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COMPARISON OF VARIOUS SPECTRAL MODELS FOR 100-YEAR EXTREME VALUES OF OFFSHORE STRUCTURAL RESPONSE

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ABSTRACT

Offshore structures are exposed to random wave loading in the ocean environment and assumed wind-generated random waves as the dominant load. Ensuring their safe and economical design; the fundamental consideration must give at an earlier stage of the design process. Thus, the appropriate design loads allowance introduced in the probability distribution of the extreme values response to wave loading where the ocean surface elevation is defined using wave energy spectra. The linear random wave theory (LRWT) and Morison equation were implemented to simulate the offshore structural responses. This paper investigates the effects of Pierson-Moskowitz and JONSWAP spectrum to variations in wave height and wave period. These variations affected water kinematics in wave and observed in the response magnitude of base shear and overturning moment experienced by the structure. Therefore, in this paper, the Monte Carlo time simulation (MCTS) procedure has been used to compare the magnitude of the 100-year extreme responses derived from different spectra models. The accuracy of the predictions of the 100-year responses from Pierson-Moskowitz and JONSWAP spectrums then investigated.

Keywords: *Probabilistic approach, Monte Carlo time simulation, wave spectra, extreme surface elevations*

1.0 INTRODUCTION

This paper investigates the primary response of the offshore structure to environmental loading. Explicitly, the response of base shear (BS) and overturning moment (OTM) were considered in the presence of random wave-induced loading onto submerged leg platform structure. The structure would be analysed on a single leg of the structure. On the other

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hand, it was known to be two of the most significant spectrum throughout the structure's operational period. The most popular spectrum model would be used in this study, namely, Pierson-Moskowitz (P-M) and JONSWAP wave model. Surface elevation and corresponding water particle kinematics at different nodes were simulated according to linear random wave theory (LRWT). By applying Morison force, the wale force would be analysed on the submerged structure. The environmental parameters considered in this study comprises of wave height, wave period, current velocity and force coefficients. The studies performed and the criteria used for each study are given as shown in Table 1. The range of values chosen for each parameter is applicable for the North Sea region, and they are either used in current design practice or in present research predictions. The assessment of structural response was performed for wave action coming from one direction of attack only because the configuration of the structure has a square plan shape [1].

2.0 STRUCTURAL MODEL AND GEOMETRY

A single-legged platform structure is modeled and analyzed in this study. The distributed load on each leg is represented by 30 point loads that reaching a total number of nodal loads [2]. The structure is assembled from tubular steel of certain diameter and thickness according to specified, designed dimensions. The structural parameters are determined with consideration of loadings and response that are likely to experience by the structure in its service life. The prediction of loading at its possible extreme values as well as consideration of safety expects of the structure fixed in its location throughout the intended design life [3].

Figure 1 shows a jacket structural model considered in this study that was installed at a water depth of 110 m in the North Sea. The structure is a four-legged platform having horizontal, vertical and inclined members then piled-fixed to the seabed. The total mass is 17665 tonnes, and the square cross-section jacket measures 38 m x 35 m (plan view) at the platform deck. The fixed platform consists of one large-diameter tubular legs framed together. These legs have a diameter of 1.5 m and thickness of 0.04 m extended from elevation (-) 110 m (depth) to elevation (+) 5 m above Mean Sea Level (MSL).

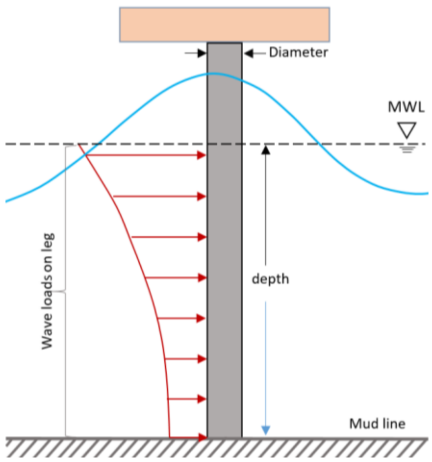

Figure 1: Characteristic fixed offshore platform structure

2.1 Loading structural data

Loadings on the structure are coming from the environment predominantly contributed by waves. Platform characteristics and structure data parameters considered in this study is presented in Table 1. Other environmental loading inputs are from wind, wave and current as presented further section.

Table 1: Platform characteristics and structure data

Parameter	**Method / Value**
Structure condition	Quasi-static
Offshore fixed structure	Single-legged
Wave spectrum	P-M and JONSWAP
Wave Theory	LRWT
Current Profile	Vertical stretching
Water depth, d	110 m
Diameter vertical legs (m)	1.5
Wall thickness (mm)	40
Length of the cylinder (m)	5
Drag coefficient, Cd	1.05
Inertia coefficient, Cm	1.20

3.0 WAVE FORCE

Wave height, wave period and water depth are known to be the main parameters that have a very significant influence on the sensitivity of structural loading and responses. Platform structure installed in the sea will experience several types of loading [1, 2]. Study on nonlinear response especially drag force of platform structure under extreme wave may be referred elsewhere. Current profile is a 'stretched profile' with values based on the extreme design current for the North Sea [4, 5]. The structure is assumed to have a rough surface with *Cd* = 1.05 and *Cm* = 1.20 as referred to in Table 1. Variation in wave height and water depth adopted in this study is presented in Table 2. Estimation of structural response under environmental loading having variation values may be referred to in Table 3 and 4. As refer to platform characteristics and structure data, and extreme wave condition and simulated records value, it could calculate wave load magnitude of structural response for base shear (BS) and overturning moment (OTM) respectively. Loading and response due to these input parameters are considered as an extreme response in comparison with P-M and JONSWAP spectrum in 100-year lifespan.

3.1 Wave loading formulation

The Airy wave theory is assumed in this study where the wave amplitude a, is considered very small as compared to the water depth, d. The wave-induced water particle kinematics at different nodes from the surface elevation record using linear random wave theory can be defined using the following equation: Water particles velocities in the x-direction, u and z-direction, v at any point of time, t is given as:

$$\boldsymbol{u}(\boldsymbol{x},\boldsymbol{t}) = \frac{\boldsymbol{a\omega}\,\mathbf{cosh}\big(\boldsymbol{k}(\boldsymbol{z}+\boldsymbol{d})\big)}{\mathbf{sinh}(\boldsymbol{kd})}\mathbf{cos}(\boldsymbol{kx}-\boldsymbol{\omega t}) \tag{1}$$

The associated acceleration of water particles, $\dot{u}$ and, $\dot{v}$ at any point of time, *t* is defined as:

$$\dot{\boldsymbol{u}}(\boldsymbol{x},\boldsymbol{t}) = \frac{\boldsymbol{a\omega}\,\mathbf{cosh}\big(\boldsymbol{k}(\boldsymbol{z}+\boldsymbol{d})\big)}{\mathbf{sinh}(\boldsymbol{kd})}\mathbf{sin}(\boldsymbol{kx}-\boldsymbol{\omega t}) \tag{2}$$

where

Symbol	Parameter	Unit
u	water particle velocity	m/s
$\dot{u}$	water particle acceleration	m/s^2
x	horizontal direction	m
z	elevation above the seabed	m
t	time	s
d	water depth	m
k	wave number	N/A
ω	angular frequency	rad/s

This is how the simulation of water particle kinematics be done using fast Fourier transform. Then, the transfer function transforms take part for calculating surface elevation from point x_1 to x_2, or surface elevation from point x_1 to water particle kinematics at point x_2 and z_2. Therefore, the transfer function converts the coefficient A_η (at point x_1) to coefficient A_u (at point x_2, z_2), which is equivalent to:

$$\boldsymbol{TF_u(\omega_a) = \omega_r \frac{\cosh k(z_2+d)}{\sinh kd} e^{ik(x_2-x_1)} = |TF_u|\, e^{ik(x_2-x_1)}} \tag{3}$$

$$\boldsymbol{\omega_r = \omega_a - ku\cos\alpha} \tag{4}$$

$|TF_u|$ expresses how much the amplitude of the surface elevation must increase or decrease to obtain the amplitude of the horizontal water particle velocity. The term $e^{ik(x_2-x_1)}$ shows the phase shift between surface elevation at the point, x_1 and horizontal velocity at the point, x_2. The above equation is only suitable for kd < 10 (d is water depth). For kd > 10, the result may not be accurate. Hence, the following equation can be used when kd > 10.

$$\boldsymbol{\frac{\cosh\big(k(z+d)\big)}{\sinh(kd)} \approx \frac{\sinh\big(k(z+d)\big)}{\sinh(kd)} \approx e^{kz}} \tag{5}$$

For horizontal water particle acceleration ($\dot{u}$), the transfer function converts the coefficient A_η at point x_1 to coefficient A_u at point (x_2, z_2) where it can be expressed as the following:

Later the spectrum was modified and the spectral shape was re-parameterized into two parameters, H_s and T_z. In real practice, the wave spectrum is more favourable and it is described as a function of significant wave height, H_s, rather than wind speed (Barltrop and Adams, 1991). The following definition of the P-M spectrum has been used for current study is given by:

$$\boldsymbol{TF_{\dot{u}}(\omega_a) = i\omega_r^2 \frac{\cosh k(z_2+d)}{\sinh kd} e^{-ik(x_2-x_1)} = |TF_{\dot{u}}|\, e^{-ik(x_2-x_1)}} \tag{6}$$

After that, when a wave moves from x_1 to x_2 (e.g. one leg structure to another leg structure), the amplitude does not change, so the absolute value of transfer function would be equal to unity. Hence, the transfer function to converts the surface elevation coefficient will only involve a phase shift as shown below.

$$|\boldsymbol{TF_u}|(\boldsymbol{\omega_a}) = \boldsymbol{e^{-ik(x_2-x_1)}} \tag{7}$$

Lastly, wave loads on a submerged section of offshore fixed structure estimated by using Morison equation [6].

$$\boldsymbol{F_{wave}(z,t) = F_{drag} + F_{inertia}} \tag{8}$$

$$\boldsymbol{F_{wave}(z,t) = \frac{1}{2}\rho C_D u|u| + \frac{\pi}{4}\rho C_M D^2 \dot{u}} \tag{9}$$

where

Symbol	Parameter	Unit
F_{wave}	wave load	kN/m
F_{drag}	drag force	kN/m
$F_{inertia}$	inertia force	kN/m
C_D	drag coefficient	N/A
C_M	inertia coefficient	N/A
ρ	water density	kg/m^3
u	water particle velocity	m/s
$\dot{u}$	water particle acceleration	m/s^2
D	diameter of cylinder section	m

The quasi-static response from the Morison nodal loads can be calculated. Assuming the structural system is linear and dynamic effect will be negligible. The quasi-static base shear (BS) and overturning moment (OTM) at the seabed can be calculated using the following equation:

$$\boldsymbol{BS} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{NS}} (\boldsymbol{F_i} * \Delta \boldsymbol{l_i}) \tag{10}$$

$$\boldsymbol{OTM} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{NS}} (\boldsymbol{F_i} * \Delta \boldsymbol{l_i} * \boldsymbol{z_i}) \tag{11}$$

where

Symbol	Parameter	Unit
NS	number of nodal loads	N/A
F_i	Morison load per unit length at node *i*	N@Nm
Δl_i	length of the element associated with node *i*	m
z_i	elevation of node *i* from the seabed	m

In fact, the Morison equation [6] has been widely used to estimate the wave force acting on offshore structures such as oil drilling platforms, submerged floating tunnels (SFT), the catenary anchor leg mooring (CALM) system, supporting structures of deep water wind turbines and so on. Because of the concise expressions of hydrodynamic pressure, the standard Morison equation is widely used as an approximate method to estimate the wave force acting on offshore structures. Figure 2 illustrates the base shear and overturning moment on the cylinder structure.

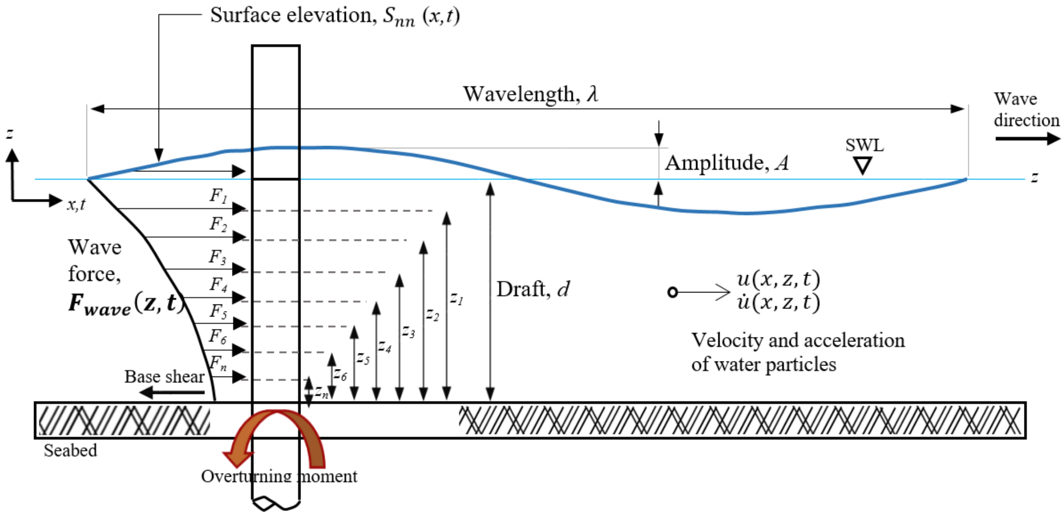

Figure 2: Morison force on cylinder member

3.2 Loading environmental parameter

In this study, the significant wave height (*Hs*) of 5, 10 and 15 m with corresponding to zero up-crossing wave period (*Tz*) of 7.94, 11.23 and 13.75 s, and water depth of 110 m were selected together with two wave spectrum model to investigate the sensitivity of structural response due to the presence of random wave-induced loading as shown in Tables 1.

The extreme responses value associated with its distribution are considered in the modeling of overall structural sizes and design parameter values. Distribution of responses on the structure is shown in Figure 2. Surface roughness is determined from related values of Cd is obtained from [1, 2]. In all cases, the values of Cm is assumed to be 1.20. More details describing the summary coefficient of drag and inertia have been discussed by [7].

Generally, the simulation duration of structure's and responses record would be done as shown in Table 2. This condition will directly correspond to the loading on the structure. Data first collected are labelled as number of simulated records for 10000 records. Data on the distribution of extreme responses distribution are typical of the North Sea platform.

Table 2: Simulation records condition

Parameter	Value
Simulation duration (h)	3.64
Number of response record	10000
Iteration	50
Return period (year)	100

3.3 Research Methodology

In this study, the probabilistic method also known as the stochastic method will be used to evaluate the results. It is a statistical analysis tool that estimate and representation of a randomness phenomenon. The stochastic model includes both a deterministic component and a random error component [8]. Monte Carlo is the best technique in a stochastic method for predicting responses of an offshore structure random wave [9, 10]. As shown in Figure 3, the research flowchart on statistical analysis procedure of the probability distribution of response process followed and orderly sequence.

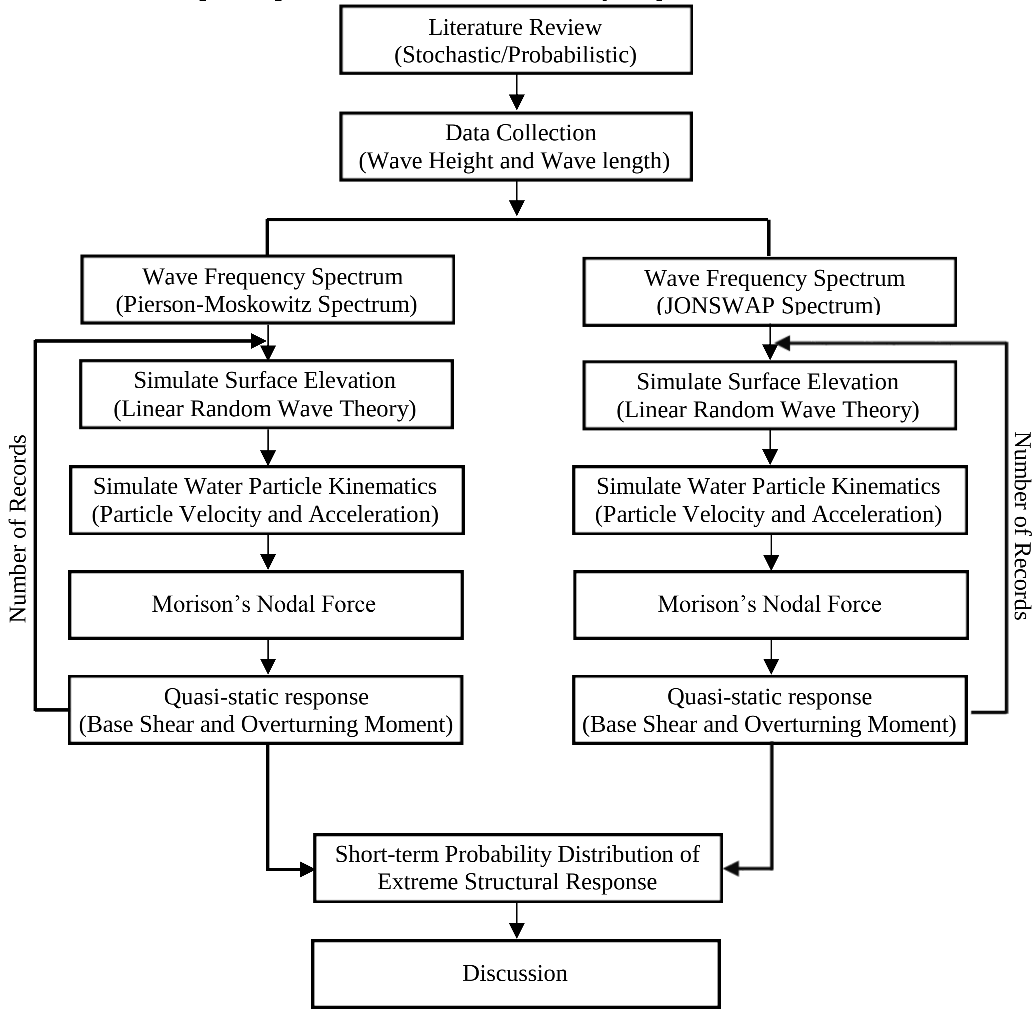

Figure 3: Statistical analysis procedure of the probability distribution of response

4.0 RESULTS AND DISCUSSION

As previously mentioned, this study aims to investigate the effects of predicting the 100-year responses from various wave spectrum models. The comparison is carried out using a different level of significant wave heights, *Hs* (5m, 10m, and 15m) and different wave zero up-crossing periods, *Tz* = 7.94 sec, 11.23 sec, 13.75 sec values for two different ocean wave spectra (Pierson-Moskowitz and JONSWAP spectrums). The analysis is made on a simulated random wave generated using linear random wave theory (LRWT). Then, the Monte Carlo time simulation method is utilised for predicting the short-term statistical properties of the 100-year design wave load due to its capability of accounting for their accuracy. In this section, a comparison between two different spectra will be analysed first followed by the design wave load investigation.

By P-M spectrum, the wave height of 15 m is referred to quasi-static base shear for 100-year return period for North Sea area as shown in Figure 4. From the graph, the quasi-static base shear stated 3850 kN wave response and more detail can be referred in Table 3.

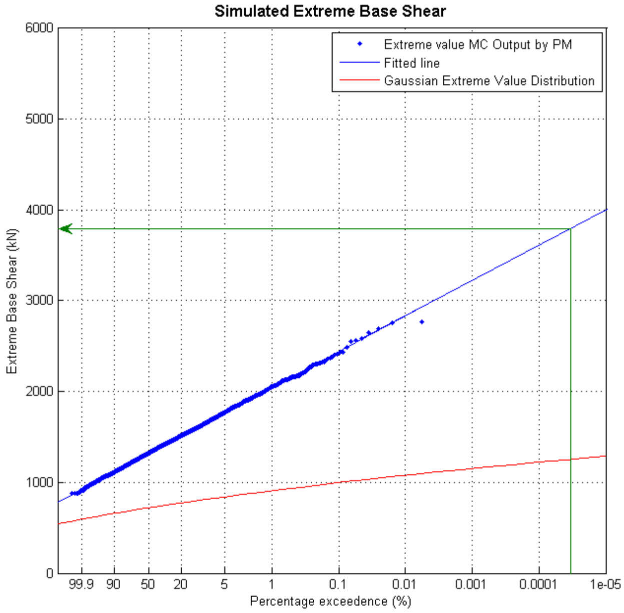

Figure 4: Probability distribution of extreme values of P-M spectrum quasi-static base shear Hs = 15m, Tz = 13.75sec, U = 0 m/s and T = 3.64 hrs with number of response records = 10000.

4.1 Comparison between P-M and JONSWAP spectrum

The wave force can be predicted by using a formula of Morison equation as mentioned in Eq. (9), (10) and (11). The extreme value response of base shear in either the P-M or JONSWAP spectrum is defined by using its significant wave height, *Hs*. In Figure 5 and 6 can be seen, the two wave spectra; between the P-M and JONSWAP spectrum corresponding to their wave height of 15 m. As well, In Figure 7 and 8 can be seen, the two wave spectra; between the P-M and JONSWAP spectrum corresponding to their wave height of 5 m.

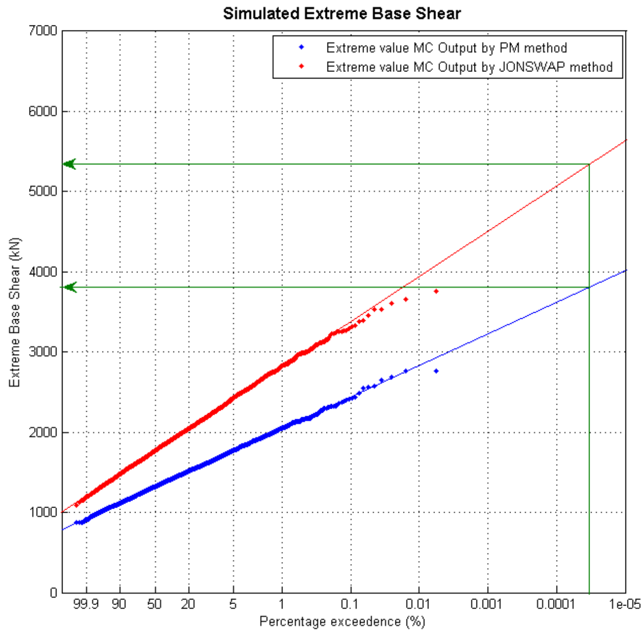

Figure 5: Probability distribution of extreme values using P-M and JONSWAP spectrum for quasi-static base shear *Hs* = 15m, *Tz* = 13.75sec, *U* = 0 m/s and T = 3.64hrs with number of response records = 10000.

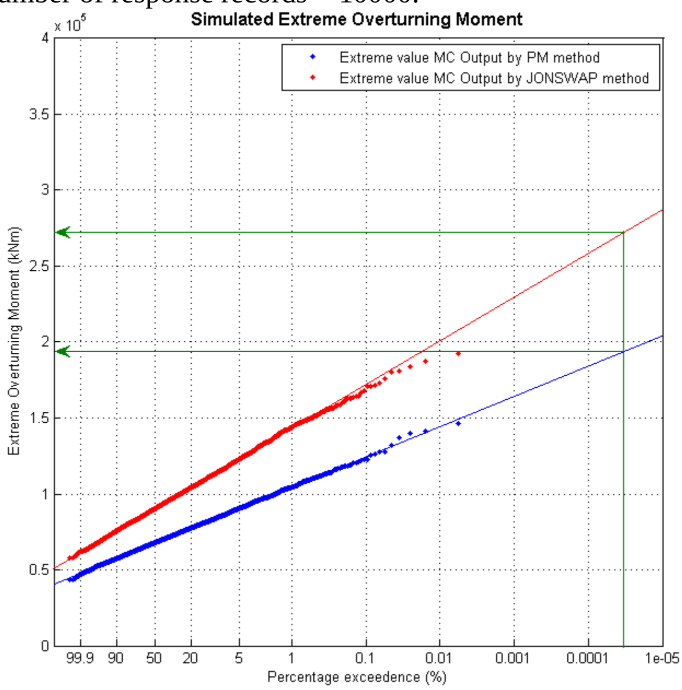

Figure 6: Probability distribution of extreme values using P-M and JONSWAP spectrum for quasi-static overturning moment *Hs* = 15m, *Tz* = 13.75sec, *U* = 0 m/s and T = 3.64hrs with number of response records = 10000.

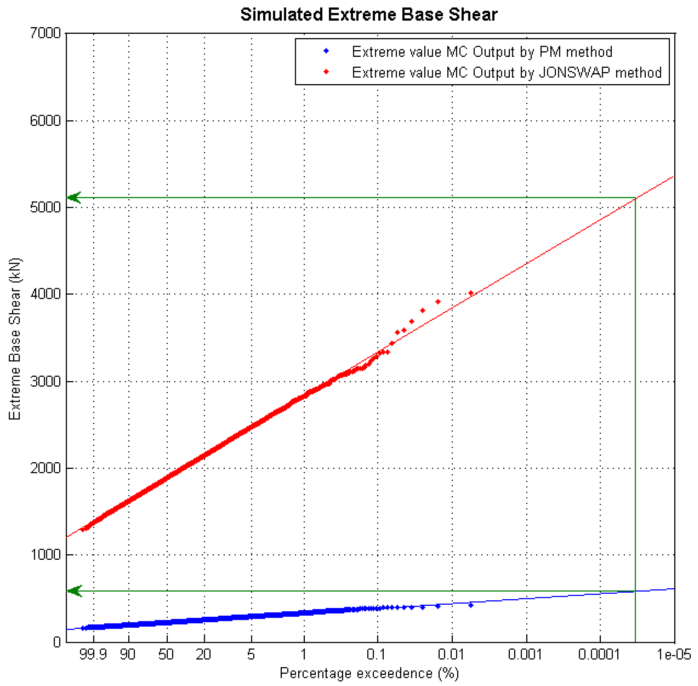

Figure 7: Probability distribution of extreme values using P-M and JONSWAP spectrum for quasi-static base shear *Hs* = 5m, *Tz* = 7.94sec, *U* = 0 m/s and T = 3.64hrs with number of response records = 10000.

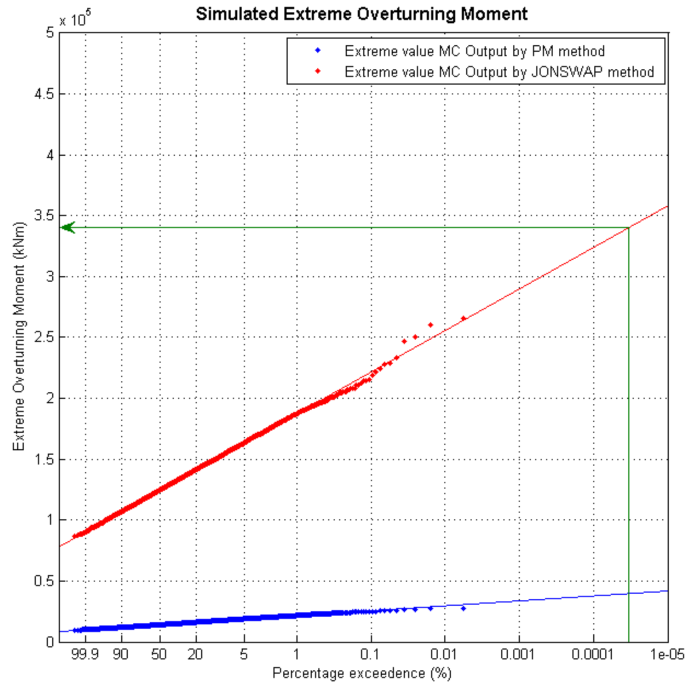

Figure 8: Probability distribution of extreme values using P-M and JONSWAP spectrum for quasi-static overturning moment *Hs* = 5m, *Tz* = 7.94sec, *U* = 0 m/s and T = 3.64hrs with number of response records = 10000.

Thus, Figures 5 and 6 show the comparison of the specified wave spectrum between P-M and JONSWAP spectrum for the three different wave heights of *Hs* = 15m. Besides that, Figures 7 and 8 show the comparison of the specified wave spectrum between P-M and JONSWAP spectrum for the three different wave heights of *Hs* = 5m. Both wave spectra improved that rising the wave height as an increase the wave force are tabulated in Table 3. From that table, the wave spectrum value experienced an increment rate of base shear and overturning moment proportional to the increasing wave height. Otherwise, there is only JONSWAP for overturning moment that decreased gradually proportional to increasing wave height. Each spectrum experienced a decline in spectrum ratio while wave height is growing up and stated the lowest of wave height is less practicable for JONSWAP. The reason is JONSWAP spectrum is better for a high-frequency region and practicable in deep water [11].

Table 3: Short-term of probability distribution extreme values of quasi-static base shear For the P-M and JONSWAP spectrum for various significant wave height.

Hs (m)	**Base Shear (kN)**		**Overturning Moment (kNm)**		**Load ratio**
	P-M	JONSWAP	P-M	JONSWAP	$\frac{\text{JONSWAP}_{\text{response}}}{\text{PM}_{\text{response}}}$
5	600	5100	40	340	8.5
10	1580	5040	90	280	3.1
15	3850	5350	190	275	1.4

Comparing both wave spectrum, it is clear that the load (response) ratio decrease with increasing the significant wave height. The response ratio for the significant wave height of Hs = 15m is quite small value compared to others. From the graph also, it can be seen the gap between P-M and JONSWAP spectrum getting away each other especially when the significant wave height make smaller until Hs = 5m. It means each wave spectrum form different significant wave height and have dissimilar peak frequency which is the significant wave height associated with the variance of wave spectrum. That means the significant wave height values increase proportional to decreasing of peak frequency values. On the other hands, the reason is the JONSWAP result is more stable and not affected their spectrum changes with correspond to significant wave height. The JONSWAP spectrum also provide an alternative spectral shape with a higher and sharper peak compared to the P-M spectrum. Obviously, P-M spectrum has their limitation because a sea state is not always fully developed. With the JONSWAP spectrum not only requires Hs and Tz but also a peak enhancement factor (ϒ) in their parameters. Eventually, the spectrum ratio value produces the same value for both response of base shear and overturning moment. It denotes the ratio between JONSWAP concerning P-M spectrum has the same value that is achieving a good agreement in this study.

5.0 CONCLUSIONS

The extreme response of the study was used to examine the effect of using P-M and JONSWAP spectrum towards wave loading on platform structure. The results of base shear and overturning moment of typical shallow water fixed offshore structure associated changes in wave height and wave period parameter. The response structure focused on quasi-static response and rough structures. From the analysis, it shows that base shear and overturning moment are significantly increased concerning structures submerged for both spectra P-M and JONSWAP. However, the result totally differs with the JONSWAP spectrum for an overturning moment. It indicates decline rates in overturning moment proportional to the increasing wave height.

By comparing the results from two wave models, it can be verified that this program provides a reasonable representation of the P-M and JONSWAP wave spectrum models. The effect of fetching parameters in the JONSWAP spectrum would give a higher embedded energy spectrum compared to the P-M spectrum. The number of different parameter usage between the P-M spectrum models with two-parameter spectrum and the

JONSWAP spectrum with five parameters also make a difference in the final results. This is the reason why the P-M spectrum gives a bit more freedom to reproduce realistic spectra of developing sea. Otherwise, the existing JONSWAP spectrum offers more flexibility and can produce more realistic spectra compared to the P-M spectrum [11, 17].

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