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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, considering survival conditions with the most probable extreme waves for a return period of 100 years, the determination of their design values is not straightforward owing to the complex procedures and a large amount of hydrodynamic analyses which require significant 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. As an applied example, a very large crude oil carrier (VLCC)-class floating, production, storage, and offloading (FPSO) unit in survival conditions are considered at six different seas. A comparison is made among the present solutions, environmental contour-based solutions, and the long-term stochastic method-based classification society rule values.

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Ship-shaped offshore installations; survival conditions; wave-induced vertical bending moments; site-specific metocean data; long-term analysis; environmental contours

1. Introduction

For the 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 the main load 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, 2024). However, the determination of wave-induced loads is not straightforward due to the many uncertainties and complexities of oceanic environmental conditions, and difficulties in predicting the extreme values of wave loads acting on the hull structures.

Progress and challenges in the prediction of wave-induced loads acting on ship-shaped offshore installations have been widely acknowledged (Temarel et al. 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 a combined-table approach that is applicable to complicated wave conditions with both swell and 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 their 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 an FPSO and analysed the reliability of hull girder ultimate strength. 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) presented 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

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Table 1. Distribution of 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
Others	23	14.1

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 significant 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 analyses and long-term stochastic processes.

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 wavelength equal to the vessel's length in head sea. To demonstrate the proposed method, a hypothetical very large crude oil carrier (VLCC)-class 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 effects of sea states. The results obtained by the proposed method are compared with those of the long-term stochastic method and environmental contour-based solutions in Section 3. Rule values that consider the specific regulations of each classification society are presented and compared with the results obtained from the proposed method in Section 4.

2. Hypothetical FPSO model for wave load analysis

To demonstrate the proposed method, a hypothetical FPSO model was created for ship motion and wave load analysis. Table 2 presents the principal dimensions of the hypothetical FPSO model. The principal dimensions of the hypothetical FPSO model were determined with reference to the principal dimensions of currently operating FPSOs constructed since 2000, as shown in Table 3. This study did not consider FPSOs converted from trading tankers, but these data are available in Chapter 1 of Paik (2022). Figure 1 shows the three-dimensional finite element model of the hypothetical FPSO hull structure.

Table 2. Principal dimensions of the hypothetical FPSO model.

Parameter	Dimension
Length Between Perpendiculars (L)	305.0 m
Breadth (B)	60.0 m
Depth (D)	32.0 m
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/B	B/T
Newly-Built FPSO Worldwide	5.1	1.9	0.7	2.8
Hypothetical FPSO	5.1	1.9	0.7	2.6

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, as well as the resulting trim condition (Paik et al. 2019). However, the details of structural scantlings are not presented in this study because the aim of this study is not structural analysis – refer to Chapter 1 of Paik (2022). FPSOs are typically subjected to significant vertical bending moments under fully loaded conditions; hence, the hypothetical FPSO model was also assumed to be fully loaded for the wave load analysis. The weights of the topside modules and living quarter were assumed to be 30,000 tons and 3,500 tons, respectively (Hwang et al. 2010; Ha et al. 2017).

3. Methods for determining the design values of wave-induced vertical bending moments

As ship-shaped offshore installations always remain on a specific site except during towing, the design value of wave-induced loads must be determined through direct wave load analysis, accounting for site-specific wave conditions, as described in Section 1. In this study, six target regions where FPSOs are currently in service

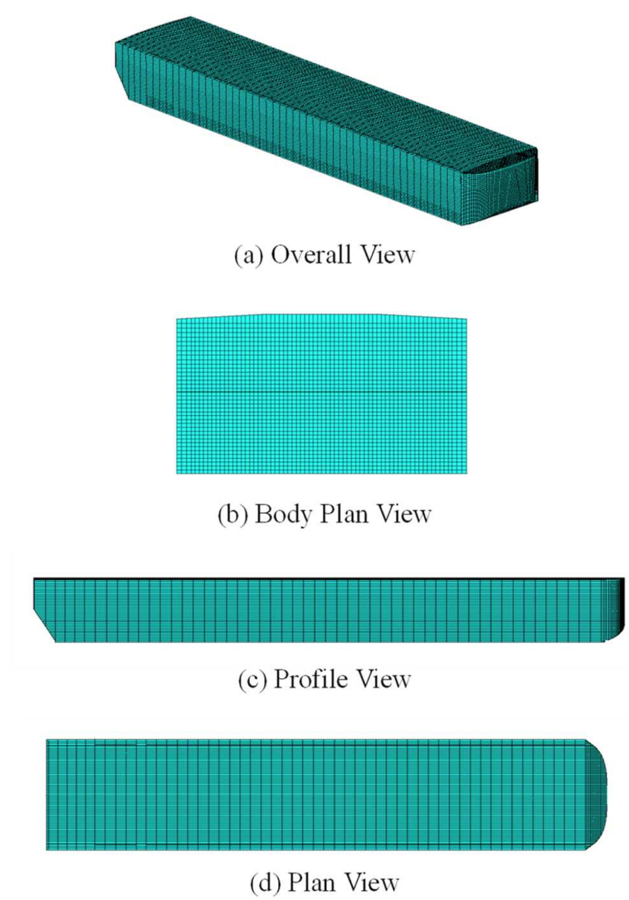

Figure 1. Three-dimensional finite element model of the hypothetical FPSO hull (This figure is available in colour online.).

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

were considered as listed in Table 4. Historical wave data spanning from 1979 to 2019 were obtained from a spectral wave model known as MIKE 21 (DHI 2019). Figure 2 illustrates the site-specific wave characteristics for each of the six target regions, including wave scatter plots representing the last 20 years and environmental contours, as detailed in Section 3.2. In Figure 2, the extreme conditions represent the sea state with the maximum significant wave height H_s. The data presented in Figure 2 serve as the basis for the comparative analysis conducted in this study.

In the industry, two approaches are generally employed to predict extreme values of wave-induced loads on offshore structures: specifically, the long-term design approach and the design sea state approach. In this section, the long-term stochastic method, as well as the inverse first-order and second-order reliability methods (IFORM and ISORM) are introduced as representative approaches. A comparative analysis with the method proposed in this study is then provided, highlighting key differences in computational efficiency and accuracy. Figure 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 wave load analyses performed in this study were carried out using the MAESTRO software (MAESTRO 2023). MAESTRO is designed to compute hull girder loads on ships through both hydrostatics (including load balancing) and hydrodynamic load analysis, based on three-dimensional potential theory. The software considers the changing wetted surface, which significantly affects the pressure distribution on the hull. Furthermore, MAESTRO allows for the direct transfer of these calculated loads into three-dimensional finite element models, enabling comprehensive structural evaluations. These evaluations include assessments of potential structural failures and design optimisations, based on the computed stresses and displacements (Ma et al. 2014). For additional technical details, refer to MAESTRO (2018).

The finite element model is used in conjunction with the hydrodynamic load calculations in MAESTRO as it facilitates the simultaneous computation of resulting structural responses, including stresses and displacements, alongside buckling and ultimate strength checks. This integration is essential for accurate, real-time assessments of the hull's response to hydrodynamic forces under different loading conditions.

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 the nonlinear method can provide more accurate response predictions. Transfer functions (i.e. response amplitude operators,

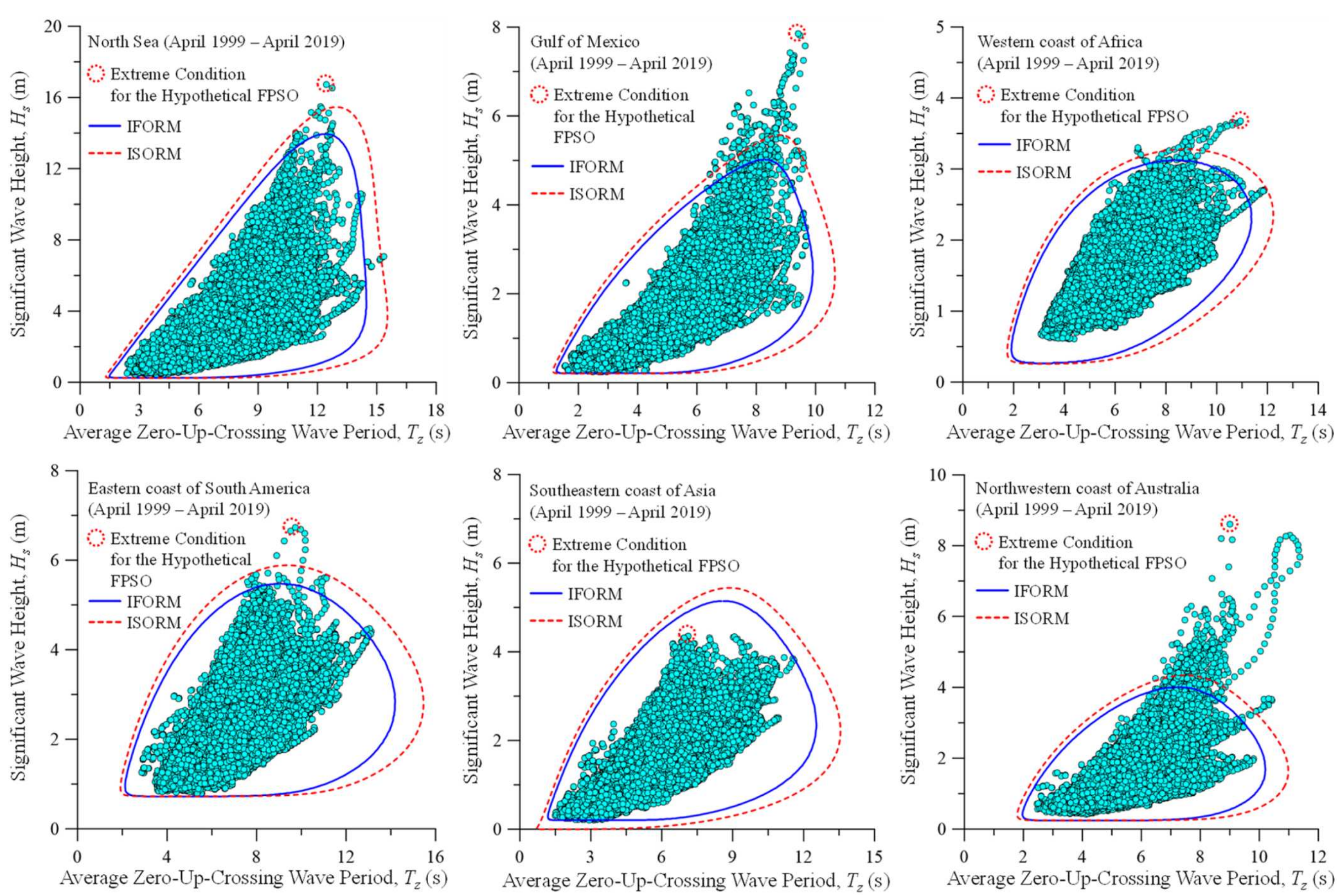

Figure 2. Site-specific wave scatter plots of the six target regions and environmental contours for a return period of 100 years (This figure is available in colour online.).

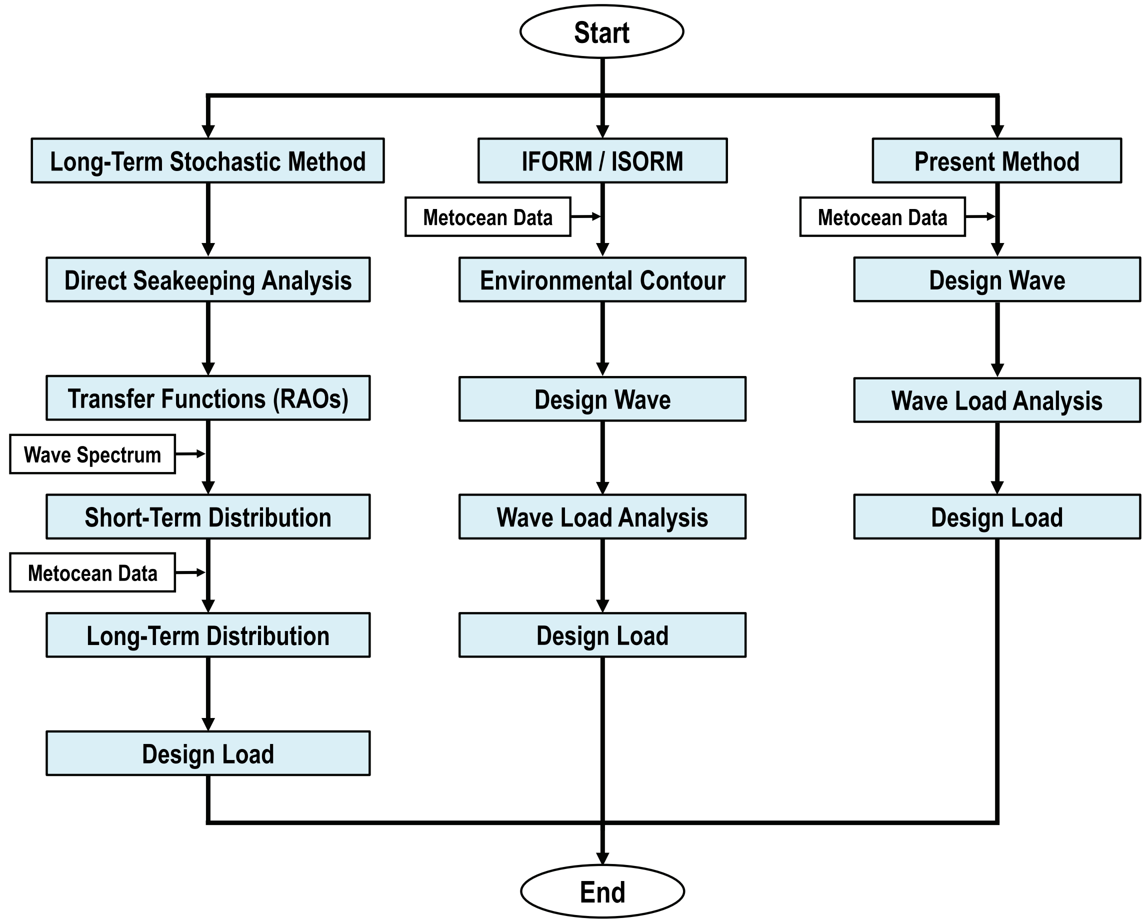

Figure 3. Procedures of the three different methods for determining design values of wave-induced vertical bending moments: long-term stochastic method, environmental contour-based methods (IFORM and ISORM), and the present method (This figure is available in colour online.).

RAOs) and short-term distribution of response are the components required to perform the method, and long-term distribution of response is estimated based on the combined results of the short-term distributions using metocean data (e.g. wave scatter diagrams and wave rosettes). As indicated in Figure 3, transfer functions can be obtained through direct seakeeping analysis. Figure 4 shows the transfer functions for the vertical bending moment at midship of the hypothetical FPSO model.

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

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

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

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

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 (wave-induced vertical bending moment in this paper), $F_L(x)$ is the long-term distribution of response, p_w is the joint probability from the wave scatter

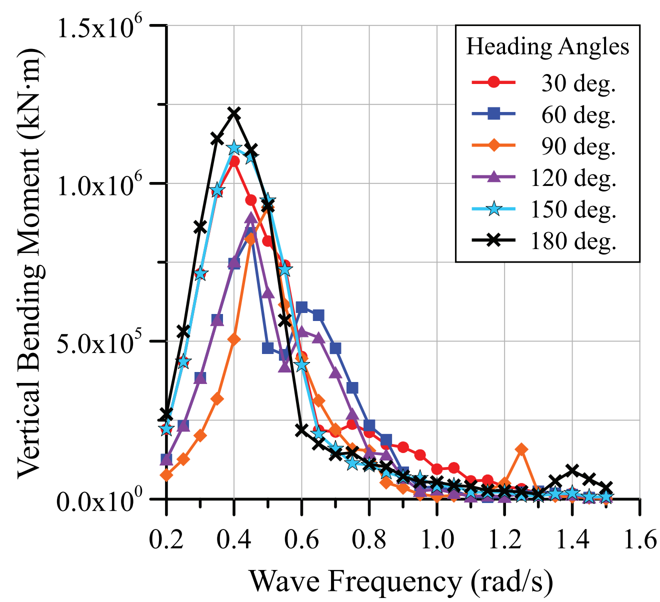

Figure 4. Transfer functions of the vertical bending moment at midship of the hypothetical FPSO (This figure is available in colour online.).

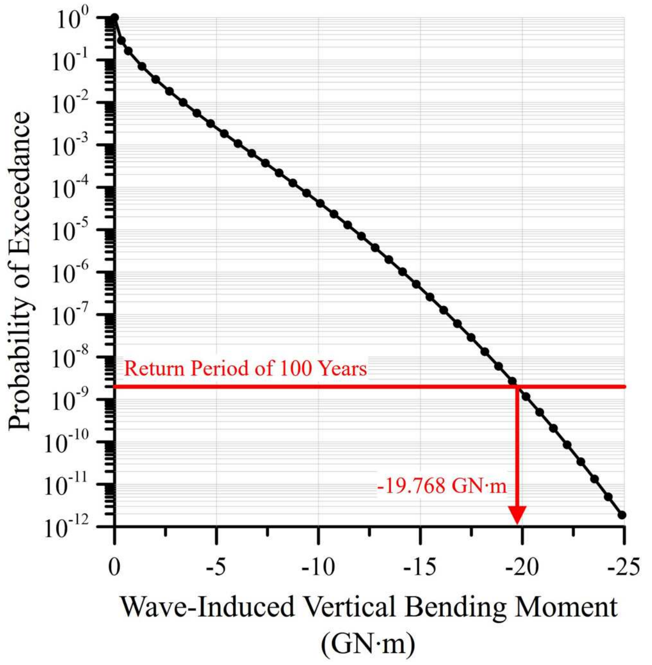

Figure 5. Long-term distribution of the wave-induced vertical bending moment at midship of the hypothetical FPSO in the North Sea (This figure is available in colour online.).

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, $T_{z,avg}$ is the average zero-up-crossing period, and T_R is the return period.

3.2. Environmental contour-based methods (IFORM and ISORM)

Environmental contours are instrumental in defining extreme wave conditions for offshore structures according to a return period. By employing these contours, design actions – such as the design waves in this study – can be defined directly using the wave parameters on the contour, such as significant wave height and zero-up-crossing wave period. In this study, the IFORM and ISORM approaches were applied to generate environmental contours of the six target regions, as shown in Figure 2. The procedures for drawing an environmental contour using the IFORM method are outlined in Figure 6. Further details can be found in Appendix 4 of Paik (2022). The ISORM method, while closely resembling the IFORM procedure, calculates the reliability index β_{ISORM} using an alternative formulation as

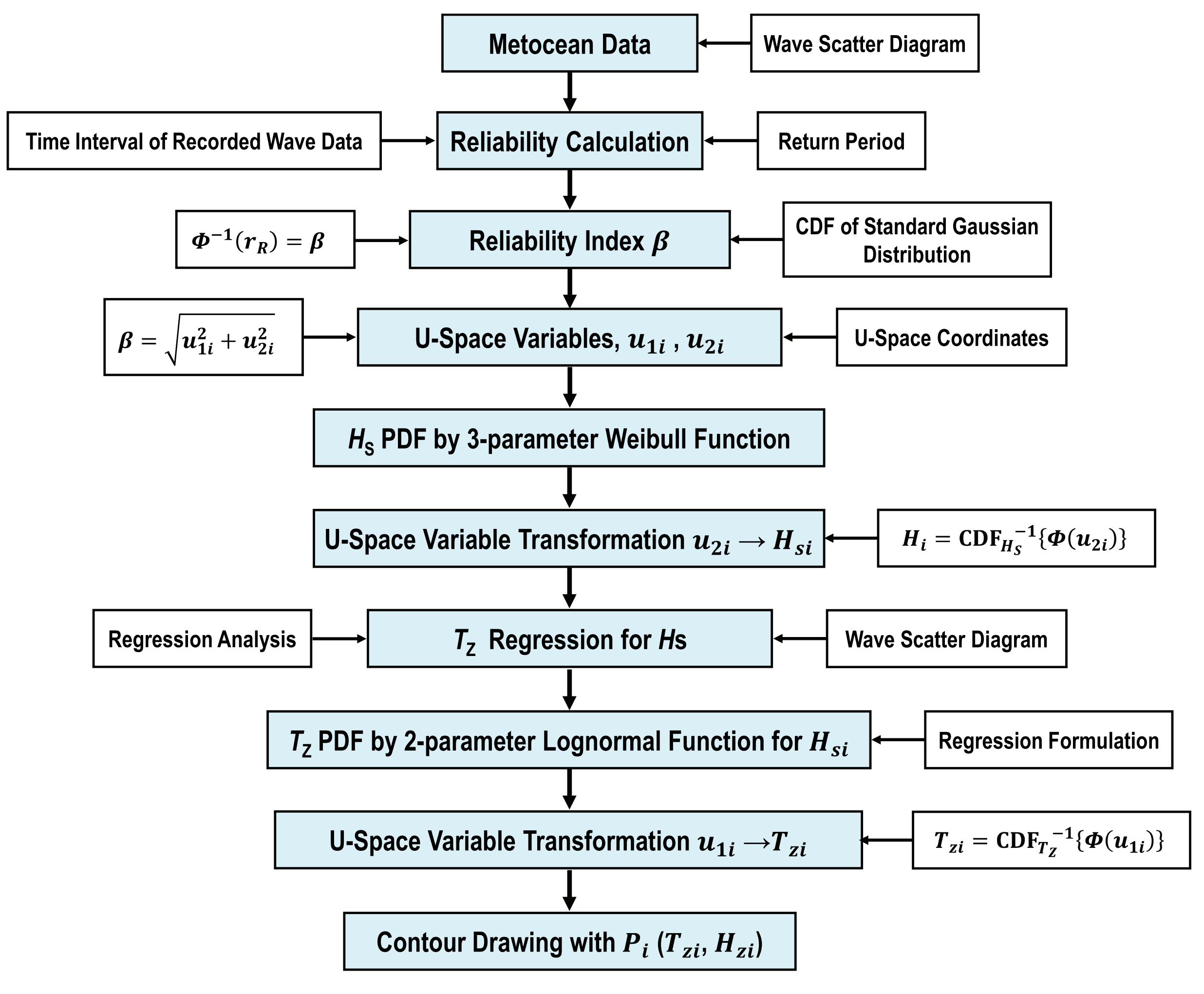

Figure 6. Procedure for drawing an environmental contour using the IFORM method (Paik 2022) (This figure is available in colour online.).

follows.

$$\beta_{\text{ISORM}} = \sqrt{\chi_n^{-1}(1 - P_f)} \tag{5}$$

where χ_n^{-1} is the inverse cumulative density function of the chi-square distribution, n is degrees of freedom, and P_f is the probability of failure, respectively. Further details on the ISORM method can be found in Chai and Leira (2018) and Mikulić and Parunov (2023).

3.3. Present method

Although the former two methods provide rational and reliable design values based on probabilistic approaches, the procedures are highly sophisticated and/or require significant 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 wave 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 intervals (e.g. 3 hours).
- Step 2: Define the design wave with a regular sine shape, the maximum wave height selected from the long-term wave data, and a wavelength equal to the vessel's length.
- Step 3: Perform wave load analysis with the design wave in head seas at varying phase angles (Figure 7).
- Step 4: Determine the design value of wave-induced vertical bending moments based on the results of the wave load analysis.

Both the present method and the environmental contour-based methods use the concept of 'design wave' which is a representative of waves defined by site-specific wave parameters, such as wave height, wave period, and wave direction, for 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 Figure 8, where the present method defines a single 'design wave' with regard to the maximum 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, as it defines the 'design wave' based on 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 worth noting 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 could be considered for more accurate results.

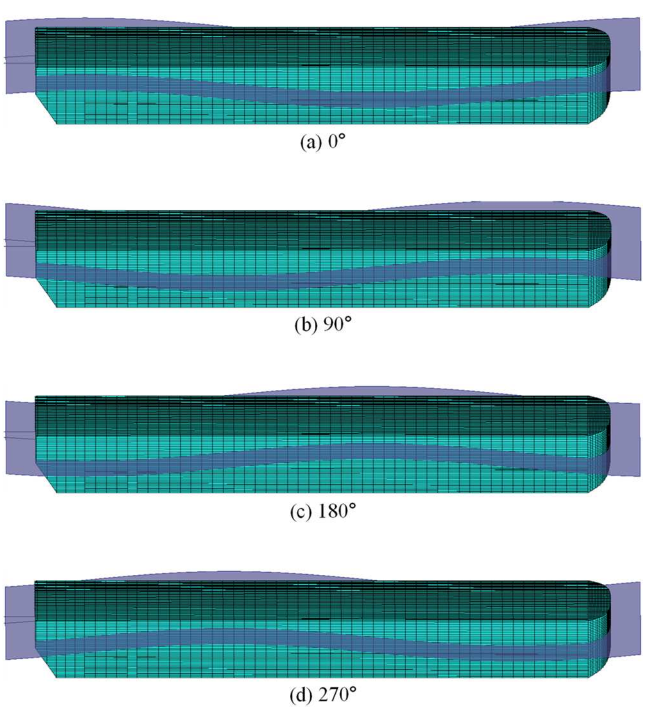

Figure 7. Varying phase angles in the wave load analysis using the MAESTRO software (This figure is available in colour online.).

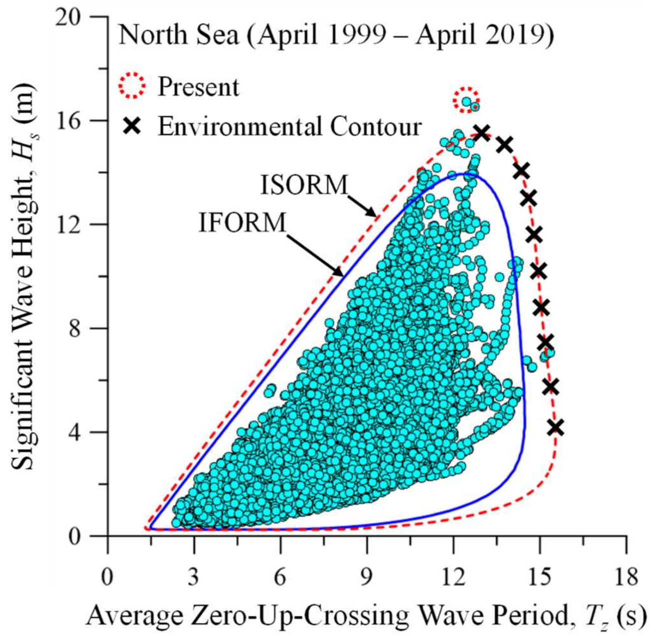

Figure 8. Illustrative example of the wave parameters defined by the present method and the environmental-contour methods (This figure is available in colour online.).

3.4. Results and discussions

Figure 9 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 methods (IFORM and ISORM), and the present method. All results presented in this study are negative values, as FPSOs are typically operated under sagging conditions. The four methods yielded

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

Site	Wave Height (m)	Wavelength (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		

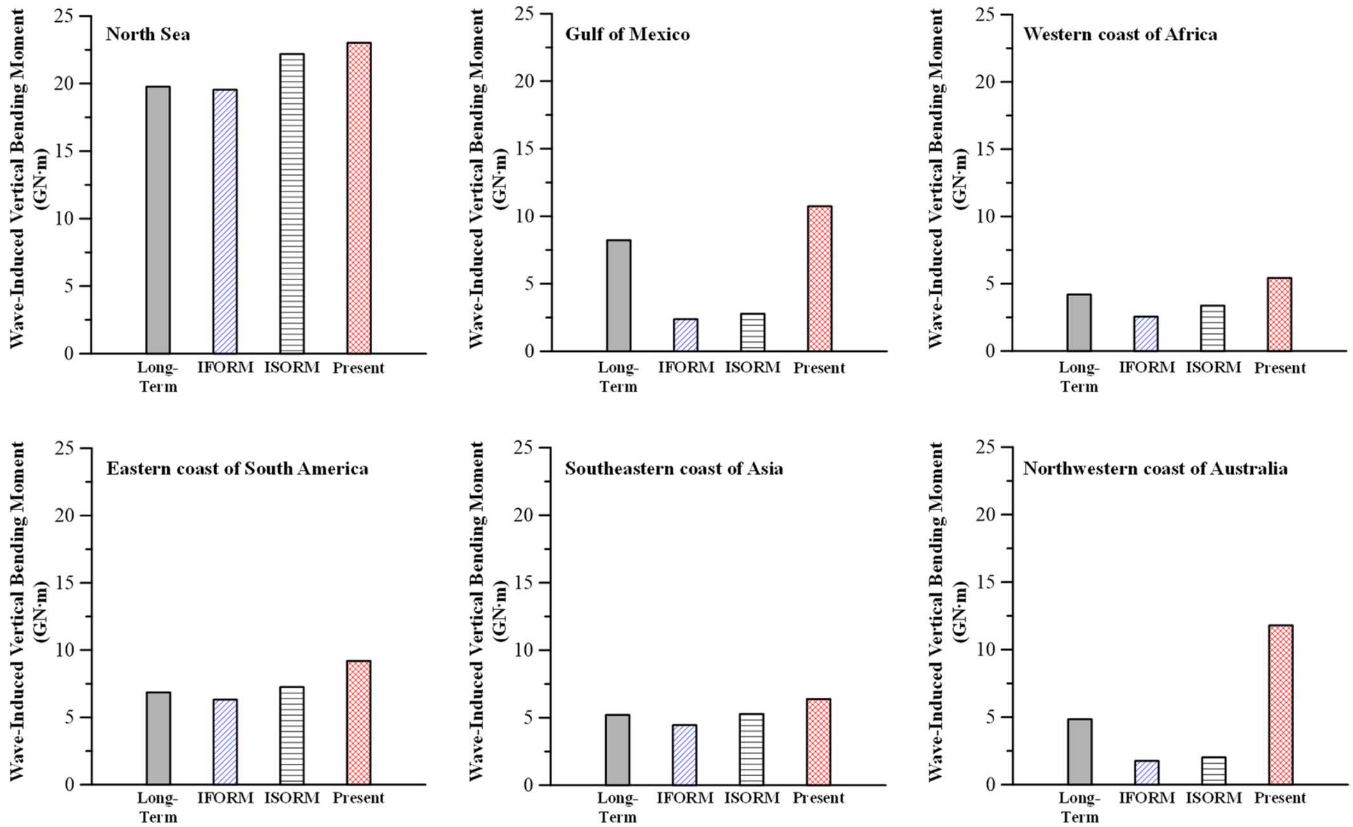

Figure 9. Extreme values of the wave-induced vertical bending moments for the six target regions obtained from the long-term stochastic method, the environmental contour-based methods (IFORM and ISORM), and the present method (This figure is available in colour online.).

different extreme values depending on the site-specific sea states. Notably, the IFORM method generally underestimated the extreme values compared to those obtained using the long-term stochastic method, consistent with observations by BV (2019). In contrast, the ISORM method produced higher extreme values than the long-term stochastic method in certain cases. The proposed method, however, yielded higher extreme values than the other three methods, especially in the Gulf of Mexico and the northwestern coast of Australia, where tropical cyclones periodically occur. These discrepancies can be attributed to probabilistic approaches being less effective at capturing the effects of tropical cyclones due to their short storm durations. Consequently, the proposed method is likely to provide more 'pessimistic' design values, taking into account all probable storms.

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 when 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 6, 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 7, and the design value must not be less than 85 percent of the M_{CSR}.

$$M_D = M_{CSR} \times \beta_{VBM} \tag{6}$$

$$\beta_{VBM} = \frac{M_{Site}}{M_{N.A.}} \tag{7}$$

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 8. The design value must not be less than 65 percent of M_{CSR}.

$$M_D = \text{n} \times M_{CSR} \tag{8}$$

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

Table 6. Navigation coefficient n 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

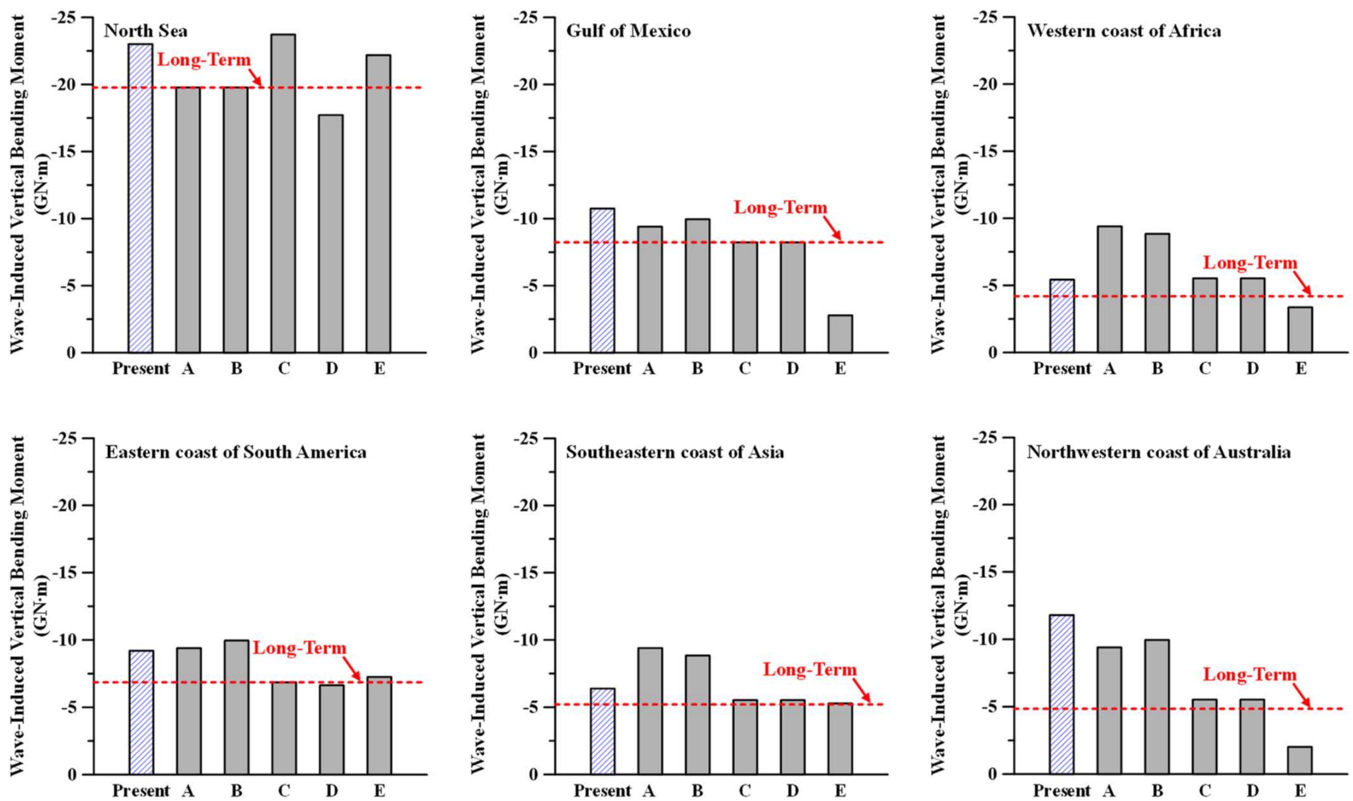

Figure 10. Comparison of the design wave-induced vertical bending moments between the present method and classification society rule values for the six regions: A = ABS (2023), B = BV (2016), C = DNV (2021), D = LR (2022), E = ISORM (This figure is available in colour online.).

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 environments (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 percent 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 9. The guideline provides DLCF and f_{Env} for the primary oil and gas production fields. The design value must not be less than 50 percent of M_{CSR}.

$$M_D = M_{CSR} \times \mathrm{DLCF} \times f_{Env} \tag{9}$$

4.5. Results and discussions

Figure 10 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 increased structural scantlings, construction costs, weight of hull structures, as well as reduced cargo capacity. In this regard, the design value obtained from the proposed method appears 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

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

	Design Wave-Induced Vertical Bending Moments (GN·m)					
Method	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: ISORM	−22.186	−2.780	−3.368	−7.253	−5.277	−2.020
Long-Term	−19.768	−8.231	−4.192	−6.858	−5.208	−4.846

because the present method is straightforward to use and yields higher results compared to the long-term stochastic method.

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 wave load analysis. The design values obtained from the proposed method for the six target regions were compared to those obtained from the long-term stochastic method and the environmental contour-based methods (IFORM and ISORM). 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 both long-term stochastic method and the environmental contour-based methods. In particular, the proposed method requires significantly less computation time than the long-term stochastic method, which involves extensive calculations, especially for deriving transfer functions.
2. The proposed method yielded higher results than both the long-term stochastic method and the environmental contour-based methods, 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. Notably, the IFORM method underestimated the design values compared to other methods.
3. The proposed 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 proposed 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, which utilises simple and efficient approaches, the proposed method can be applied prior to detailed designs with precise analysis. It enables an initial assessment of whether the minimum requirements are satisfied for the target structures, as it is straightforward to implement and produces higher results compared to the long-term stochastic method. However, since the proposed method was specifically developed for ship-shaped offshore installations, its applicability to other types of ships requires further investigation.

Disclosure statement

No potential conflict of interest was reported by the authors.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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