years Return Periods
1 Hour Wind	38.0 Mph	63.0 Mph

Table 3: Wave design

Description	1-year Return Periods	100-years Return Periods
Heigh of Maximum Wave	16.4 ft.	27.3 ft.
Period of Maximum Wave	7.0 sec.	9.3 sec.

Table 4: Current profile

Percent of depth (%)	Current speed (ft/sec)	
	1-year Operating	100-years Storm
0	2.6	3.6
10	2.4	3.3
20	2.3	3.1
30	2.1	2.8
40	2.0	2.6
50	1.8	2.4
60	1.7	2.2
70	1.5	2.0
80	1.4	1.8
90	1.2	1.5
100	0.8	0.9

Table 5: 10-year directional wave height distribution for fatigue analysis

Wave Height (ft.)	N 315	NE 270	E 225	SE 180	S 135	SW 90	W 45	NW 0
2	6.714.600	8.996.200	19.296.200	8.083.600	1.825.300	1.564.600	9.713.300	8.996.200
6	229.880	308.050	660.750	276.760	63.640	54.490	332.600	308.050
10	7.752	10.390	22.270	9.336	1.060	910	11.212	10.390
14	260	348	754	314	0	0	375	348
18	8	11	25	10	0	0	13	11
22	0	1	1	0	0	0	0	1
TOTAL	6.952.500	9.315.000	19.980.000	8.370.020	1.890.000	1.620.000	10.057.500	9.315.000

3.0 METHODOLOGY

The procedure for reassessment of B1C offshore platform for this study is refers to the standard API RP2A-WSD2 1st edition and the 13th edition of AISC-ASD. In-place, seismic and fatigue analysis are performed using structure analysis computer program by considering all loads conditions. All the loads are calculated using the information provided by PT. Tripatra Engineers and Constructors.

3.1 Static Analysis

Static analysis performed by considering loading conditions for Still Water Case, 1-Year Condition and 100-Year Condition. Still Water condition cases combines maximum load operation without taking into account the environmental load, while operational conditions using extreme environmental loads with return period 1 year, and for extreme conditions using extreme environmental loads with return period of 100 years. Design and strength of structures are expressed in Unity Checks (UC) as the ratio between the actual stress that occurs on the member of structure with allowable stress. The UC criteria for each member in the structure should be less than 1.0. The flowchart for in-place analysis can be seen in Figure 2.

3.2 Seismic Analysis

Seismic analysis is the type of analysis conducted to study the response of structures to earthquake loads. The main source in the seismic analysis is information related to the movement of soil that affects the structure. In general, seismic analysis is performed to determine the pile strength of jacket leg, the strength of each joint of jacket leg (punching shear), and strength members on deck. Detail of flowchart for seismic analysis in this study can be seen in Figure 3.

3.3 Fatigue Analysis

Fatigue analysis is performed to determine the structural response to continual wave loading. Wave induced dynamic force is one of the most significant force leading to fatigue of offshore member structures. Numerical fatigue assessment method is based on S-N curve approach for API standard utilizing spectral method. The calculation of cumulative fatigue damage is based on Palmgren-Miner's rule, which can be written as:

$$D = \sum_{i=1}^{J} \frac{n_i}{N_i}$$

Where, D is the cumulative fatigue damage, n_i is number of stress cycles of a particular stress range, N_i is average number of loading cycles to failure under constant amplitude loading at that stress range according to the relevant S-N curve, and J is number of considered stress range intervals. Failure is predicted to occurs when the cumulative damage (D) over J exceeds a critical value equal to unity.

In this study, the B1C platform is analyzed for the design service life for next 20 years. Originally, the B1C platform was designed to have service life for 40 years or until 2015. Based on API RP2A, the value of the safety factor 2.0 is used for the next 20 year service life. So, the entire joint in the structure should have fatigue life more than 59 years. Detail of procedure for fatigue analysis in this study can be seen in Figure 4.

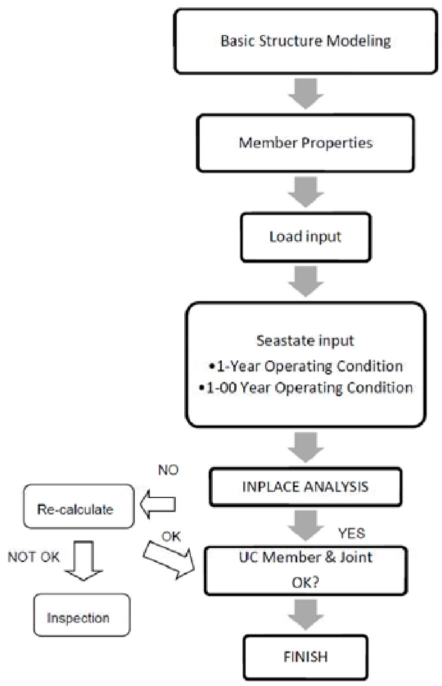

Figure 2: In-place analysis methodology

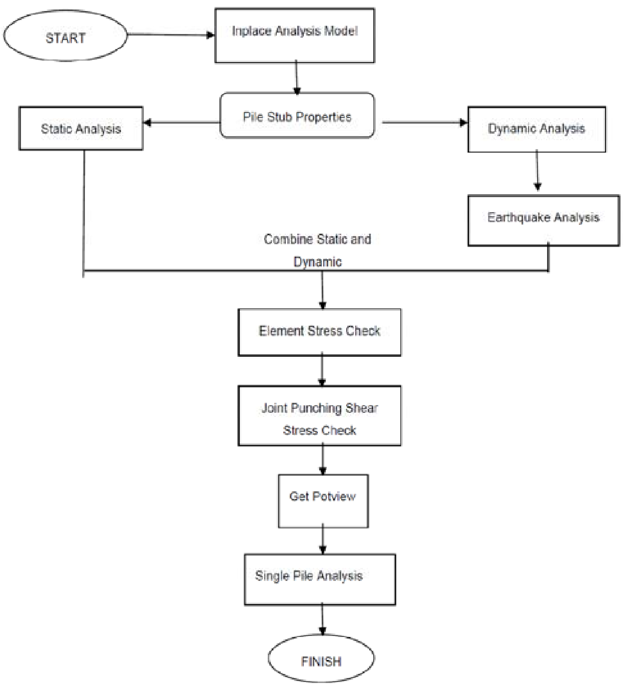

Figure 3: Seismic analysis methodology

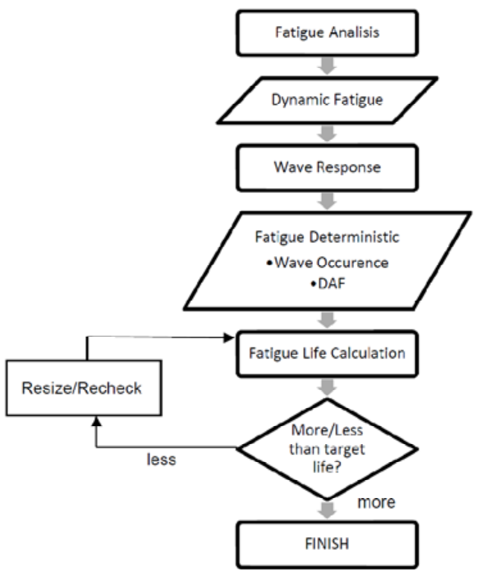

Figure 4: Fatigue analysis methodology

4.0 RESULTS

Structure and results of the above analysis is modeled with programs structure analysis computer system. The output generated from the three analysis of in-place, seismic and fatigue is shown in Table 6-9 below, respectively.

Based on the computer modeling analysis, the outline of the result can be concluded as follows:

1. For in-place analysis as shown in Table 6, the entire values of UC members on operational conditions and storm condition are under 1 (UC<1).
2. Pile Safety Factor and Joint Punching Shear results from in-place analysis shown that all members have a safe UC value (UC<1) as indicated in Table 7 and 8. Table 7 and 8 presented the maximum value of stress unity members check on each part of the structure based on in-place analysis.
3. For seismic analysis, as shown in Table 7 and 8 below, there are no members who failed and needs to be redesigned due to the lateral load on seismic analysis of DLE conditions.
4. From the results of fatigue analysis, it is known that three joints have the fatigue life less than 59 years or the intended total service life as shown in Table 9. These joints are joint 301L, 303L and 304L with age serviceability 42.2, 50.54, 48.45 years, respectively. Therefore, the inspection and monitoring of B1C offshore platform must be scheduled in 2015 for these three joints.

5.0 CONCLUSION

In this study, reassessment of B1C offshore platform that owned by PHE ONWJ is numerically evaluated for service life extension in the next twenty years. This platform structure located in the Ardjuna Field, Northwest of Java and was installed on 1975. The reassessment analyses of B1C platform focus on in-place analysis, seismic analysis and fatigue analysis. These analyses refer to recommended practice Codes and Standards, Specifications, and Regulations issued by American Petroleum Institute (API RP2A). The results showed that the entire values of unity check for all members fulfill the requirements of API RP 2A - WSD. Meanwhile, fatigue analysis result showed that three joints have the fatigue life less than 59 years.

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Table 6. Members stress Unity Check (UC)

Location	Still Water Case			1-Year Operating			100-Year Storm		
	Member	**Group**	**UC**	**Member**	**Group**	**UC**	**Member**	**Group**	**UC**
Maximum Jacket and Pile Stress Unity Check									
Jacket Leg	403L-0055	P4B	0.17	303L-0055	P4B	0.46	303L-0055	P4B	0.54
Jacket Vertical Brace	201L-303L	B2	0.12	201L-303L	B2	0.48	201L-303L	B2	0.61
Jacket Horizontal Brace	0177-204L	B1	0.13	0177-204L	B1	0.26	303L-302L	B1	0.41
Pile above Mudline	003P-103P	PL6	0.45	103P-203P	PL2	0.72	103P-203P	PL2	0.60
Pile Below Mudline									
Maximum Topside Member Stress Unity Check									
Main Deck	0236-180	W20	0.71	W20	W20	0.99	W20	W20	0.96
Cellar Deck	151-125	W21	0.71	W21	W21	0.85	W21	W21	0.74
Deck Leg	503L-111	P36	0.41	P36	P36	0.80	P36	P36	0.73
Deck Leg Truss	171-111	P14	0.64	P14	P14	0.94	P14	P14	0.89

Table 7. Joint Punching Shear Check Summary

Location	Still Water Case			1-Year Operating			100-Year Storm			Seismic		
	Joint	**Properties**	**UC**	**Joint**	**Properties**	**UC**	**Joint**	**Properties**	**UC**	**Joint**	**Properties**	**UC**
Elev. (+) 10’-00’’	403L	41’’O.D 1.0’’WT	0.12	403L	41’’O.D 1.0’’WT	0.31	404L	41’’O.D 1.0’’WT	0.34	404L	41’’O.D 1.0’’WT	0.33
Elev. (-) 32’-00’’	302L	41’’O.D 1.0’’WT	0.14	302L	41’’O.D 1.0’’WT	0.55	302L	41’’O.D 1.0’’WT	0.82	303L	41’’O.D 1.0’’WT	0.67
Elev. (-) 78’-00’’	202L	41’’O.D 1.0’’WT	0.07	201L	41’’O.D 1.0’’WT	0.28	201L	41’’O.D 1.0’’WT	0.41	201L	41’’O.D 1.0’’WT	0.60
Elev. (-) 131’-00’’	104L	41’’O.D 1.0’’WT	0.16	104L	41’’O.D 1.0’’WT	0.32	103L	41’’O.D 1.0’’WT	0.42	103L	41’’O.D 1.0’’WT	0.45

Table 8. Pile safety factor

Conditions	Pile Group	Pile Penetration (ft)	Pile Weight (kips)	Pile Axial Load (kips)	Pile Axial Safety Factor
Still Water Case	PL1	165	69.8	787.4	2.74
	PL2	165	69.8	863.4	2.48
	PL3	165	69.8	781.1	2.72
	PL4	165	69.8	738.6	2.87
1-Year Operating	PL1	165	69.8	795.9	2.70
	PL2	165	69.8	687.0	3.09
	PL3	165	69.8	1213.0	1.82
	PL4	165	69.8	1088.0	2.02
100-Year Storm	PL1	165	69.8	1081.5	2.14
	PL2	165	69.8	976.8	2.37
	PL3	165	69.8	1430.5	1.62
	PL4	165	69.8	1262.5	1.83
Ductility Level Eartquake	PL1	165	69.8	864.8	2.50
	PL2	165	69.8	928.6	2.34
	PL3	165	69.8	865.7	2.50
	PL4	165	69.8	884.9	2.45

Table 9. Maximum Joint Fatigue Life

Joint	Location	Member	Group ID	Type	Result	
					Fatigue Life	Inspection Schedule
301L	Elev.(-) 32"	301L-401L	P4	TUB	42.24	2015
303L	Elev.(-) 32"	303L-0055	P4B	TUB	50.54	2015
304L	Elev.(-) 32"	304L-0052	P4B	TUB	48.45	2015

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