Ain Shams Engineering Journal 13 (2022) 101550

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Civil Engineering

Effect of directional spreading angles on the wave hydrodynamic coefficients for vertical cylinder

Cheng Yee Ng [a],*, Siti Nor Adha Tuhaijan [a], V. John Kurian [b], Zahiraniza Mustaffa [a], Edwar Yazid [c], Hooi Siang Kang [d]

[a] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[b] Providence College of Engineering, Kerala State, India
[c] Research Center for Electrical Power and Mechatronics, Indonesian Institute of Sciences, 41035 Bandung, West Java, Indonesia
[d] Marine Technology Centre, Institute for Vehicle System & Engineering, School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia

ARTICLE INFO

Article history:
Received 4 March 2021
Revised 17 June 2021
Accepted 13 July 2021
Available online 05 August 2021

Keywords:
Experimental investigation
Hydrodynamic coefficients
Short-crested waves
Wave directionality
Directional spreading angles
Reynolds number

ABSTRACT

In the prediction of accurate wave force, the consideration of short-crested wave is important in representing the actual ocean condition. Owing that, nonlinear wave characteristics are expected to change the flow properties when the wave passes the structures, which showing these characteristics are crucial to be accounted. However, literature reported that the overestimation on the design of marine structures has shown a lower reliability in the wave force prediction considering long-crested wave. Further in detail, the effect of wave directionality and directional spreading angle from the actual sea conditions, i.e. the short-crested waves, have been neglected in a way. To prove the validity of this statement, an experimental investigation was conducted to quantify the effects of wave directionality on the wave forces and to propose the hydrodynamic coefficients incorporated the effect of directional spreading angles. The wave directionality in term of directional spreading angles were considered, ranging from 5 to 45°. Then, the measured wave surface elevation and wave forces were processed using least square method to compute the hydrodynamic coefficients and to evaluate the wave forces. To quantify the effect, force ratio factor was adopted. Based on the finding, short-crested waves led to 20 % force reduction as compared to the long-crested. On top of that, a reduction of 1.12 % of wave force has also been observed for every one-degree incremental of the directional spreading angle. As conclusion, the wave directionality was found contributing to the reduction of wave force which may provide new improvement on the accuracy of wave force formulation for the design of lean marine structures.

1. Introduction

In designing a lean marine structure, an accurate prediction of the actual ocean environmental forces is essential. Generally, the ocean environmental forces are consisted of wind, wave, current, etc. Among these, wave is dominating, as it contributes to almost three quarter of the total forces that exerted on the marine structures. In general, wave can be classified as unidirectional or long-crested waves, and multi-directional or short-crested waves, whereby the latter is defined as superposition of long-crested waves with variation of frequencies that are propagated from multiple directions [1].

The prediction of the wave force considering the actual ocean characteristic is important and deeply discussed in some of the recent studies. It has been reported that the long-crested wave is practically being used in the structural design, and this practice is found to be conservative and has overdesigned [2]. The evaluation on the overdesigned structure is observed during the risk assessment of the aging platform, which the finding has highlighted that the platform has exceeded its service life [3]. For structural reliability, it can be specified as a good indicator, but indeed it might contribute to the company losses as some of the platform

---

* Corresponding author.

E-mail addresses: chengyee.ng@utp.edu.my (C.Y. Ng), john.k@providence.edu.in (V.J. Kurian), zahiraniza@utp.edu.my (Z. Mustaffa), edwar.yazid@lipi.go.id (E. Yazid), kanghs@utm.my (H.S. Kang).

Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.asej.2021.07.004

service is no longer needed due to the deficiency of the oil in the reservoir. Certainly, the perceptible enhancement in the mechanics of the ocean wave, including the characteristics of short-crested waves, is still not clearly evaluated. This is due to the complexities of the numerical solution and computationally expensive in modelling the kinematics properties [4,5]. Although the designer prefers to implement the kinematic reduction factor [6] in considering the wave directionality effects of the ocean wave, however, this value shows no reliable trend in representing the unpredictable condition and behaviour of the ocean wave-structure interaction [7,8]. On top of that, the reduction of the factor is not clearly chosen due to the consideration of the favourable direction which leads to a smaller value with respect to the long-crested wave and becomes greater at the extreme conditions [9]. Generally, the directional spreading effect of short-crested wave contributes to the reduction of the wave force [10], and this wave is found to be weaker if it has the transverse component as this mechanism has given hydrodynamic effect to the loadings. Meanwhile, in long-crested wave or unidirectional condition, the returning wave has given positive contribution to the instantaneous force, which leads the increment on the force magnitude. It is concluded that the estimation of the incident waves might be overestimated when long-crested wave is adopted, in which the wave force is getting greater as the waves become less short-crested.

Additionally, the comparison between these waves was investigated on the behaviour of spar platform and greater responses in long-crested wave was observed as compared to the short-crested wave [11], which indicated that the long-crested wave exerted larger forces as compared to the short-crested wave. Similar finding was also found in the study of the barge's structural response. The study reported that the barge was found to have an insignificant responses and performances as evaluated in the real ocean condition [12]. Further evaluation on the short-crested wave has been conducted incorporating the current effects and it was observed that short-crested wave gave a conspicuous influence on the loadings [13,14]. The effect of short-crested waves was also found to be carried out within the scope of platform foundation. A study on the composite bucket foundation has highlighted that the short-crested wave gave a significant reduction of the wave forces [15] and it was found to be affected by the wave phases [16].

Generally, the cylindrical components are commonly used in the marine structures as less resistance is observed when being exerted by the surrounding environmental forces. Hence, the consideration of the cylindrical structure is expected to provide a good overview and basic understanding on the ocean wave-structure interaction especially in the short-crested wave environment. Basically, various studies that focused on the prediction of the short-crested wave force on slender cylinders have been performed. Example of this structure, i.e. brace and legs of the jacket truss structures, pipelines, and the umbilical cables that usually attached to the underwater vehicles [17]. A numerical investigation was conducted by Isaacson and Nwogu [18] on a long floating cylinder considering boundary element method in the short-crested wave environment. The findings revealed a significant reduction of force factor and response ratio. The reduction was also observed by Hogedal et al. [19], whereby in the experimental measurements on a smooth vertical cylinder, the inline and resultant forces in short-crested waves were found to be lower as compared to the long-crested wave for the same spectral properties. Also, further reduction on the inline force was observed to be reduced with the incremental of the directional spreading. Another comprehensive experimental investigation on a vertical cylinder was conducted by Subbiah and Irani [20], and the results in terms of peak force showed that in the short-crested wave environment, wave force was found to be greater at the mean water level. Another experimental study on a vertical cylinder was conducted by Chaplin et al. [10], whereby a reduction of the wave forces was observed due to the effect of wave directionality. Also, due to the significant contribution of the short-crested wave on the total forces, Zhu and Satravaha [21] have studied the short-crested wave in depth by developing a method to estimate the velocity of the short-crested for a vertical cylinder. The study has been extended to investigate on various structural cross-sectional shapes [22]. The studies reported herein have supported the statement that short-crested wave yields a lower wave force as compared to the long-crested one. This provides a good indication on the importance of considering the short-crested wave for an accurate prediction of the wave forces in the design of lean marine structures. It also can be drawn that the reduction of the wave force has given a significant highlight on the importance of considering the appropriate wave condition in predicting the forces that exerted on the marine structures. Substantially, from the finding, it can be interpreted that consideration of the long-crested waves in the evaluation of the wave forces may result in structural design overestimation due to the negligence of the nonlinear properties of the ocean wave [23]. As a result, this practice will affect the life cycle cost of the design, which can be evaluated through the prolonged strength and stability of the structures that exceeding the design life.

In addition, the direction of the wave propagation is important in the design and operation of the marine structures [37]. Distribution of the wave energy within the angle of the propagated wave direction is defined as the directional spreading angles. Investigation by Hogedal et al. [19] has highlighted greater reduction of the wave forces at the larger spreading angle, due to the wider distribution area of the wave energy at greater angle. This has led to a smaller wave force measurement at a particular point. This discussion reveals that the consideration of the wave directionality and the directional spreading angles, are able to represent the behaviour of the actual ocean and it is expected to be more accurately predict the wave force.

In evaluating the wave forces, Morison equation is commonly used, whereby it comprises of the structural and wave kinematic properties. Inclusion of the suitable hydrodynamic coefficients is essential for Morison equation, in which studies have showed that the accuracy shall increase accordingly [24,25]. Keulegan and Carpenter [26] have instigated a study on hydrodynamic coefficients and presented the values to the dimensionless parameter. Following with that, many researchers have expanded the study on the hydrodynamic performance of cylinders considering various parameters, e.g. the structural geometrical shapes [22,27–30], structural inclination [31–33], surface roughness [34–36], array configurations [37–39], effects of current [40–42], and the effects of water depth [43,44]. Despite these various parameters, the hydrodynamic coefficients for slender structures were still computed with the negligence of the short-crestedness characteristic.

Aforementioned, the selection of the hydrodynamic coefficients will affect the accuracy on the prediction of the wave forces [45]. To provide a solution on the issue pertaining on the overestimation in the structural design, the effect of wave directionality of short-crested wave incorporated within the hydrodynamic coefficients and wave forces exerted on cylinders is deficient and requires additional investigations. With that, the aims of this paper are to quantify the effects of wave directionality on the wave forces and to propose the hydrodynamic coefficients incorporated the effect of directional spreading angles. Generally, the behaviour of the fluid is best to be described by the dimensionless number [46], i.e., Keulegan-Carpenter (KC) number and Reynolds (Re) number [1]. In the previously published work of the authors [47], the influence of the Keulegan-Carpenter (KC) numbers to the hydrodynamic coefficients has been reported. Noting that the continuation of the work is presented in this work, which involves the quantification of the findings due to the influence of Reynolds (Re) number. The proposed hydrodynamic coefficients are expected to elude the structural overestimation due to the consideration of the long-crested wave force, thus optimizing the life cycle cost of the structural design. It is worth noting that the application of the current findings is only for the circular cylindrical structures and, further investigation is needed to study the effect of directional spreading angles on the hydrodynamic coefficients for the other cross-sectional shapes, e.g., elliptical cylinder, triangle cylinder, and rectangular cylinder.

The remainder of the paper is followed by the sequence of methodology that inclusive of experimental procedure and data analysis. The discussion of the findings will be presented in Section 3. Later, the overall findings will be summarized in the final section.

2. Experimental procedure and data analysis

The experimental investigation was conducted at the wave tank with a dimension of 10 m width, 2 m length, and 1.5 m depth, in Offshore Laboratory, Universiti Teknologi PETRONAS, Malaysia. The wave tank is equipped with a wave generator that consists of 16 individual flat type of wave paddles installed across the width of the front end. The wave generator is capable to generate both long and short-crested waves in the frequency range of 0.3 Hz – 2.0 Hz. This wave tank is also installed with an inclined mesh beach that fitted across the width of the opposite side of the wave generator, to absorb the energy of the incoming waves. Along with these, three movable bridges and side-glass windows are installed for a good handling process and observation during the experiment.

To design the scaled model and environmental properties of the experiment, the limitation on controlling the actual size of the prototype were resolved by considering the capability of the wave tank and instrumentations. Fundamentally, the scale effects are governed by the viscosity and surface tension in the selection of the scaling law [40]. For a free surface flow condition, the gravitational effect is predominated. This leads to a reduction in the viscosity and surface tension effects, eventually been neglected [48]. With that, the evaluation of ocean wave-structure interactions commonly adopts the Froude's scaling law, whereby the correlation of the scaling factor with the model and prototype variables is stated as in Eq. (1).

$$l_p = \lambda l_m \tag{1}$$

where l_p is a characteristic length in the real-world prototype, l_m is corresponding length in the model, and λ is scale factor for the model.

In this study, the model dimensions were generally adopted within the range of typical size of the existing jacket platforms legs installed within Malaysia water. Upon the model design, the dimensions were selected by fulfilling the slender structure condition, whereby the ratio between the cylinder diameter to the wavelength has to be less than 0.2 [49]. Three different diameters ranging from 40 mm to 60 mm with 10 mm interval, were selected and constructed. Considering the capability of the facilities in evaluating the prototype scale, a scale ratio of 1:100 was selected.

The experiment was conducted in a water depth of 1 m and the laboratory measurement involved the data collection of the wave surface elevation and wave forces exerted on the cylindrical models. The measurement of the wave surface elevation was conducted by using 900 mm length twin wire wave probes. As shown in Fig. 1, two wave probes were placed in transversely with the axis of the cylinder to measure the wave surface elevation. Another two additional wave probes were placed at the front and back of the cylinder, aimed to monitor the phase angle of the wave across the length of the tank. Prior to the test, calibration was performed regularly as the height level of the probes was changed in still water by measuring the difference of the output voltage.

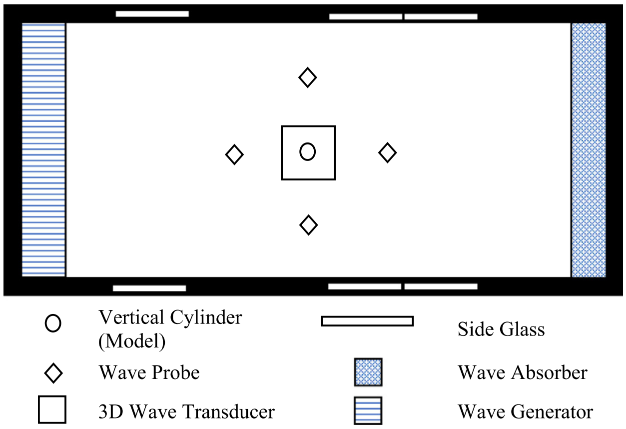


Fig. 1. Sketch of the experimental setup.

Meanwhile, for the measurement of the wave forces, the cylindrical model was instrumented with the wave force transducer at the bottom of the structure as shown in Fig. 2. The wave force transducer was designed and assembled with eight loadcells that were arranged on one platform, in which it was designed to be able to measure the 3D wave. This arrangement was referring to the work by Bazergui et al. [50], whereby it has provided a reliable measurement of the 3D loadings. Each load cell can measure the tension and compression loads up to 250 N. The wave forces measured by the loadcells were captured as the wave acting from the corresponding directions.

Fig. 2. Vertical circular cylindrical model with the 3D force transducer.

In evaluating the effect of the wave directionality on the wave forces, the long and short-crested waves were generated. In the generation of these waves, the significant wave height and the peak period, with the JONSWAP spectrum of peak enhancement factor equals to 3.3 were specified. The wave parameters were identified as the input to the wave generation software installed in the host computer and connected to the wave generation system. The long-crested wave was generated by considering the wave height and the wave frequency of the specified wave condition. Meanwhile, for the short-crested wave, an additional information on the directional spreading were implemented and computed in the system by adopting the energy spectrum values for each frequency for the directional spreading angle of 5°, 15°, 25°, 35°, and 45°. The generation of these wave considered the reflected wave from the side walls, in producing a full quality of the short-crested waves over the whole area of the wave tank [51]. To avoid the spurious wave, the limitation of the maximum angle of propagation with relevant frequency was considered. In total, 600 numbers of waves were generated in this investigation.

As the data analysis required accurate wave properties, a careful setup and calibration of the model and the equipment was conducted prior to the full data measurement. The reliability of the results was identified by comparing the targeted and the measured spectrum of the wave surface elevation as plotted in Fig. 3. It is observed that the measured spectrum is well agreed to the targeted spectrum with a small difference, which is due to the wider frequency band.

Alongside with the data collection, which involved the measurement of wave surface elevation and wave forces as functions of time, the measurements were recorded concurrently as the waves started to generate. Further, at the beginning of each test, sufficient rest time was required between each test to ensure the water level was stayed still and had no disturbance. Later, these data were undergoing the post-data processing, which required meticulous attention to detail [52]. In present investigation, the least square method considering the force spectrum was implemented to determine the hydrodynamic coefficients [53]. The estimation of the drag and inertia coefficients, C_D and C_M, are given as Eqs. (2) and (3) respectively.

$$C_M = \frac{4}{\pi \rho D^2}\left[\frac{s2s3 - s1s5}{s2^2 - s1s4}\right]^{1/2} \tag{2}$$

$$C_D = \frac{2}{\rho D \sigma_u}\sqrt{\frac{\pi}{8}}\left[\frac{s3s4 - s2s5}{s1s4 - s2^2}\right]^{1/2} \tag{3}$$

$$s1 = \sum_{i=1}^{Nf} S_u^2(\omega_i);$$

$$s2 = \sum_{i=1}^{Nf} S_u(\omega_i) S_{\dot{u}}(\omega_i);$$

$$s3 = \sum_{i=1}^{Nf} S_u(\omega_i) S_F(\omega_i);$$

$$s4 = \sum_{i=1}^{Nf} S_{\dot{u}}^2(\omega_i);$$

$$s5 = \sum_{i=1}^{Nf} S_{\dot{u}}(\omega_i) S_F(\omega_i);$$

$S_u(\omega), S_{\dot{u}}(\omega)$,and $S_F(\omega)$ are the spectral densities of the velocity, acceleration, and wave force, σ_u is the standard deviation of the velocity, and ω is the wave angular frequency.

Substantially, the interpretation of the hydrodynamic coefficients using the dimensionless analysis is essential, as it provides an overview of the potential influencing parameters that govern the hydrodynamic forces considering the properties of the ocean wave–structure interactions. In present findings, the evaluations of the wave forces and hydrodynamic coefficients are presented due to the influence of Reynolds (Re) numbers. As this study investigated the short-crested wave, hence this parameter was presented as the average of the third highest value as it was more indicative on the contribution of the wave component [20]. This approach has been adopted in the previous studies and comprehensive findings were discussed [54–56]. The formulation of the average values of the Re numbers was calculated using the maximum velocity of mean water level for a wave with significant wave height, H_s, and peak period, T_p, as shown in Eq. (4).

$$Re = \frac{\pi H_s D}{T_p v}\coth(kh) \tag{4}$$

In which D is the diameter of the cylinder, h is the water depth, k is the wave number, and ν is the fluid viscosity.

3. Results and discussion

The main purpose of this experimental investigation is to quantify the effects of wave directionality on the wave forces and to

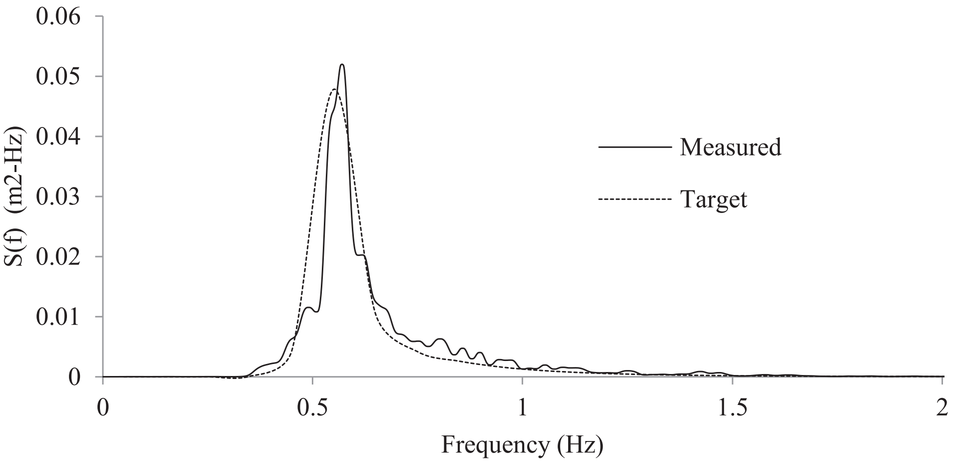


Fig. 3. Comparison of target and measured JONSWAP spectrum (peak frequency, f_p = 0.56 Hz, γ = 3.3).

propose the hydrodynamic coefficients incorporated the effect of directional spreading angles. Prior to the quantification of the effects. the significance differences of the effects on the wave forces were statistically assessed by adopting the hypothesis testing. This allows the comparison of the total wave forces of the long and short crested waves, which will provide good information on the hydrodynamic force for the structural design. Subsequently, the results are presented based on the laboratory measurements on the vertical cylinder subjected to the aforementioned wave conditions.

3.1. Assessment on significance differences of the effect on wave force using hypothesis testing

The wave directionality effect or the short-crestedness effect on the total wave force was validated using the statistical analysis by comparing the long and short-crested waves. The hypothesis testing using paired *t*-test was adopted to identify the differences between the standard deviation of the peak forces for the waves. In the comparison, same wave properties were considered for long and short-crested waves. Whilst additional parameter by using the spreading function of $\cos^2$ model was considered for the wave directionality effect.

In the hypothesis testing, the identification of peak force standard deviation different could be observed for p-value less than 0.05, or the standard deviations differ at 0.05 level of confidence. The finding generally observed that the p-value is too small and less than 0.05, which may provide a conclusion that the peak force standard deviations of the long and short-crested waves are significantly different. The distribution of the differences between the wave cases is shown in Fig. 4. In the graph, there is no unusual data being observed, hence the interpretation of the results is statistically reliable.

On top of that, short-crested waves are mainly governed by the directional spreading angles. Henceforth, the effect of the directional spreading angles on the wave force was statistically tested prior to its quantification. Similarly, paired *t*-test was adopted to determine the significant differences of the peak force standard deviation of short-crested wave for different directional spreading angles. For the exceptional validation, the wave forces for the directional spreading angles of 5° and 45° were selected and analysed. From the test, the p-values were found to be less than 0.05, which concluded that the peak force standard deviation values for both cases are significantly different. Nevertheless, this interpretation is also reliable, as no unusual difference is observed from the distribution of the differences as shown in Fig. 5. Later, the quantification of the effect of directional spreading angles on the wave forces was conducted and the results are discussed in the following section.

3.2. Force ratio factor (*ϕ*) for the effect of wave directionality

The initial analysis involved the quantification on the changes of the hydrodynamic performance for different types of wave forces. There are several ways in expressing the change in loading associated with the wave spreading [19]. The indication of the changes in the behaviour of the waves is recommended by using a statistical quantity, i.e. the force ratio factor, ϕ. The force ratio factor is defined in Eq. (5), in which the peak force standard deviation, σ, is computed over the entire duration of each test from the measurement of the forces.

$$\phi_\sigma = \frac{\sigma_{F_{short-crested\ wave}}}{\sigma_{F_{long-crested\ wave}}} \tag{5}$$

This ratio is adopted for the quantification of the standard deviation of the peak wave force for both long and short-crested waves [20]. By adopting the same properties of the wave spectrum, these factors disclose the differences in the standard deviation of the measured forces in long and short-crested waves. The evaluation of the long-crested wave involves the computation of the peak standard deviation of the in-line force in the x–direction, while an additional transverse force in y-direction was included for the short-crested wave in the resultant force. The force ratio factors, ϕ_σ is derived from the measurement of the total force on the vertical cylinders subjected by both long and short-crested wave are presented as a function of Re numbers in Figs. 6 and 7. It can be observed that the force ratios are within the range of 0.8, which indicates that the short-crested wave force is lessen by 20 % than the long-crested waves. This has affirmed that the consideration of the effect of the wave directionality in the computation of the wave force will reduce the force magnitude [19].

3.3. Force ratio factor (*ϕ*) for the effects of directional spreading angles

Referring to the previous findings of the force ratio factor, ϕ_σ, it has validated the statement of the short-crested wave yields lower force as compared to the long-crested wave [18]. This has attributed to the further quantification on wave force due to the short-crested waves incorporated with the directional spreading angles, by adopting the specific directional spreading angles in the design.

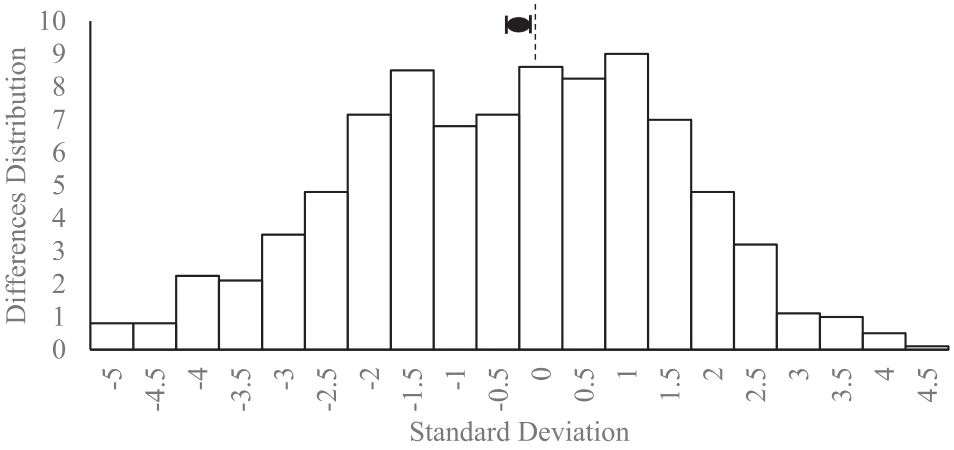


Fig. 4. Distribution of the wave force differences.

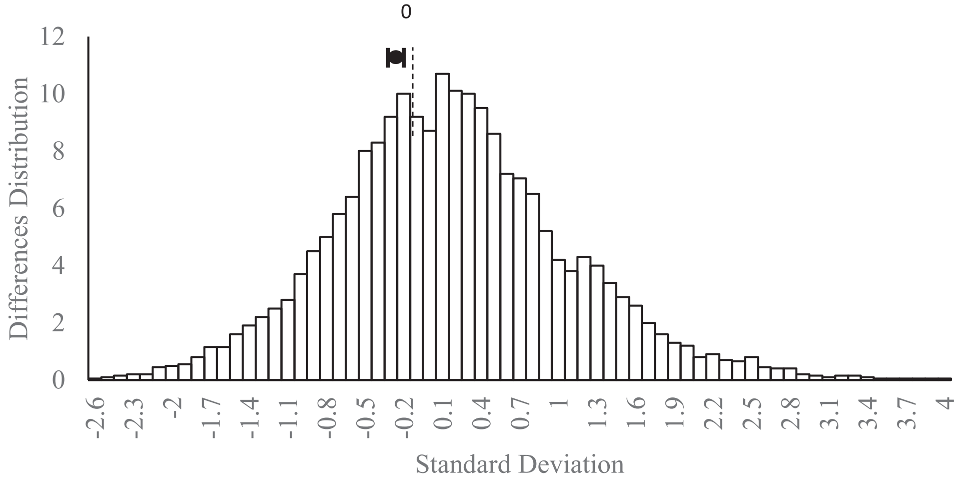


Fig. 5. Distribution of the directional spreading angle difference.

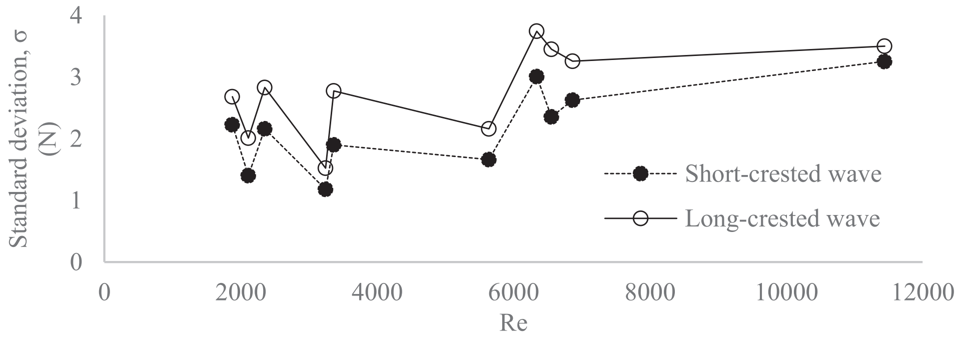


Fig. 6. Comparison of standard deviations of short-crested and long-crested waves.

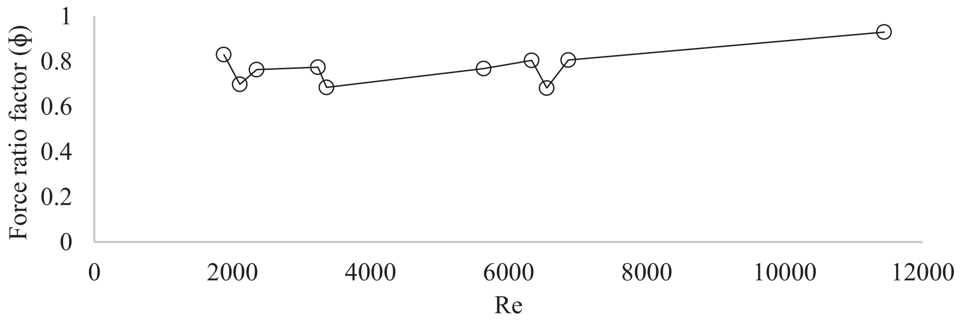


Fig. 7. Ratio of the standard deviation of short-crested wave force to the long-crested wave force as a function of Re at the mean water level.

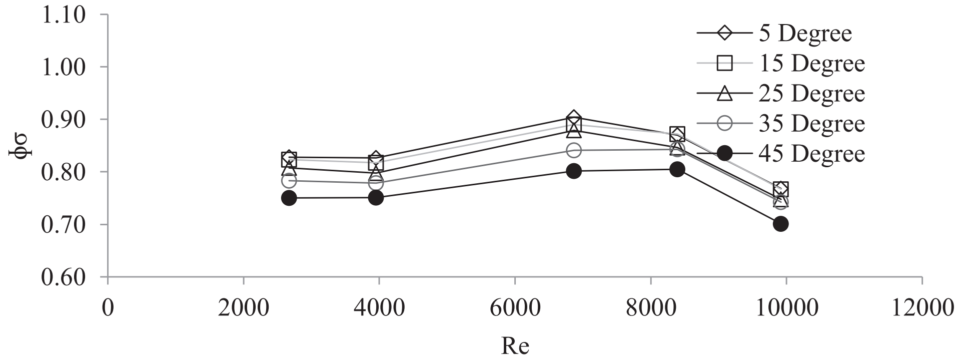
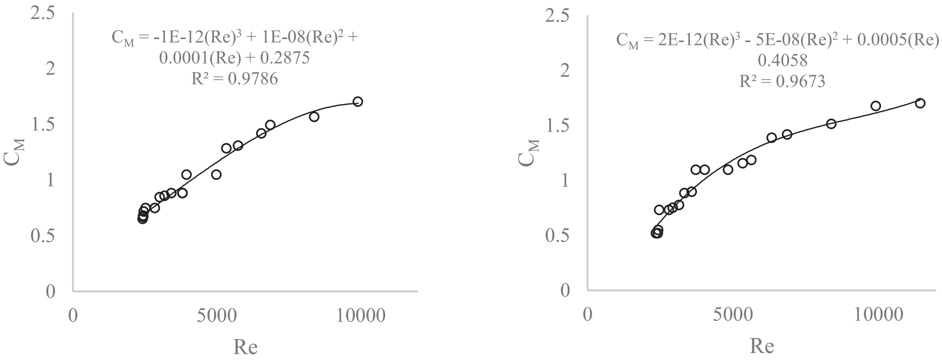


Fig. 8. Ratio of the standard deviation of short-crested wave force for directional spreading angles of 5°, 15°, 25°, 35°, and 45° to the long-crested wave force as a function of Re.

The quantification was conducted by computing the force ratio factors ϕ_σ considering the directional spreading angles ranging between 5° to 45°. The factors are presented as a function of Re as plotted in Fig. 8. From the results, the higher reduction of the force ratio factors was observed at greater directional spreading angle. Overall, it could be quantified that the total wave force is reduced by 1.12 % with every 1° incremental of the directional spreading angle. As highlighted by Hogedal et al. [19], this illustrates that the energy spreading distribution is greater as the directional spreading angle increases, which leads to a reduction of the wave forces.

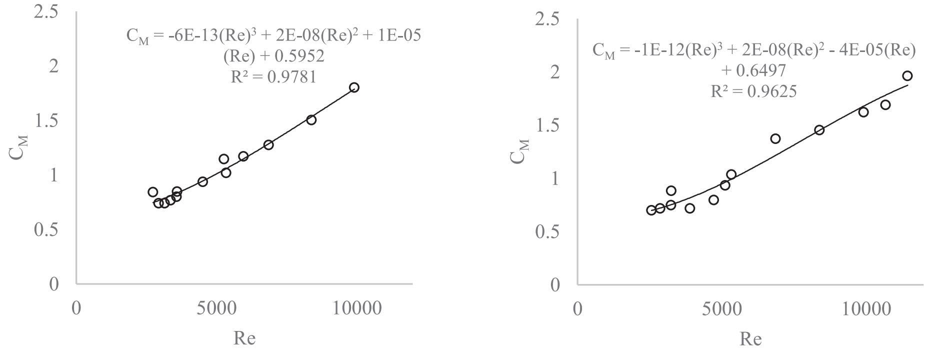
3.4. Hydrodynamic coefficients as function of Re numbers

The quantification of the wave directionality and directional spreading angles effects on the wave forces that exerted on a vertical cylinder within the Morison regime has extended to the computation of the hydrodynamic coefficients, i.e. inertia (C_M) and drag (C_D), by using the least squares method. The computation of C_M and C_D values for the directional spreading angles of 5°, 15°, 25°, 35°, and 45°, as a function of Re number are presented in Fig. 9(a-e) and 10(a-e) respectively. It can be observed that the hydrodynamic coefficients are presented as cubic functions, which best fit the



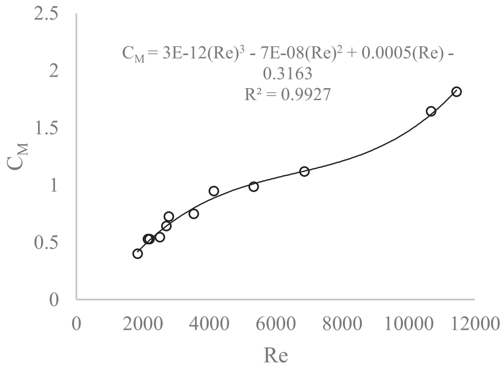
(a) Directional spreading angle, θ = 5°.

(b) Directional spreading angle, θ = 15°.



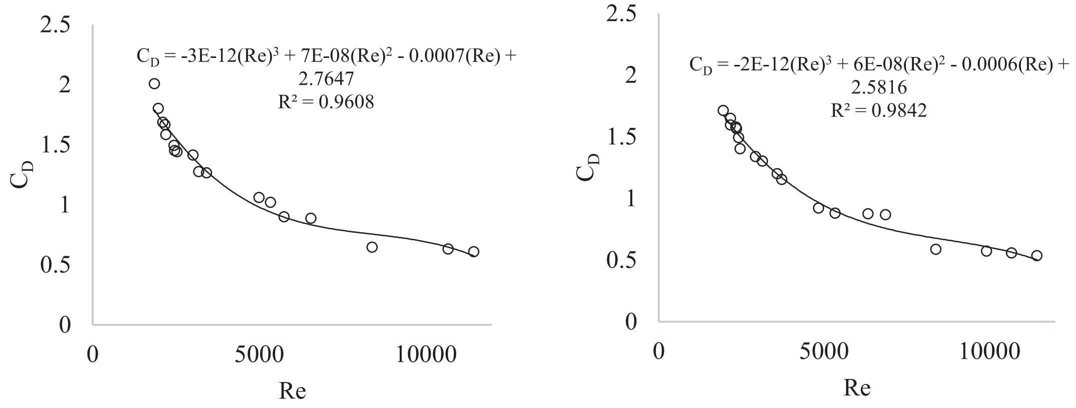
(c) Directional spreading angle, θ = 25°.

(d) Directional spreading angle, θ = 35°.



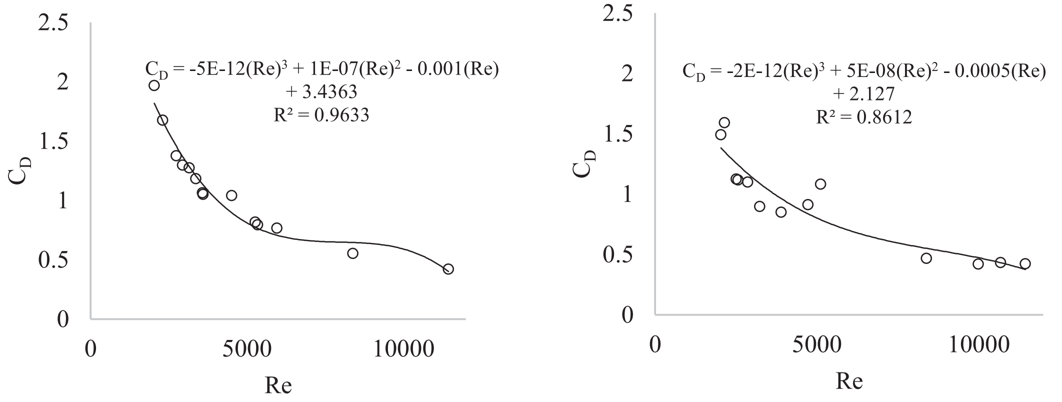
(e) Directional spreading angle, θ = 45°.

Fig. 9. C_M values for different directional spreading angles as function of Re.



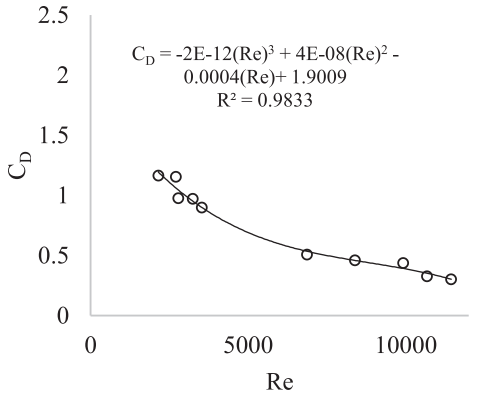
(a) Directional spreading angle, θ = 5°.

(b) Directional spreading angle, θ = 15°.



(c) Directional spreading angle, , θ = 25°

(d) Directional spreading angle, θ = 35°.



(e) Directional spreading angle, θ = 45°.

Fig. 10. C_D values for different directional spreading angles as function of Re.

data. To support this, the R^2 value for each function, which statistically measures the closeness of the data to the fitted regression plot, are also presented [57]. The R^2 values were found to be greater than 0.85, which indicates that the cubic functions serve well for these regression plots.

In present investigation, Re numbers from 2000 to 12,000 has been identified. Within these Re ranges, the transition and turbulence are gradually move upstream along the free shear layers and the wake becomes increasingly irregular. As the transition coincides with the separation point, laminar separation is

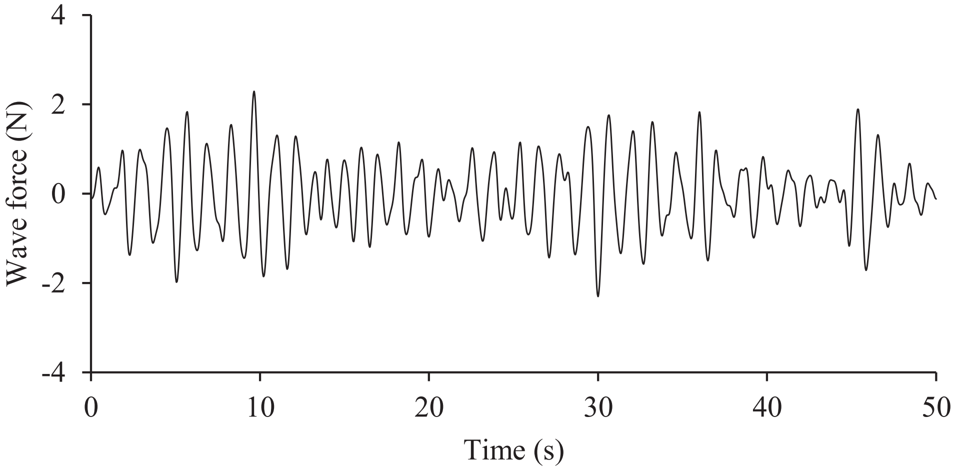


Fig. 11. Computed time history of wave forces.

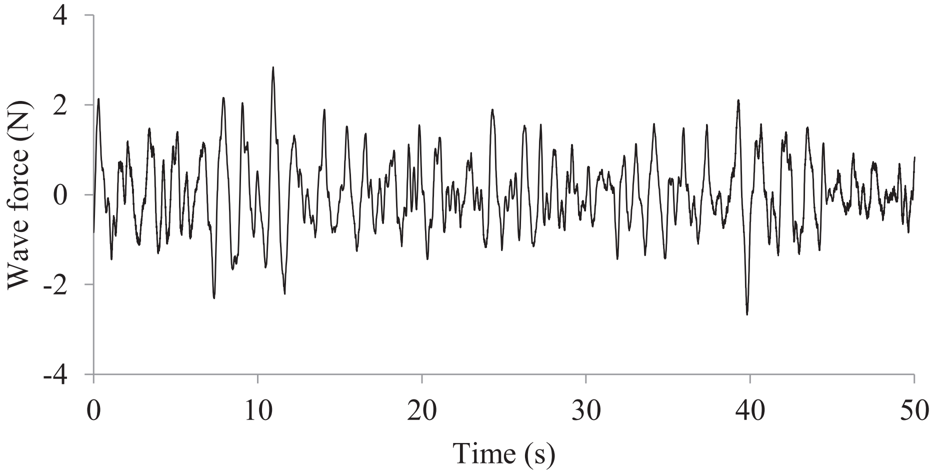


Fig. 12. Measured time history of wave forces.

expected. This is then followed by reattachment to the cylinder, whereby a turbulent separation occurs resulting in a narrower wake. The reduction of the wake size due to the separation points, has retreated the results to become a smaller drag, thus it is eventually resulting in a large fall in the coefficient values [58]. These findings are significantly importanti to distinguish the relationship between the hydrodynamic coefficients and Re numbers, especially to interpret the effect of the nonlinear properties of the short-crested wave on the hydrodynamic coefficients.

From these values, it is obvious that the C_M and C_D are found to be strongly affected by the directional spreading angles, whereby the values have slightly increased with the reduction of the directional spreading angle [19]. The reason being is that the larger directional spreading angle has caused a wider distribution of the total wave energy. Henceforth, this condition has lessened the magnitude of the total loading acting on the structures. Meanwhile, a smaller directional spreading angle may contribute to a more concentrated wave energy distribution, causing the generation of the wave energy focuses on the structures located within the wave region [59]. As the small discrepancy of the directional spreading angles may give a significant reduction or increment to the total wave force, the evaluation of the wave force using the existing formulation considering an accurate hydrodynamic coefficient is essential.

3.5. Application of proposed hydrodynamic coefficients in wave force prediction

To validate the reliability of the proposed C_D and C_M values, a comparison between the measured and computed wave forces, by commercial software, is presented herewith. The comparison, is performed considering significant wave height of 0.15 m and peak period of 1.4 s. The results of the comparison for directional spreading angles of 45°, with C_D is 0.51 and C_M is 1.00, are shown in Figs. 11 and 12 respectively. The comparison is found to be good in magnitude although at some period the crests are underpredicted. For a better interpretation of the time series, the comparison between the spectrum densities of the measured and computed forces is presented in Fig. 13. From the observation, a good agreement is observed at the peak frequency. However, some discrepancies are observed at higher frequency of the measured wave force, which expected to be contributed from the remaining noises in the data. As the frequency increases, both spectra are found to be constant and having nearly zero magnitude. Also, the measured and computed peak forces are plotted in Fig. 14, whereby each point represents the peak values of the wave forces. The comparison shows a good agreement with no discrepancy at both positive and negative peaks of the wave forces.

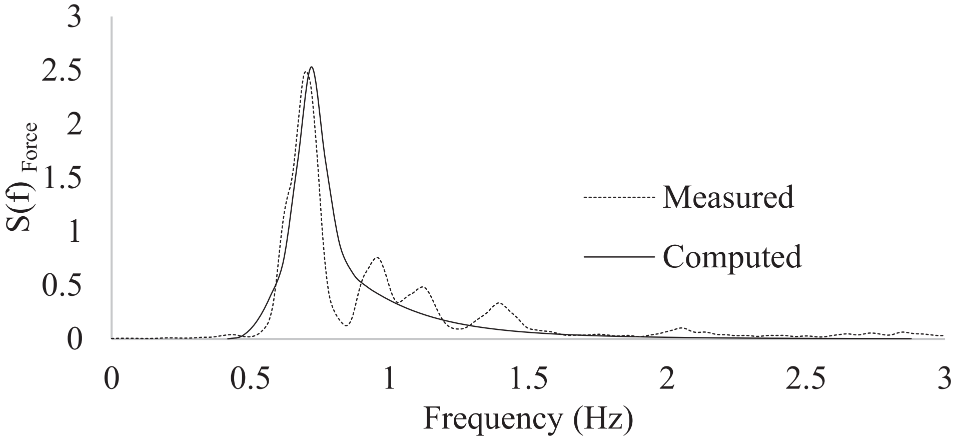


Fig. 13. Comparison of measured and computed wave force spectrum.

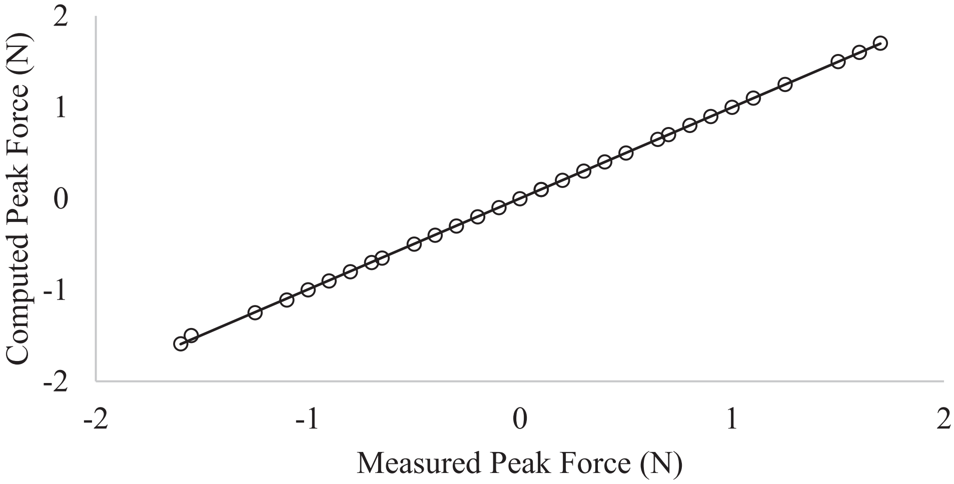


Fig. 14. Comparison of measured and computed peak wave force.

4. Conclusion

An experimental investigation was conducted to quantify the effects of wave directionality on the wave forces and to propose the hydrodynamic coefficients incorporated the effect of directional spreading angles. The quantification of the effects is presented in terms of force ratio factor, ϕ_{σ}, which is defined as the ratio of peak force standard deviation. Prior to the effects' quantification, the standard deviation of the peak wave forces are statistically assessed by using the hypothesis testing, and the significance differences of the effects on the wave forces are observed as the p-values are less than 0.5. In evaluating the effect of wave directionality, the force ratio factors of short-crested wave to long-crested wave are computed. The factors are observed at the range of 0.8, which indicates that the short-crested wave forces yield 20 % less loading as compared to the long-crested wave. Further quantification for the effect of directional spreading angles is also conducted. A reduction of the ratio factor with the increasing directional spreading angle is observed. From the results, a reduction of 1.12 % of the wave force is quantified for every 1° incremental of the directional spreading angle. This is mainly due to the larger wave energy distribution at a greater directional spreading angle that has reduced the magnitude of the wave force. Meanwhile, at smaller directional spreading angles, the wave energy is more concentrated, which permits the structure to experience a higher magnitude of the wave force. Referring to all these factors, the hydrodynamic coefficients incorporated with different directional spreading angles are then proposed. Based on the quantifications, a reduction of the hydrodynamic coefficient values has been observed at higher directional spreading angles. It is believed that by adopting the proposed hydrodynamic coefficients in the design and analysis of the marine structure, the total wave force is expected to be reduced. Moreover, the life cycle cost is also expected to be reduced, which enable a cost-effective and a more lean design of the marine structure.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This project has been funded by YUTP grant (Cost centre: 015LC0-120) and UNPAR grant (Cost centre: 015ME0-128). Also, the support and encouragement provided by Universiti Teknologi PETRONAS are gratefully acknowledged.

References

[1] Chakrabarti SK. Hydrodynamics of Offshore Structures. WIT Press Publisher; 1987.

[2] Zhu S. Diffraction of short-crested waves around a circular cylinder. Ocean Eng J 1993;20(4):389–407. doi: https://doi.org/10.1016/0029-8018(93)90003-z.

[3] Mat Soom E, Abu Husain MK, Mohd Zaki NI, M Nor MNK, and Najafian G. Lifetime extension of ageing offshore structures by Global Ultimate Strength Assesment (GUSA). Malaysian J. Civ. Eng. 2018;30(1):152–171. doi: 10.11113/mjce.v30.174

[4] Walker DAG, Taylor PH, Taylor RE. The shape of large surface waves on the open sea and the Draupner New Year wave. Appl Ocean Res 2004;26(3):73–83. doi: https://doi.org/10.1016/j.apor.2005.02.001.

[5] Dalzell JF. A note on finite depth second-order wave-wave interactions. Appl Ocean Res 1999;21(3):105–11. doi: https://doi.org/10.1016/S0141-1187(99)00008-5.

[6] American Petroleum Institute. API Design Guidelines. 2014. https://www.api.org/media/files/publications/ whats new/2a-wsd_e22 pa.pdf 2014.

[7] Venugopal V, Wolfram J, Linfoot BT. The properties of extreme waves. Health and Safety Executive Reserch Report 401. Edinburgh: Hariot-Watt University; 2005.

[8] Society of Naval Architects and Marine Engineers (U.S.). Panel OC-3. Loads, guidelines for site specific assessment of mobile jack-up units. Society of Naval Architects and Marine Engineers. 1991.

[9] Haver S. On the modelling of short crested sea for structural response calculations. First European Offshore Mechanics Symposium 1990;2:13–20.

[10] Chaplin JR, Subbiah K, Irani M. Loading on a vertical cylinder in multidirectional waves. J Offshore Mech Arct Eng 1995;117:151–8. doi: https://doi.org/10.1115/1.2827083.

[11] Kurian VJ, Ng CY, Liew MS. Numerical investigation on dynamic responses of classic spar platforms: Long crested waves vs. Short crested waves. IEEE Colloquium on Humanities, Science & Engineering Research 2012:724–8. doi: https://doi.org/10.1109/chuser.2012.6504407.

[12] Fang M, Lee Z. Portable dynamic positioning control system on a barge in short-crested waves using the neural network algorithm. China Ocean Eng 2013;27(4):469–80. doi: https://doi.org/10.1007/s13344-013-0040-x.

[13] Jian Y, Zhan J, Zhu Q. Short crested wave – current forces around a large vertical circular cylinder. Eur J Mech B/Fluids 2008;27(3):346–60. doi: https://doi.org/10.1016/j.euromechflu.2007.08.001.

[14] Wang P, Zhao M, Du X. Short-crested wave-current forces on composite bucket foundation for an offshore wind turbine. Math Probl Eng 2019;2019:1–9. doi: https://doi.org/10.1155/2019/5932742.

[15] Wang P, Zhao M, Du X, Liu J. Analytical solution for the short-crested wave diffraction by an elliptical cylinder. Eur J Mech B/Fluids 2019;74:399–409. doi: https://doi.org/10.1016/j.euromechflu.2018.10.006.

[16] Wang P, Zhao M, Du X. Short-crested, cnoidal, and solitary wave forces on composite bucket foundation for an offshore wind turbine. J. Renew. Sustain. Energy 2018;10(2):023305. doi: https://doi.org/10.1063/1.4995649.

[17] Journee JMJ, Massie WW. Offshore Hydromechanics. First Edition. Delf University of Technology; 2001.

[18] Isaacson M, Nwogu OU. Wave loads and motions of long structures in directional seas.. Journal of Offshore Mechanics and Arctic Engineering ASME 1987 May 1;109(2):126–32. doi: https://doi.org/10.1115/1.3257000.

[19] Hogedal M, Skourup J, Burcharth HF. Wave forces on a vertical smooth cylinder in directional waves. Proc Int Offshore Polar Eng Conf 1994;3:218–24.

[20] Subbiah K, Chaplin JR, Irani M. Loading on a vertical cylinder near mean water level in long- and short-crested waves. Int Soc Offshore Polar Eng 1995:324–31.

[21] Zhu S, Satravaha P. Second-order wave diffraction forces on a vertical circular cylinder due to short-crested waves. Ocean Eng J 1995;22(2):135–89. doi: https://doi.org/10.1016/0029-8018(94)00002-6.

[22] Zhu S, Moule G. Numerical calculation of forces induced by short-crested waves on a vertical cylinder of arbitrary cross-section. Ocean Eng 1994;21(7):645–62. doi: https://doi.org/10.1016/0029-8018(94)90043-4.

[23] Gudmestad OT, Moe G. Hydrodynamic coefficients for calculation of hydrodynamic loads on offshore truss structures. Marine Structures 1996 Sep;9(8):745–58. doi: https://doi.org/10.1016/0951-8339(95)00023-2.

[24] Ghoshal S, Deo MC, Narasimhan S. Wave force coefficients for inclined rough cylinders. Proc First Int Offshore Polar Eng Conf 1991;3(August):220–7.

[25] Wolfram J, Naghipour M. On the estimation of Morison force coefficients and their predictive accuracy for very rough circular cylinders. Appl Ocean Res 1999;21(6):311–28. doi: https://doi.org/10.1016/S0141-1187(99)00018-8.

[26] Keulegan G, Carpenter L. Forces on cylinders and plates in an oscillating fluid. Natl Bur Stand 1958;60(5):423–40. doi: https://doi.org/10.6028/jres.060.043.

[27] Yeung RW, Seah R. On the behavior of twin-body heave hydrodynamic coefficients. Proceedings of the Sixteenth (2006) International Offshore and Polar Engineering Conference. 2006;4:230-235.

[28] Lou X, Zhou T, Cheng L. Hydrodynamic coefficients of a yawed square cylinder in oscillatory flows. Ocean Eng 2017;130:510–22. doi: https://doi.org/10.1016/j.oceaneng.2016.11.038.

[29] Sooraj P, Agrawal A, Sharma A. Measurement of drag coefficient for an elliptical cylinder. J Energy Environ Sustain 2018;5:1–7. doi: https://doi.org/10.47469/jees.2018.v05.100050.

[30] Nouri NM, Mostafapour K. Development and evaluation of calibration procedure for a force-moment balance using design of experiments. Lat Am J Solids Struct 2016;13(1):119–35.

[31] Sundar V, Vengatesan V, Anandkumar G, Schlenkhoff A. Hydrodynamic coefficients for inclined cylinders. Ocean Eng 1998;25(4–5):277–94. doi: https://doi.org/10.1016/S0029-8018(97)00014-0.

[32] Sarpkaya T, Raines TS, Trytten DO. Wave forces on inclined smooth and rough circular cylinders. Offshore Technology Conference 1982;731–736. doi: https://doi.org/10.4043/4227-MS.

[33] Cotter DC, Chakrabarti SK. Wave force tests on vertical and inclined cylinders. J Waterw Port, Coast Ocean Eng 1984;110(1):1–14. doi: https://doi.org/10.1061/(asce)0733-950x(1984)110:1(1).

[34] Buresti G. The effect of surface roughness on the flow regime around circular cylinders. J Wind Eng Ind Aerodyn 1981;8(1–2):105–14. doi: https://doi.org/10.1016/0167-6105(81)90011-8.

[35] Mohd Ghazali MK, Shaharuddin NMR, Ali A, Siang KH, Mohd Nasir MN, Talib MHA. Surface roughness effect on vortex-induced vibration phenomenon in cross-flow direction of a bluff body. J Adv Res Fluid Mech Therm Sci 2019;2(2):253–63.

[36] Nath JH. Hydrodynamic coefficients for macro-roughnesses. Offshore Technology Conference 1981::337–56. doi: https://doi.org/10.4043/3989-ms.

[37] Kurian VJ, Sebastian AA, Al-Yacouby AM, Liew MS, Idichandy VG. Wave forces on linear arrays of rigid vertical circular cylinders in regular waves. Res J Appl Sci Eng Technol 2014;7(24):5249–57. doi: https://doi.org/10.19026/rjaset.7.921.

[38] Kurian VJ, Al-Yacouby AM, Sebastian AA, Liew MS. Idichandy VG. Hydrodynamic coefficients for array of tubular cylinders. Proceedings of the Twenty-Fourth International Ocean and Polar Engineering Conference 2014;3:641–8.

[39] Borgarino B, Babarit A, Ferrant P. Impact of wave interactions effects on energy absorption in large arrays of wave energy converters. Ocean Eng 2012;41:79–88. doi: https://doi.org/10.1016/j.oceaneng.2011.12.025.

[40] Sarpkaya T, Bakmis C, Storm MA. Hydrodynamic forces from ccombined wave and current flow on smooth and rough circular cylinders at high Reynolds numbers. Offshore Technology Conference 1984;455–462. doi: https://doi.org/10.4043/4830-MS.

[41] Li Y, Lin M. Hydrodynamic coefficients induced by waves and currents for submerged circular cylinder. Procedia Eng 2010;4:253–61. doi: https://doi.org/10.1016/j.proeng.2010.08.029.

[42] Teng CC. Hydrodynamic forces on a horizontal cylinder under waves and current Master thesis. Oregon State University; 1983.

[43] Lavrov A, Rodrigues JM, Gadelho JFM, Soares CG. Calculation of hydrodynamic coefficients of ship sections in roll motion using Navier-Stokes equations. Ocean Eng 2017;133:36–46. doi: https://doi.org/10.1016/j.oceaneng.2017.01.027.

[44] Aoki S. Shallow water effect on hydrodynamic coefficients of very large floating structures. In: Proceedings of 7th International Offshore Polar Engineering Conference, Vol.. I; 1997. p. 253–60.

[45] Chakrabarti SK. In: Handbook of Offshore Engineering. Elsevier; 2005. p. 133–96.

[46] Sattar S, Rana S. Significance of dimensionless numbers in the fluid mechanics. Fifth Multidisc Student Res Int Conference 2019.

[47] Ng CY, Tuhaijan SNA, Abdul Fattah MZ, Kurian VJ, Mustaffa Z. Experimental investigation of directional hydrodynamic coefficients and the effects on wave force due to spreading angles.. Ain Shams Eng J 2020;11(4):1021–34. doi: https://doi.org/10.1016/j.asej.2020.01.012.

[48] Chakrabarti SK. Offshore Structure Modelling. Appl Ocean Res 1995;17(6):391–2. doi: https://doi.org/10.1016/s0141-1187(96)00012-0.

[49] PETRONAS.. PETRONAS Technical Standard: Design of Fixed Offshore Structures. (Working Stress Design) 2012.

[50] Bazergui A, Eryuzlu NE, Saucet J-P. A submersible 3-d load transducer platform. Exp Tech. 1987;11(9):25–29. http://doi.org/10.1111/j.1747-1567.1987.tb00258.x.

[51] HR Wallingford. Wave Tank Manual.; 2010.

[52] Islam M, Jahra F, Hiscock S. Data analysis methodologies for hydrodynamic experiments in waves. J Nav Archit Mar Eng 2016;13(1):1–15. doi: https://doi.org/10.3329/jname.v13i1.25347.

[53] Isaacson M, Subbiah K, Baldwin J. Force coefficient estimation from random wave data. First (1991) International Offshore and Polar Engineering Conference 1991;3:149–57.

[54] Sarpkaya T, Collins NJ, Evans SR. Wave forces on rough-walled cylinders at high Reynolds numbers. Offshore Technol Conf 1977;175–184. doi: https://doi.org/10.4043/2901-MS.

[55] Kasahara Y, Shimazaki K, Koterayama W. Wave forces acting on rough circular cylinders at high Reynolds numbers. Proc Nineth Annu Offshore Technol Conf 1987;153–160. doi: https://doi.org/10.4043/5372-ms.

[56] Lyons GJ, Brown DT, Lin HM. Drag coefficients for mooring line hydrodynamic damping. In: Proceedings of the Seventh (1997) International Offshore and Polar Engineering Conference. 1997;3:473–9.

[57] Deb S. A novel robust R-squared measure and its applications in linear regression. Comput Intellingence Inf Syst 2016:131–42. doi: https://doi.org/10.1007/978-3-319-48517-1_12.

[58] Dell'Isola A. Value Engineering: Practical Applications... for Design, Construction, Maintenance and Operations. Wiley 1997.

[59] Hughes S. Directional wave spectra using cosine-squared and cosine 2s spreading functions. Coastal Eng Technical Note 1985.

Dr Ng ChengYee is current a senior lecturer in Civil and Environmental Engineering Department of Universiti Teknologi PETRONAS (UTP). She received her BEng in Civil Engineering (2008), MSc in Civil Engineering (Offshore Structures) in 2010 and PhD in Civil Engineering (Offshore Structures) in 2014 from UTP. She returned to her alma mater UTP in year 2014 as a lecturer. In her current research, she's focusing on Engineering Education, Offshore Structures, Wave hydrodynamics and Marine Renewable Energy. She was invited as a visiting scholar by Sepuluh Nopember Institute of Technology (ITS), Indonesia. Recently, she was also been invited under the EU Erasmus+ Staff Mobility Program for Teaching to Middle East Technical University (METU), Turkey to deliver a series of lectures and seminars. In 2018, she was seconded in the Project Management Office of UTP as a data analyst as well the university ranking data management. Nevertheless, she is also a Lean Six-Sigma Greenbelt Practitioner. She's truly passionate and actively seeking opportunity in both academic as well research collaborations