Extreme wave loading on jacket structures

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Abstract. Substructure load is sometimes the most concerned wave induced load exerting on jacket structures. In computing these loads, one of the most sensitive parameters is the characteristics of the waves hitting the structure. These waves which are usually modelled as regular waves, are in reality random in nature. The present study aims to quantify the changes on the substructure when nonlinear random waves are employed in the calculation of these forces. A simplified jacket structure located in a uni-directional wave field is considered in the present study. Also, in the computation of substructure loads, Morison’s equation is used. The wave loads simulated based on various wave theories are discussed in the present paper.

1. Introduction

Oil and gas remain as the most important source of energy in the present time. It has not only contributed to the growth of the transportation industries, such as cars, ships and airplanes, but also it has created innumerable job opportunities for the people in the world in this sector. The impact of oil and gas is significantly obvious for oil-producing countries and also the global oil and gas market. Malaysia, an oil producing country which has vast untapped resources could greatly influence the oil and gas industry globally. It is stated in [1] that Malaysia has the fourth-highest oil reserves in Asia Pacific after China, India and Vietnam. Also, Malaysia is the second-largest producer of petroleum and other liquids in Southeast Asia, following Indonesia. According to Malaysia’s economic transformation program, oil, gas and energy sector is the top and most important sector.

To date, there are more than 200 oil and gas platforms to support the industry in Malaysia. As seen in [2], offshore jacket platforms are commonly used in the oil and gas productions in shallow water depths of Malaysia which is less than 150m. Fixed offshore structures are subjected to different types of environmental loads, such as current, wave and wind. Of these, the largest contribution to the loading on the structure comes from the wave induced loading. These wave induced loads can be generally divided into substructure loads and wave-in-deck loads. Due to this need of accurately computing the wave forces acting on these structures, much research has been done on describing water waves accurately. These include regular wave and irregular wave theories.

Although it is commonly assumed in the design that the waves are regular, the real sea states are never regular, hence, the randomness and irregularity of the sea state must be taken into account from a design point of view. The probability of offshore platforms being subjected to the impacts of extreme wave events must also be considered because it can impose potential damage and danger to the existing fixed jacket platforms. To avoid the damage which could possibly be caused by extreme
events, the engineers reassessing the existing offshore structure, are interested in knowing the substructure loads.

While regular waves maybe used in the calculation of wave induced substructure loads on jacket structures, concerns have been raised about this approach by authors such as Djunaidi [3]. He argued that the nonlinearity and randomness of the wave field must be taken into account when calculating these loads. This in turn can lead to significant changes in the substructure loads because wave kinematics is the most sensitive parameter in the calculation of these loads. An underestimated substructure loads could lead failure of the offshore structure, for example of what happened in the sinking of the Sleipner A offshore platform. It is reported in [4], [5] and [6] that there are up to 30% increase in crest heights and 50% increase in wave crest velocities when nonlinearity interactions are included.

Therefore, the present study will quantify the changes on the substructure when typical wave fields in South China Sea are modelled as nonlinear irregular wave fields when compared to a regular wave field. The wave kinematics are computed based on Airy linear wave theory, Stokes’s fifth order wave theory, linear random wave theory, Wheeler Stretching and second order random wave theory. A simple force model based on Morison’s equation ignoring the dynamic response of the jacket is implemented in MATLAB for the present study.

2. Previous work

Linear wave theory was introduced by Airy [7] to describe a first order approximation for a water wave propagating over a flat sea bed. It was derived under the assumptions that the fluid is incompressible, wave motion is irrotational and periodic in space and time, as described in [8]. The wave amplitude is assumed to be much smaller than wavelength $\lambda$ and water depth $d$. The basic hydraulic definitions of a sinusoidal surface wave are wavelength $\lambda$, wave number $k$ ($= \frac{2\pi}{\lambda}$), wave frequency $\omega$ ($= \frac{2\pi}{T}$), water surface elevation $\eta$ ($= a\sin(\omega t - kx)$), wave period $T$, wave height $H$, wave amplitude $a$ ($= \frac{H}{2}$), wave celerity $c$ and water depth $d$ from still water level. The equation for obtaining horizontal wave kinematics is:

$$u(x, y, t) = \frac{a\omega \cosh(k(y+d))}{\sinh(kd)} \sin(\omega t - kx)$$  \hspace{1cm} (1)

Higher order (in terms of wave steepness) corrections were obtained first by Stokes [9] and later by Fenton [10] by expressing the solution as a perturbation series. While Stokes [9] expressed the solution for regular waves up to third order while Fenton [10] obtained it up to fifth order. According to [11], it is stated that most design conditions and survival conditions are exposed to very steep and high waves where nonlinearity is a very important parameter to be employed in the design. By assuming the waves are regular, the wave kinematics and loading calculation will be more convenient and easier to establish.

However, it does not fully represent the real condition of the waves. Nonlinear wave groups could result in 40% higher maximum wave crest elevation when compared to linear regular waves and thus it also leads to huge increase in underlying wave kinematics according to [4] and [6]. Chen, et al. [5] has also observed that linear wave loading can contribute less than 40% of the total wave loading where higher order harmonics and nonlinearity can contribute more than 60% of the total loading. This has emphasized the importance of the consideration of nonlinear wave loading in design. To this end, linear random wave theory is derived based on the superposition of a large number of individual and
linear regular waves to describe the uni-directional random waves. The horizontal water particle velocity defined in this theory is given as:

\[ u(x, y, t) = \sum_{n=1}^{N} a_n \omega_n \frac{\cosh(k_n(y+d))}{\sinh(k_n d)} \cos(k_n x - \omega_n t + \psi_n) \]  

(2)

where the subscript ‘n’ indicates the wave component number.

Second order random wave theory included the importance of unsteadiness and non-linearity in modelling the real sea states. The basis for this theory was first derived by Longuet-Higgins and Stewart [12] based on the interaction of two linear freely propagating wave components. This solution is then simplified and generalized by Sharma and Dean [13] as a sum of all possible pairs of individual waves. Various boundary conditions were imposed in this derivation, such as bottom boundary condition, kinematic free surface boundary condition, dynamic free surface boundary condition and combined free surface boundary condition. The velocity potential for two interacting freely propagating waves are expressed as:

\[ \phi = \phi_1 + \phi_2 + \frac{E \cosh[(k_1-k_2)(y+d)] \sin(\phi_1 - \phi_2)}{g(k_1-k_2) \sinh(k_1 d - k_2 d) - (\omega_1 - \omega_2)^2 \cosh(k_1 d - k_2 d)} \]

\[ + \frac{g(k_1-k_2) \sinh(k_1 d - k_2 d) - (\omega_1 - \omega_2)^2 \cosh(k_1 d - k_2 d)}{E \cosh[(k_1-k_2)(y+d)] \sin(\phi_1 - \phi_2)} \]  

(3)

Morison’s equation was proposed by Morison et al. [14]. The drag force \( F_d \) is proportional to the square of velocity component \( u \) of wave particle and the inertia force \( F_m \) is proportional to the acceleration of wave particles. They assumed that the equation is applied only for non-breaking surface waves whose water splashing is not considered. For a vertical cylinder in waves, the diameter of the cylindrical body must be relatively small compared to the wavelength \( \lambda \) and water depth \( d \). Drag force is comprised of a drag coefficient \( C_d \) and a fluid particle velocity term. Inertia force comprises of an inertia coefficient \( C_m \) and a fluid particle acceleration term. The Morison’s equation is given as follows:

\[ F = C_d \frac{1}{2} |u(z,t)| D + C_m \rho \frac{\pi D^2}{4} \frac{\partial u(z,t)}{\partial t} \]  

(4)

3. Wave force model generation

Before a generic force model is coded in the MATLAB software for all waves, a simple validation is done on three basic members of the jacket platform, which are beam, column and inclined member by comparing the software results with analytical solutions. Table 1 shows the substructure loads computed from MATLAB and also validation of the result based on analytical solution for three basic members:
Table 1. Validations on the force model.

| Member type         | Origin                  | Matlab result [N] | Analytical result [N] |
|---------------------|-------------------------|-------------------|-----------------------|
| Vertical column     | Drag, $F_d$             | 0.0183            | 0.0185                |
|                     | Inertia, $F_m$          | -0.0382           | -0.0382               |
| Horizontal beam     | Drag, $F_{dx}$ (horizontal) | 0.0058          | 0.0058                |
|                     | Inertia, $F_{mx}$ (horizontal) | -0.0280       | -0.0280               |
|                     | Drag, $F_{dy}$ (vertical) | $-1.0773 \times 10^{-8}$ | $-1.1327 \times 10^{-8}$ |
|                     | Inertia, $F_{my}$ (vertical) | $-3.0449 \times 10^{-18}$ | 0                      |
| Inclined member     | Drag, $F_d$             | 0.0185            | 0.0185                |
| ($\theta = 0$)     | Inertia, $F_m$          | -0.0382           | -0.0382               |

After the results are validated, all of the basic members can be assembled to form a complete force model. The basic members include four columns, eight horizontal beams and sixteen diagonal members. All four sides of the structure are identical. A 4-legged fixed jacket platform is modelled as shown in figure 1.

Figure 1. Simplified jacket model.

The loading with fixed jacket platform which is shown in figure 1 is assumed to be quasi-static. Morison’s equation is then applied to obtain the substructure loads which acts on the all types of jacket members, which include beams, columns and diagonal members of the platform. The drag and inertia coefficients are shown in table 2.
Table 2. Drag and inertia coefficient.

| Drag coefficient, $C_d$ | 1.05 |
|-------------------------|------|
| Inertia coefficient, $C_m$ | 1.6 |

The drag and inertia flows are summed up to analyze the total effect of substructure loads on the jacket members. Airy’s wave theory is used to compute the water particle kinematics in linear regular wave condition in accordance with Metocean criteria. Table 3 shows the input parameters for 100-year storm event regular waves.

Table 3. Water depth, max. wave height and associated period.

| Water depth | 62m |
|------------|-----|
| Maximum wave height | 11m |
| Associated period | 9s |

To model nonlinear regular waves, Stokes’s fifth order theory is used. The mean fluid transport velocity is set to 0. After computing the wave kinematics for nonlinear regular waves, they can be applied in the force model based on Morison’s equation to generate the wave-induced substructure loads exerting on the jacket model.

Linear random wave theory is used in generating a force model in accordance with the Metocean criteria stated in Petronas Technical Standards. The criteria are:

Table 4. Significant wave height and peak period.

| Significant wave height | 5.7m |
|-------------------------|------|
| Peak period | 6.9s |

JONSWAP spectrum is used to generate the energy distributions of the wave components over a range of frequency so that these energy distributions can be used for generating the wave kinematics on linear random and second order random wave theories. The equation for JONSWAP spectrum and the parameters are shown in equation (5) and table 5:

$$G_{\eta}(\omega) = \frac{ag^2}{\omega^5} \exp\left(-\frac{\beta \omega_p^5}{\omega^5}\right) \exp\left(-\frac{(\omega - \omega_p)^2}{2\sigma^2}\right)$$

Table 5. Alpha, beta, sigma, gamma and peak angular frequency.

| Alpha, $\alpha$ | 0.0081 |
|----------------|--------|
| Beta, $\beta$ | 1.25 |
| Sigma, $\sigma$ (if $\omega \leq \omega_p$) | 0.07m |
| Sigma, $\sigma$ (if $\omega > \omega_p$) | 0.09m |
| Gamma, $\gamma$ | 1.5 |
| Peak angular frequency, $\omega_p$ | 0.6478 s$^{-1}$ |

Horizontal water particle velocity from linear random wave theory, Wheeler Stretching and second order random waves are plotted by using MATLAB software. The Wheeler Stretching empirical solution is applied after the linear random wave theory. It will predict a lower horizontal water particle velocity to avoid the over-prediction with high frequency wave components. Second
order random wave theory is also computed, thus the wave kinematics from three random wave theories are plotted in Figure 2:

![Figure 2. Depth against horizontal velocity.](image)

Figure 2 shows the variation of horizontal wave kinematics beneath the largest wave crest computed using linear random wave theory, Wheeler Stretching and second order random wave theory. It is observed that linear random wave theory has yielded the highest wave kinematics as compared to two other random wave theories. Hence, it is a major interest for the present study to quantify the changes in substructure loads when the waves are modelled as nonlinear random and compared with that of linear regular waves. The kinematics generated from both regular and random waves will be substituted into Morison’s equation to obtain the total substructure loads exerted on the jacket legs over time.

**4. Results and discussion**

Figure 3 shows the total horizontal base shear acting on all cylindrical members of the jacket structure in Figure 1. The simulations were done using Airy wave theory. From this model simulation, the maximum horizontal base shear generated is $9.741 \times 10^5$ N at $t = 2.312s$. 
Figure 3. Time history of total horizontal force based on Airy linear wave theory.

Figure 4. Time history of total horizontal force based on Stokes’ fifth order wave theory.

Figure 4 shows the same calculation, using Stokes’s fifth order theory. It shows that 11.36% higher maximum horizontal force than the Airy’s linear wave theory. 10.99 x 10^5 N at 26.82s is obtained in this case. The increase in the wave kinematics could be explained from the power series expansion in term of wave steepness, truncated after fifth order in solving this nonlinear wave problem.
Figure 5. Time history of total horizontal force based on linear random wave theory.

Figure 5 provides the same analysis, but for random waves modelled using linear random wave theory. Total horizontal force exerted on all jacket members are plotted and the maximum horizontal force obtained is $10.28 \times 10^5$ N at 2618s, which is 5.24% higher than Airy’s linear wave theory and 6.46% lower than Stoke’s fifth order theory for steady waves. The probabilistic properties of this theory is applied on the superposition of many elementary waves with various frequencies and all the nonlinear interactions between wave components are neglected.

Figure 6. Time history of total horizontal force based on Wheeler Stretching.

From figure 6, the highest total horizontal force acting on all members based on Wheeler Stretching empirical technique is $4.623 \times 10^5$ N, which is 51.21% smaller than Airy’s linear wave theory, 56.75% lower than 53.76% lower than Stokes’s fifth order theory and linear random wave theory. This can be explained that Wheeler Stretching simply predicted a lower wave kinematics at
wave crest to avoid overprediction of wave kinematics. It has a limitation such that this empirical solution could not model a real fluid flow, hence it is actually not recommended to be used in obtaining the substructure loads although it is commonly used in the industry.

Figure 7. Time history of total horizontal force based on second order random wave theory.

The maximum total horizontal force exerted on all members based on second order random wave theory is $4.79 \times 10^5$ N, which is 0.77% higher than that of Wheeler Stretching. It is 53.4% lower than the maximum horizontal force generated based on linear random wave theory, 56.41% lower than Stoke’s fifth order theory and 50.83% lower than Airy’s linear wave theory. From the results above, Stoke’s fifth order wave theory has predicted the highest maximum horizontal base measured from the still water level SWL, which is $10.99 \times 10^5$ N. Linear random wave theory has also predicted a very high maximum horizontal base shear, which is $10.28 \times 10^5$ N. The reason of low wave loads simulated based on second order random wave theory remains unknown. It may have resulted from the inadequacy of JONSWAP parameterization of the frequency spectrum. This is currently under investigation.

5. Conclusion

In the present paper, the wave kinematics generated for regular waves are validated upon analytical results and the force model for regular waves has been generated by the written MATLAB source code. From the time histories of horizontal wave forces exerting on the simplified jacket legs, it is observed that nonlinear steady wave theory according to Stoke’s fifth order has predicted 11.36% higher wave kinematics and horizontal base shear as compared to Airy’s linear wave theory. By comparing the wave forces computed using linear random wave theory, it has yielded 5.24% higher base shear on the jacket’s substructure than Airy’s linear wave theory but 6.46% lower of that than Stoke’s fifth order theory for steady waves. Assuming the waves are regular may under-predict the extremeness of the wave loading which could occur on jacket structure throughout its entire service life. The wave loads simulated based on second order random waves is 56.41% lower than Stoke’s fifth order theory. Further clarification might be needed from investigating the cause of this matter.
6. References

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