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A New Method for Determining the Design Values of Wave-Induced Vertical Bending Moments Acting on Ship-Shaped Offshore Installations in Survival Conditions

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Abstract

The aim of this study is to develop a new method for determining the design values of wave-induced vertical bending moments acting on ship-shaped offshore installations in survival conditions. Although the guidelines of classification societies are useful for determining the design values of wave-induced loads, considering survival conditions with the most probable extreme waves for a return period of 100 years, the determination of their design values using long-term stochastic method is challenging owing to the complex procedures and a large amount of hydrodynamic analyses which lead to huge computation time. In this paper, a new method is developed to determine the design values of wave-induced vertical bending moments for ship-shaped offshore installations in survival conditions where the maximum wave height selected from metocean data is used with a wave length equal to vessel's length in head sea. As an applied example, a very large crude oil carrier (VLCC)-class floating, production, storage, and offloading (FPSO) unit in survival conditions is considered at six different seas – the North Sea, Gulf of Mexico, western coast of Africa, eastern coast of South America, southeastern coast of Asia, and northwestern coast of Australia. A comparison is made among the present solutions, environmental contour-based solutions, and the long-term stochastic method-based classification society rule values.

Keywords: Ship-shaped offshore installations; Survival conditions; Wave-induced vertical bending moments; Site-specific metocean data; Long-term analysis; Inverse first-order reliability method (IFORM)

1. Introduction

For structural design of ships and ship-shaped offshore installations, it is crucial to determine proper design values of wave-induced vertical bending moments, which are considered as main loading acting on primary hull structures together with still water bending moments, to ensure the structural safety throughout their lifetime (Hughes and Paik, 2013; Paik, 2018, 2020, 2022). However, the determination of wave-induced loads is not straightforward due to many uncertainties and complexities of ocean environmental conditions, and difficulties in predicting the extreme values of wave loads acting on the hull structures.

Progress and challenges on the prediction of wave-induced loads acting on ships and ship-shaped offshore installations have been recognised (Temarel, 2016). Sogstad (1995) developed a simplified method to predict the wave-induced vertical bending moments acting on floating, production, storage, and offloading units (FPSO) and concluded that the simplified method is useful in preliminary design but cannot be replaced with direct hydrodynamic analysis for the final design stage. Zhao and Wu (2002) proposed combined-table approach that is applicable to complicated wave conditions with both swell and

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sea waves in separate directions. Hamdan (2003) investigated the factors affecting wave-induced loads on FPSOs. Moan et al. (2005) analysed the statistical variability of wave conditions with the extreme values of wave-induced vertical bending moments on an FPSO. Guedes Soares et al. (2006) experimentally and numerically analysed the wave-induced vertical bending moments on an FPSO in rogue waves and compared the results with classification society rule values. Kim et al. (2007) proposed the criteria to be used for predicting the extreme wave loads on an FPSO in complicated wave conditions with both swell and sea waves. Fonseca et al. (2010) investigated wave-induced vertical bending moments on an FPSO in regular and irregular waves, and compared the results obtained from numerical analysis and experiments. Ivanov et al. (2011) discussed the probability density distributions of wave-induced bending moments and its effect on the total bending moment of FPSOs. Oberhagemann et al. (2012) proposed a method based on the combination of environmental contour and Monte-Carlo simulations for long-term extreme value analysis of wave loads. Chen (2016) presented a stochastic model for the extreme value of wave-induced vertical bending moments on FPSO and analysed the reliability of hull girder ultimate strength of an FPSO. Cabrera-Miranda et al. (2018) estimated the wave-induced bending moments on disconnectable FPSOs using probabilistic scenario sampling and kriging metamodels. Kim et al. (2021) proposed a method for predicting the design values of wave-induced vertical bending moments acting on an FPSO in benign conditions. Paik (2022) presents the methodologies to determine wave-induced hull girder loads acting on ship-shaped offshore installations in benign, survival and tow conditions.

Unlike in trading ships, in which the design value is determined by closed-form equations composed of principal dimensions and operational parameters, the design wave loads of ship-shaped offshore installations should be determined through direct hydrodynamic load analysis taking into account site-specific sea states. The guideline of classification societies is effective for determining the design values of wave-induced vertical bending moments considering survival conditions with the most probable extreme waves for a return period of 100 years. However, the determination of their design values using the long-term stochastic method is challenging owing to the complex procedures and a large amount of hydrodynamic analyses which lead to huge computation time. While classification societies recommend using the linear long-term stochastic method to address the aforementioned challenges in the long-term approach, the procedures remain complex and time-consuming, requiring seakeeping analysis and long-term stochastic process.

In this paper, a new method is developed to determine the design values of wave-induced vertical bending moments for ship-shaped offshore installations in survival conditions where the maximum wave height selected from metocean data is used with a wave length equal to vessel's length in head sea. To demonstrate the proposed method, a hypothetical very large crude oil carrier (VLCC)-class floating, production, storage, and offloading unit (FPSO) model is used in this study. Details of the hypothetical FPSO model are presented in Section 2.

Six regions, namely the North Sea, Gulf of Mexico, western coast of Africa, eastern coast of South America, southeastern coast of Asia, and northwestern coast of Australia, which are the primary oil and gas production fields for FPSOs represented in Table 1, are considered as the target locations for comparing the effect of sea states. The results obtained by the proposed method are compared with those of long-term stochastic method and environmental contour-based solutions in Section 3. Rule values considering specific regulations of each classification society are presented and compared with the results obtained from the proposed method in Section 4.

Table 1. Distribution of floating, production, storage, and offloading units (FPSOs) in primary oil and gas production fields in 2022 (Boggs et al., 2022).

Location	Operating FPSO	Percentage (%)
Worldwide	163	100.0
North Sea	18	11.0
Gulf of Mexico	6	3.7
Western coast of Africa	41	25.2
Eastern coast of South America	48	29.4
Southeastern coast of Asia	21	12.9
Northwestern coast of Australia	6	3.7

2. Hypothetical FPSO Model for Hydrodynamic Load Analysis

To demonstrate the proposed method, a hypothetical FPSO was modelled for ship motion and wave load analysis. Table 2 indicates the principal dimensions of the hypothetical FPSO model. The principal dimensions of the hypothetical FPSO model were determined using data related to currently operating FPSOs built since 2000, as represented in Table 3. This study did not consider FPSOs converted from trading tankers, but the data are available in Chapter 1 of Paik (2022). Fig. 1 shows the three-dimensional finite element model of the hypothetical FPSO hull structures.

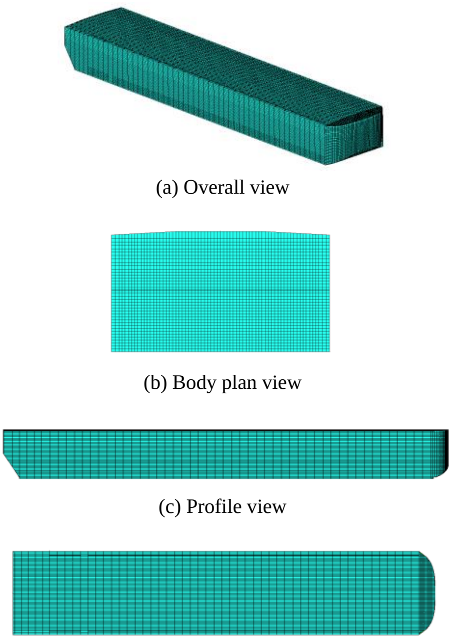
The hull structures were modelled in detail, including longitudinal structures, longitudinal and transverse bulkheads, and transverse web frames, since the centre of gravity and buoyancy need to be assigned properly, together with the subsequent trim condition (Paik 2019). However, the details of structural scantlings are not presented in this study due to the fact that the aim of this study is not structural analysis – refer to Chapter 1 of Paik (2022). FPSOs are generally subjected to severe vertical bending moments under fully loaded conditions, and thus the hypothetical FPSO model was assumed to be fully loaded for the hydrodynamic analysis. The weight at the topside and living quarters are assumed as 30,000 tons and 3,500 tons, respectively (Ha et al. 2017, Hwang et al. 2010).

Table 2. Principal dimensions of the hypothetical FPSO model.

Parameter	Dimension
Length Between Perpendicular (L)	305.0 m
Breadth (B)	60.0 m
Depth (D)	32.0 m
Design Draught (T)	23.3 m
Block Coefficient (C_b)	0.975

Table 3. Comparison of the principal dimension ratios between average values of worldwide FPSOs (built in 2000-2022) and the hypothetical FPSO.

Type	L/B	B/ D	T/ D	B/ T
Newly-built FPSO worldwide	5.1	1.9	0.7	2.8
Hypothetical FPSO	5.1	1.9	0.7	2.6



(a) Overall view

(b) Body plan view

(c) Profile view

(d) Plan view

Fig. 1. Three-dimensional finite element model of the hypothetical FPSO hull.

3. Methods for Determining Design Values of Wave-Induced Vertical Bending Moments

As ship-shaped offshore installations always remain on a specific site except for tow, the design value of wave-induced loads should be determined through direct hydrodynamic load analysis taking into account site-specific wave conditions, as described in Section 1. In this study, six target regions where the actual FPSOs are in service were considered as listed in Table 4. Historical wave data from 1979 to 2019 were obtained from a spectral wave model known as MIKE 21 (DHI 2019). Fig. 2 illustrates the site-specific wave characteristics of the six regions.

In the maritime industry, two methods are generally used to predict extreme values of wave-induced loads on offshore structures: namely, long-term analysis and environmental contour-based method. In this section, the long-term stochastic method and the inverse first-order reliability method (IFORM) are introduced and compared with the present method. Fig.3 compares the procedures of the two methods and the present method for determining design values of wave-induced vertical bending moments acting on ship-shaped offshore installations. All the hydrodynamic analysis performed in this study was carried out using the MAESTRO software based on three-dimensional potential theory (MAESTRO 2023).

Table 4. Specific locations of the six target regions based on the FPSOs in service.

Site	Target FPSO	Latitude	Longitude
North Sea	PETROJARL KNARR	61.78°N	2.83°E
Gulf of Mexico	YÙUM K'AK'NÁAB	19.60°N	92.30°W
Western coast of Africa	EGINA	3.05°N	6.70°E
Eastern coast of South America	PETROBRAS 67	25.33°S	42.69°W
Southeastern coast of Asia	PFLNG SATU	6.45°N	115.44°E
Northwestern coast of Australia	PRELUDE	13.79°S	123.31°E

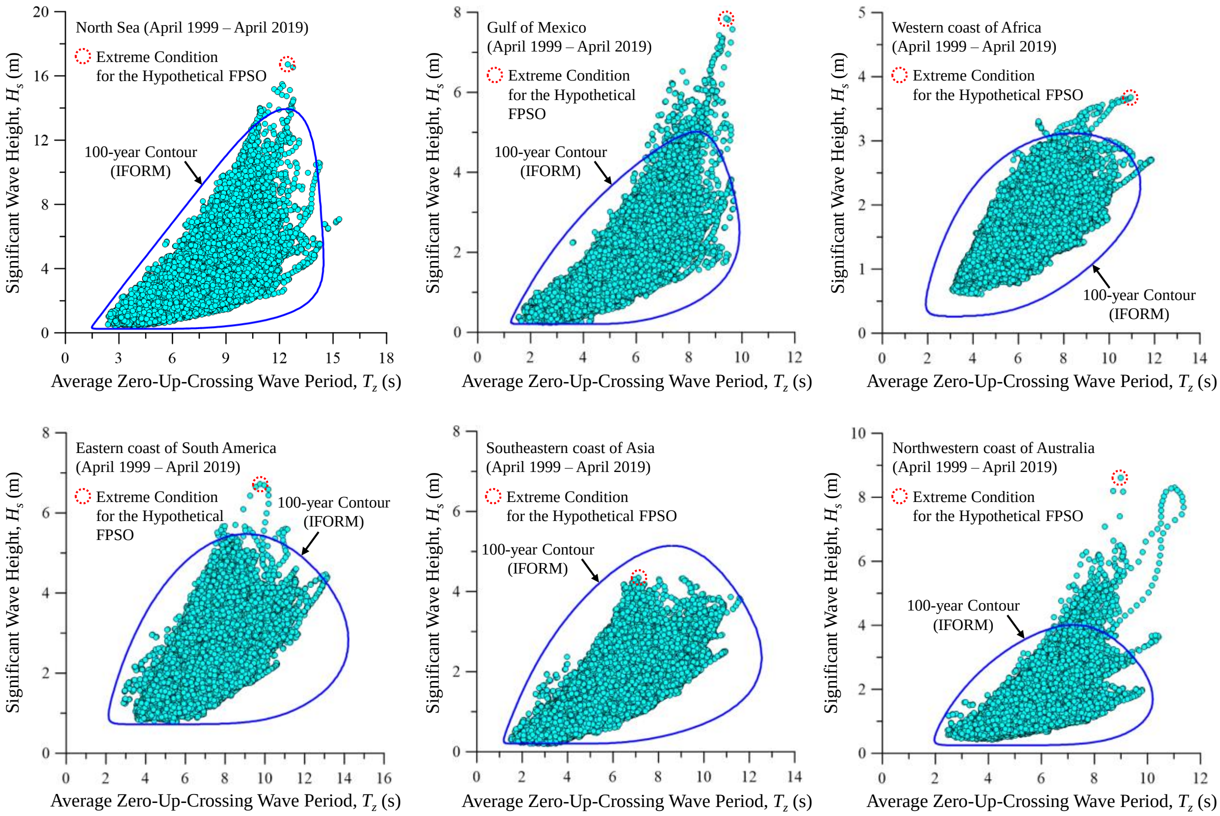


Fig. 2. Site-specific wave scatter plots of the six target regions and environmental contours for a return period of 100 years.

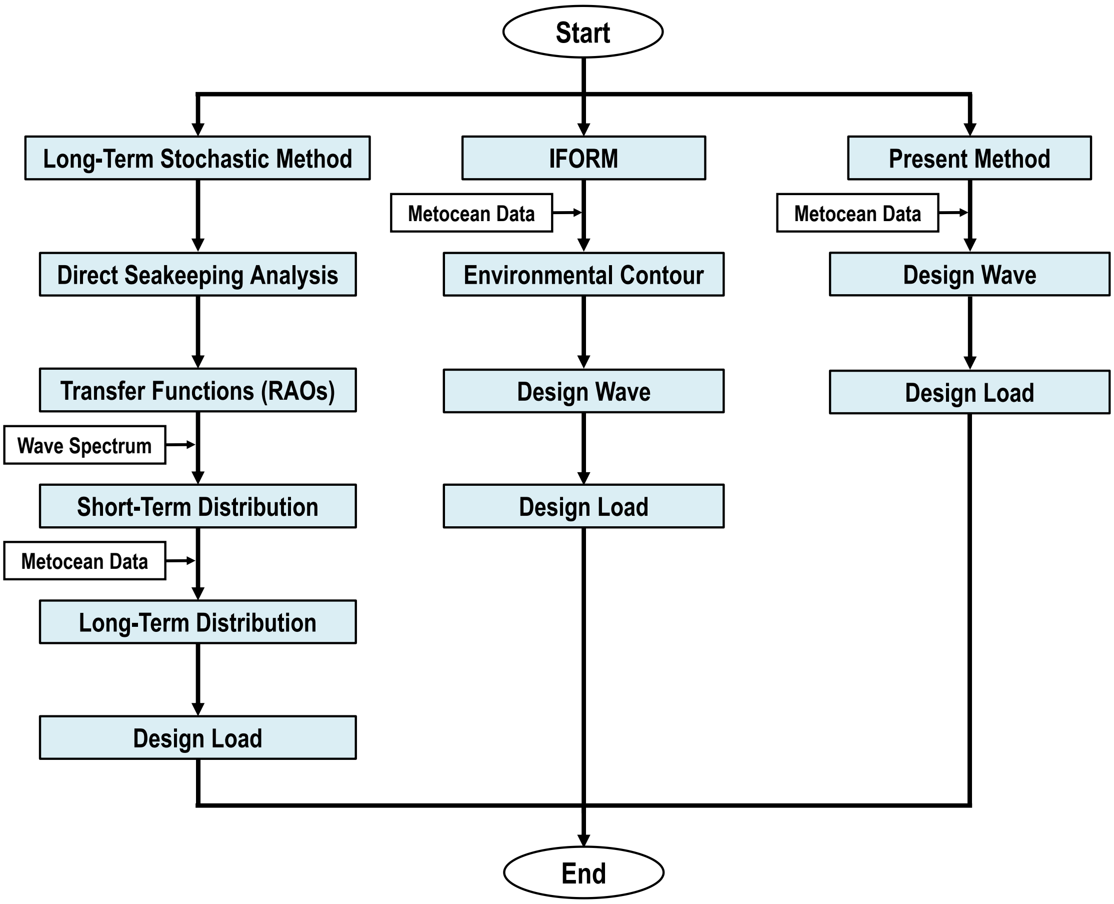


Fig. 3. Procedures of the three different methods for determining design values of wave-induced vertical bending moments: long-term stochastic method, environmental contour-based method (IFORM), and the present method.

3.1. Long-term stochastic method

The long-term stochastic analysis is the most commonly used method to estimate the extreme responses of ships and offshore structures under wave loads over a long period (typically more than 20 years) in accordance with the design life. It is noted that fully-linear or partially-linear method is normally used in the industry for the purpose of practical use to save the computation time, although nonlinear method can provide more accurate response predictions. Transfer functions (i.e., response amplitude operators, RAOs) and short-term distribution of response are the elements to perform the method, and long-term distribution of response is estimated based on the combined results of the short-term distributions with metocean data (i.e., wave scatter diagram and wave rosette). As indicated in Fig. 3, transfer functions can be obtained through direct seakeeping analysis. Fig.4 shows the transfer functions of the vertical bending moment at midship of the hypothetical FPSO model.

Long-term distribution of response can be calculated by Equations (1)-(3) and herein Rayleigh distribution and JONSWAP spectrum are used in this study. The design value of wave loads can be determined by Equation 4 in accordance with the return period. Fig. 5 shows the long-term distribution and the design value of the hypothetical FPSO in the North Sea.

$$m_n = \int_0^{2\pi}\int_0^{\infty} \omega^n \left|H_i(\omega,\theta)\right|^2 S_w(\omega,\theta)\, d\omega\, d\theta \qquad (1)$$

$$F_S(x) = 1 - \exp\left(-\frac{x^2}{2m_0}\right) \qquad (2)$$

$$F_L(x) = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} F_S(x)\, p_w\, p_\theta \quad (3)$$

where m_n is the moments of the response spectrum, ω is wave frequency, θ is heading angle, $H_i(\omega,\theta)$ is the transfer function, $S_w(\omega,\theta)$ is the wave spectrum, $F_S(x)$ is the short-term cumulative probability distribution, x is the response (i.e., vertical bending moment), $F_L(x)$ is the long-term distribution of response, p_w is the joint probability from the wave scatter diagram, and p_θ is the weight factor for heading angle from the wave rosette.

$$D(x_D) = 1 - F_L(x_D) = \frac{T_{z,avg}}{T_R \times 365.25 \times 24 \times 3600} \quad (4)$$

where x_D is the design value of the response, $D(x_D)$ is the probability of exceedance, $T_{z,\mathrm{avg}}$ is the average zero-up-crossing period, and T_R is the return period.

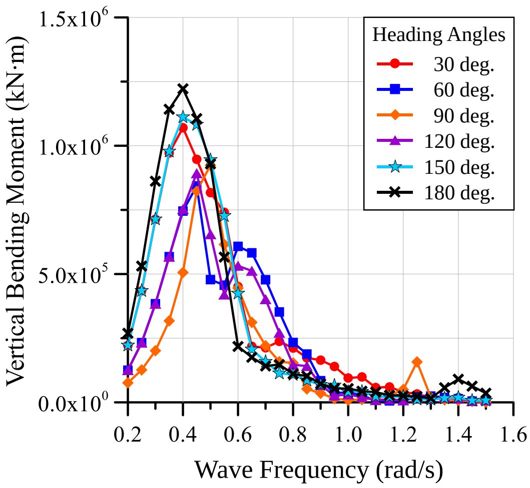


Fig. 4. Transfer functions of the vertical bending moment at midship of the hypothetical FPSO.

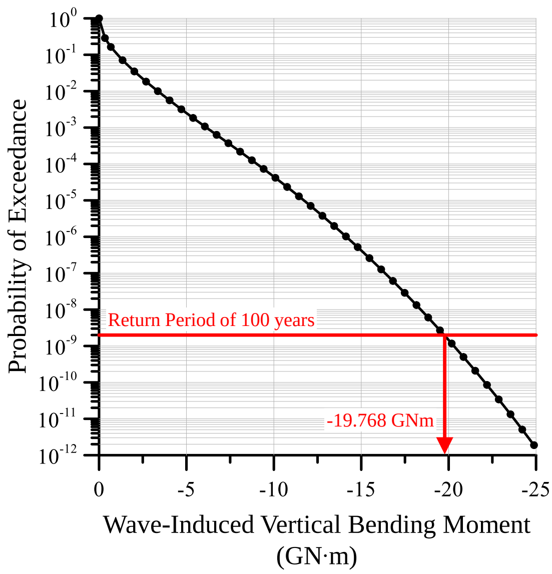


Fig. 5. Long-term distribution of the wave-induced vertical bending moment at midship of the hypothetical FPSO in the North Sea.

3.2. Environmental contour-based method (IFORM)

Environmental contour is useful to define extreme conditions of waves on offshore structures according to a return period, and design actions (i.e., design waves) can be determined directly using the wave parameters on the contour such as significant wave height and zero-up-crossing wave period. In this study, the inverse first-order reliability method (IFORM) was used to draw the environmental contours of the six target regions as shown in Fig. 2. The procedures for drawing an environmental contour using the IFORM method are outlined in Fig. 6. Further details can be found in Appendix 4 of Paik (2022).

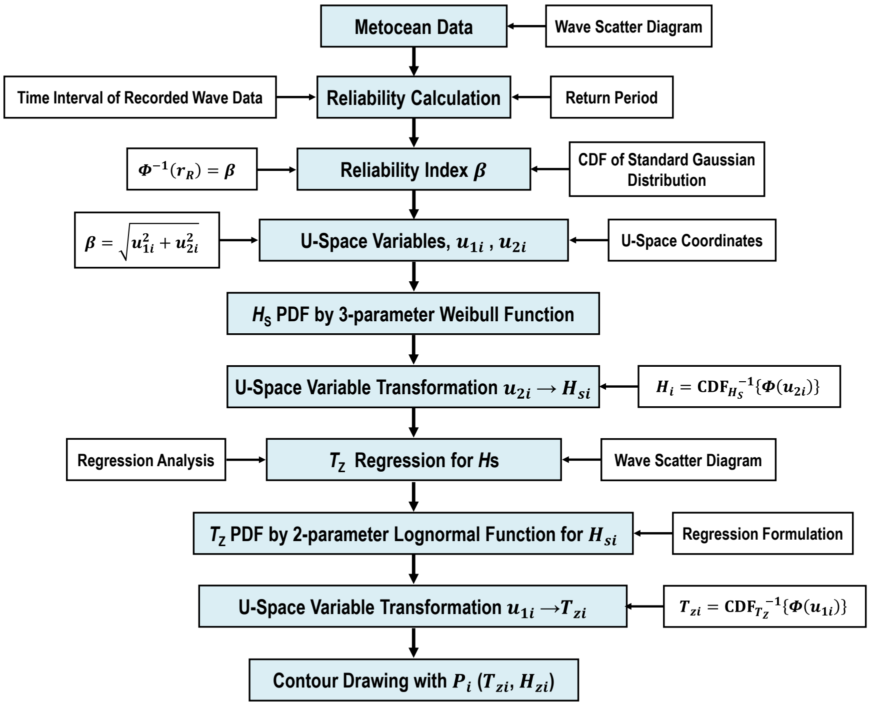


Fig. 6. Procedure for drawing an environmental contour using the IFORM method (Paik 2022).

3.3. Present method

The former two methods provide rational and reliable design values based on probabilistic approaches, while the procedures are highly sophisticated and/or require huge computation time. To overcome these difficulties, this paper presents a simplified method to determine the design values of wave-induced vertical bending moments acting on ship-shaped offshore installations. The present method is based on long-term wave measurement data, and the design values can be determined through direct hydrodynamic load analysis with the design waves as follows:

- Step 1: Establish a table or wave scatter plot of long-term wave data measured at regular time interval (e.g., 3 hours).

- Step 2: Define the design wave with the maximum wave height selected from the long-term wave data and wave length equal to the vessel’s length.

- Step 3: Perform the hydrodynamic load analysis with the design wave in head sea and different phase angles.

- Step 4: Determine the design value of wave-induced vertical bending moments based on the results of hydrodynamic load analysis.

Both the present method and the environmental contour-based method use the concept of "design wave" which is a representative of waves defined by site-specific wave parameters such as wave height, wave duration and wave angle in terms of determining the design values of wave-induced loads. However, the two methods are different from each other in defining wave parameters of the "design wave" as shown in Fig. 7, where the present method defines a single "design wave" with regard to the highest wave height in the wave scatter plot, while the environmental contour-based method defines multiple "design waves" along the contour. The present method is simpler to define the "design wave" with a single condition of the "extreme waves", while the environmental contour-based method considers multiple conditions of waves along the contour which do not necessarily present the "extreme waves". Table 5 presents the "design waves" of the six target regions defined by the present method. It is worthy to note that this study considered only head sea condition to simplify the procedure for determining the design value of wave-induced loads, but various heading angles can be taken into account for more accurate results.

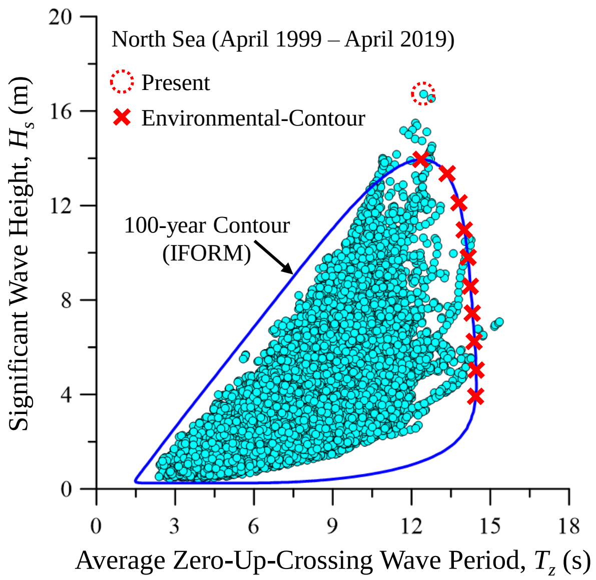


Fig. 7. Illustrative example of the wave parameters defined by the present method and the environmental-contour method.

Table 5. Design waves of the six target regions defined by the present method.

Site	Wave Height (m)	Wave Length (m)	Heading Angle (°)
North Sea	16.718	305.0	180.0
Gulf of Mexico	7.848		
Western coast of Africa	3.676		
Eastern coast of South America	6.721		
Southeastern coast of Asia	4.344		
Northwestern coast of Australia	8.609		

3.4. Results and discussions

Fig. 8 shows the extreme values of the wave-induced vertical bending moments for the six target regions obtained from the long-term stochastic method, the environmental contour-based method (IFORM), and the present method. All of the results presented in this study are negative values since FPSOs are generally deployed in sagging conditions. The three methods yielded different extreme values depending on the site-specific sea states. However, the IFORM generally underestimated the extreme values compared to those of the long-term stochastic method, as reported by BV (2019). On the other hand, the present method showed higher results than the other two methods, especially in the Gulf of Mexico and the northwestern coast of Australia, where tropical cyclones periodically occur. These differences may be attributed to the fact that the effects of such tropical cyclones are less reflected in probabilistic approaches due to their short-term period of storm. Therefore, the present method is likely to provide more "pessimistic" design values, taking into account all probable storms.

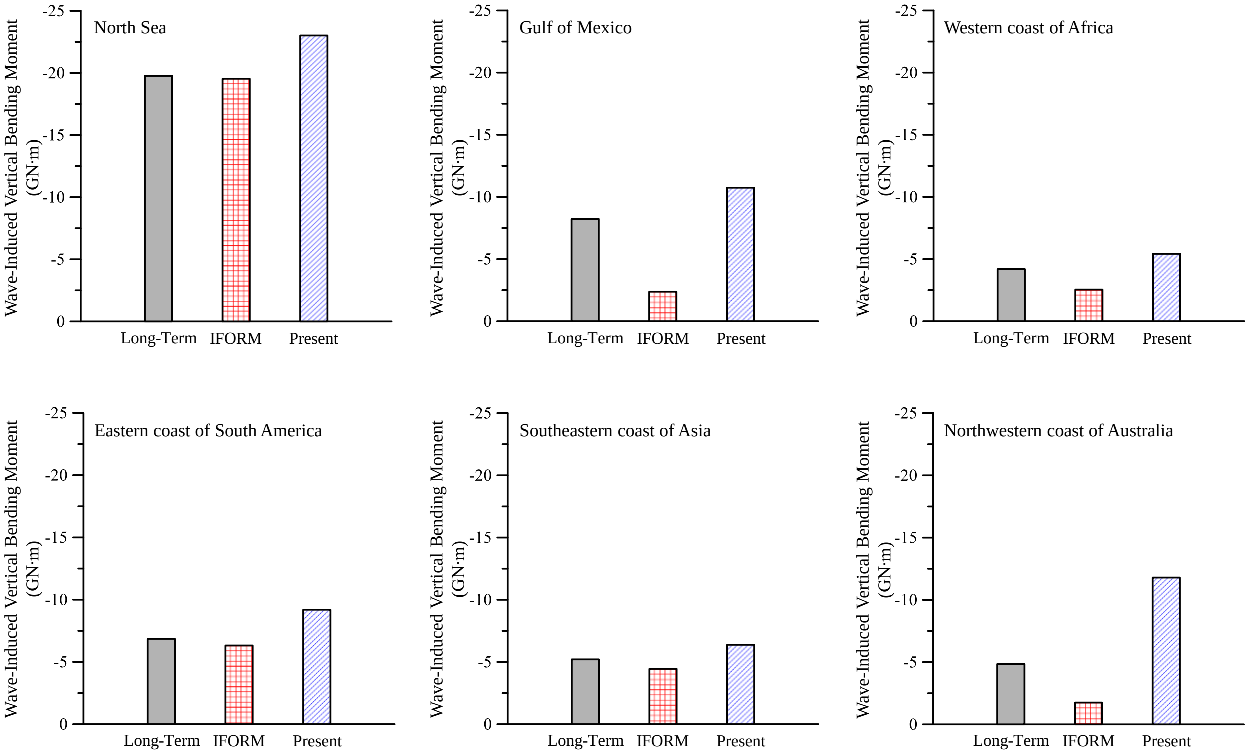


Fig. 8. Extreme values of the wave-induced vertical bending moments for the six target regions obtained from the long-term stochastic method, the environmental contour-based method (IFORM), and the present method.

4. Comparison with the Classification Society Rule Values

The design values for classification society rules are typically determined using the extreme value obtained from the long-term stochastic method. However, the design values of wave-induced loads may vary depending on the specific regulations of each classification society rule, even if the estimated extreme value is the same This section introduces the guidelines provided by the American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), and Lloyd's Register (LR). The rule values determined in accordance with these guidelines are compared with the design values obtained from the present method.

4.1. ABS (2023)

The load defined by the criterion for trading tankers (hereafter M_{CSR}) is used for determining the design value of wave-induced vertical bending moments (IACS 2023). As specified in Equation 5, the design value is determined by multiplying the M_{CSR} by the environmental severity factor β_{VBM} (ESF). The ESF can be calculated using Equation (6), and the design value must not be less than 85 per cent of the M_{CSR}.

$$M_D = M_{CSR} \times \beta_{VBM} \tag{5}$$

$$\beta_{VBM} = \frac{M_{Site}}{M_{N.A.}} \tag{6}$$

where M_D is the design value of wave-induced vertical bending moment, M_{Site} is the extreme value based on the intended site environment (return period of 100 years), and $M_{N.A.}$ is the extreme value based on the North Atlantic environment.

4.2. BV (2016)

The design wave-induced vertical bending moment is the higher value between the extreme value obtained from the long-term stochastic method and the value calculated by Equation 7. The design value must not be less than 65 per cent of M_{CSR}.

$$M_D = \mathrm{n} \times M_{CSR} \tag{7}$$

where n is the navigation coefficient as indicated in Table 6.

Table 6. Navigation coefficient provided by BV (2016).

Navigation Notation	n
Unrestricted navigation	1.00
Summer zone	0.90
Tropical zone	0.80
Coastal area	0.80
Sheltered area	0.65

4.3. DNV (2021)

The design value is the extreme value obtained from the long-term stochastic method. For ship-shaped offshore installations in harsh environment (e.g., the North Sea), nonlinear effects should be considered by multiplying the extreme value by the nonlinear correction moment factors. For sagging conditions, the nonlinear correction moment factor is 1.2. The design value must not be less than M_{CSR} and 50 per cent of M_{CSR} for harsh and benign conditions, respectively.

4.4. LR (2022)

The design value is determined using M_{CSR}, dynamic load combination factor (DLCF), and environmental factor f_{Env} as defined in Equation (8). The guideline provides DLCF and f_{Env} for the primary oil and gas production fields. The design value must not be less than 50 per cent of M_{CSR}.

$$M_D = M_{CSR} \times \mathrm{DLCF} \times f_{Env} \tag{8}$$

4.5. Results and discussions

Fig. 9 and Table 7 indicate a comparison of the design values obtained from the present method with the classification society rule values for the six regions. Overall, the present method and rule values are in good agreement for the investigated regions. However, it should be noted that the rule values of ABS and BV were significantly higher than not only the present method, but also the other classification societies, in the western coast of Africa, eastern coast of South America, and southeastern coast of Asia due to their high minimum requirements. While minimum requirements can be effective in conservative design and preventing unfavourable accidents, they can also lead to overestimation of the design value, resulting in an increase of structural scantlings, construction costs, weight of hull structures, and a decrease of cargo capacity. In this regard, the design value obtained from the proposed method may be more rational and realistic when the minimum requirements are excessively high. Moreover, the present method can be utilised in the preliminary design stage to determine whether the minimum requirements apply to the target structures because the present method is straightforward to use and yields higher results compared to the long-term stochastic method.

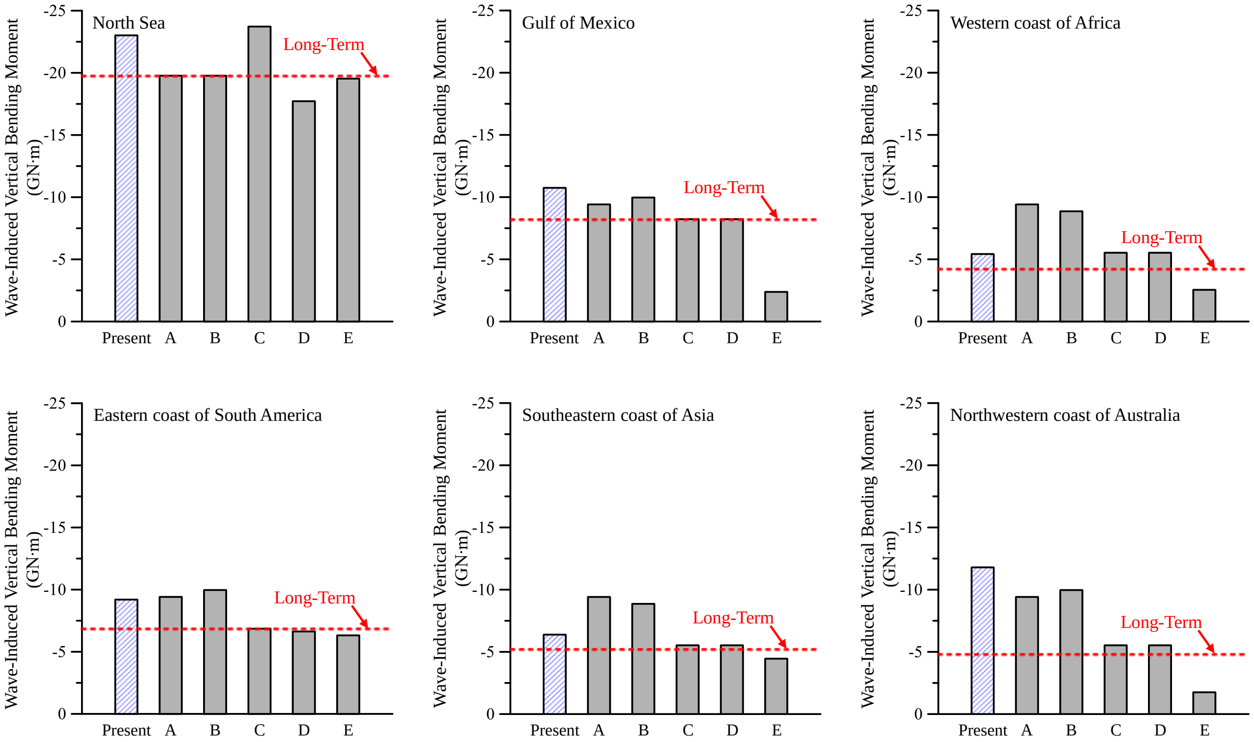


Fig. 9. Comparison of the design wave-induced vertical bending moments between the present method and classification society rule values for the six regions: A = ABS (2023), B = BV (2016), C = DNV (2021), D = LR (2022), E = IFORM.

Table 7. Comparison of the design wave-induced vertical bending moments between the present method and classification society rule values for the six regions.

Method	Design Wave-Induced Vertical Bending Moments (GN·m)					
	North Sea	Gulf of Mexico	Western coast of Africa	Eastern coast of South America	Southeastern coast of Asia	Northwestern coast of Australia
Present	-23.016	-10.744	-5.425	-9.197	-6.384	-11.792
A: ABS (2023)	-19.768	-9.397	-9.397	-9.397	-9.397	-9.397
B: BV (2016)	-19.768	-9.950	-8.844	-9.950	-8.844	-9.950
C: DNV (2021)	-23.722	-8.231	-5.528	-6.858	-5.528	-5.528
D: LR (2022)	-17.720	-8.231	-5.528	-6.633	-5.528	-5.528
E: IFORM	-19.536	-2.380	-2.547	-6.320	-4.452	-1.752
Long-Term	-19.768	-8.231	-4.192	-6.858	-5.208	-4.846

5. Concluding Remarks

The aim of this study was to present a new method for determining the design value of wave-induced vertical bending moments acting on ship-shaped offshore installations in survival conditions. To demonstrate the proposed method, a hypothetical FPSO model was used for hydrodynamic load analysis. The design values obtained from the present method for the six target regions were compared to those obtained from the long-term stochastic method and environmental contour-based method (IFORM). Moreover, rule values determined in accordance with the different classification society guidelines were also compared with the proposed method. The conclusions of this study are summarised as follows.

1. The proposed method is more straightforward compared to the long-term stochastic method and the environmental contour-based method.

2. The proposed method yielded higher results than both the long-term stochastic method and the environmental contour-based method, particularly in the regions prone to tropical cyclones such as the Gulf of Mexico and the northwestern coast of Australia, due to its ability to take into account all probable storms. On the other hand, the environmental contour-based method underestimated the design values compared to the other two methods.

3. The present method and rule values were generally in good agreement for the investigated regions, but the ABS and BV rule values were significantly higher than both the present method and other classification society rule values in some regions due to their high minimum requirements. In this regard, the design value obtained from the proposed method may be more rational and realistic when the minimum requirement is excessively high.

4. In the preliminary design stage, the proposed method can be utilised to determine whether the minimum requirements apply to the target structures since it is straightforward to use and provides higher results compared to the long-term stochastic method.

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