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RELIABILITY ANALYSIS OF OFFSHORE PLATFORM SUPPORT STRUCTURES UNDER EXTREME WAVE LOADS: A CASE STUDY APPROACH

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Abstract

Wave loads are critical factor for the design and safe operation of offshore structures. The accurate determination of these loads is essential to ensure the structural reliability and operational efficiency of such platforms at sea. This study develops analytical expressions for calculating wave loadings that affect the support of various Condeep-type offshore structures. In this regard, wave load calculations for the Draugen Monopile Condeep platform, previously constructed in Norway, were analyzed in the context of a case study. The results of this assessment provide useful information regarding the characteristics of wave loads and their relevance to the overall structural analysis. Furthermore, the investigation also covers recommendations for design and safety improvements that consider the calculated wave loads and the assessment of the structural reliability. Study is expected to contribute to the knowledge base surrounding offshore engineering practices and improve resilience and functionality against dynamic wave forces.

Keywords: offshore structures, condeep platform, wave load, reliability analysis, failure, probability

I. Introduction

Reliable operation of offshore platforms is essential for ensuring the energy security and sustainable development of the sector. The stability and reliability of operations are two of the cardinal principles in safeguarding a seamless supply of energy, as a technical or structural failure may cause extreme losses, leading to massive economic losses. In addition, the financial efficiency of oil and gas extraction and transportation processes is related to environmental events, such as hydrocarbon spills, that may occur during an accident. These accidents not only disrupt normal operations and cause financial losses but also lead to serious environmental damage, fire hazards, and explosions. Therefore, safety and effectiveness in the operation of offshore platforms are very important; this would mean enhancing the prevention of such events, reducing environmental harm, and ensuring effective recovery and work continuity [1,2].

Offshore and marine energy applications are mainly influenced by numerous uncertainties that play a fundamental role in both the design process and operational asset management. Such risks range widely from natural to man-made, and may pose a number of challenges for designers and engineers [3]. The typical reliability problem, the limit state in terms of static response, can be comparatively easily and simply evaluated for the probability of failure or the reliability index, because static analysis involves more straightforward calculations involving fewer variables. However, the same situation is far from simple and becomes quite involved if, for support structures, reliability analysis requires the response to be obtained from dynamic analysis. Dynamic reliability analysis requires that the interaction between the support structure and irregular waves, turbulent wind, and nonlinear ground soil be modeled precisely. In other words, such coupling within the dynamics of the structure with environmental conditions requires heavy computation to obtain a reliable set of dynamic responses. Moreover, the computational effort significantly increases because the number of dynamic analyses to be performed in a reliability analysis is proportional to the square of the number of random variables under consideration [4,5].

The probability of failure, commonly known as reliability, is one of the key indicators for evaluating the adequacy of a structure or member by integrating the uncertainties due to the use of loads to counter structural resistance. Failure is defined with respect to various applicable failure modes that are usually designated by the limit states. For instance, the ultimate limit states (ULS) [6] may indicate structural failure to resist the applied load effects, possibly combined with significant inelastic displacements, notable cracking, or punching shear failure in the case of bridge decks. Serviceability limit states (SLS) [7] are essentially defined as failures to meet the standard requirements for the use or durability of the structure [8-10].

Because the forces on structural elements from such a wave vary continuously as they progress along the structure, the internal stresses in those elements vary. Therefore, for a given structural element, because the position of the wave relative to the structure changes with time, so does the element at which failure is likely to occur next. Given the variability in member strengths, this would mean that, depending on the position of the wave, the most likely element to fail next would change. Otherwise, the sequence of member failures calculated for a given position corresponding to a stationary extreme wave condition may not be related to what actually could occur when the extreme wave moves [11]. This study presents an extensive analysis of the implications of variability in wave loading on the comprehensive probability of structural failure. The reaction of the structure to dynamic loads has important relevance, particularly regarding the reliability of structures utilized in offshore settings. In this study, wave loading and its effects on structural reliability were analyzed through a case study focused on the Draugen Monopile Condeep platform established in Norway [12,13]. The calculations of the wave load in the present study were based entirely on the empirical data. Therefore, the evaluation of the reliability of the structure was based on the measured data. This approach permits an extensive understanding of how the platform functions and behaves in response to prevailing wave conditions and simultaneously provides a more realistic and specific judgment of its resistance and continued reliability.

II. Wave load modelling

The wave characteristics should be correctly estimated, and a detailed investigation of the interaction between marine structures and oceanic waves is necessary, as both may have a significant impact on the design and construction of Condeep platforms. The various classes of ocean waves include one class, termed wind-generated waves, which is the most common. The energy of the wind is transferred to the water of the surface as the wind travels over the water, creating wind-generated waves. The heights, periods, and other parameters related to these waves depend on the wind speed, fetch distance, and length of time the wind blown over the water. The large fetch distances available in an open oceanic environment permit very strong winds to generate an exceptionally large size. To understand wave behavior and propagation, it is essential to know the wavelength L, which represents the spatial distance covered by a complete wave cycle, including one peak and one trough (Figure 1). The equation used to characterize a wave profile moving in the positive x-direction is shown in Equation (1):

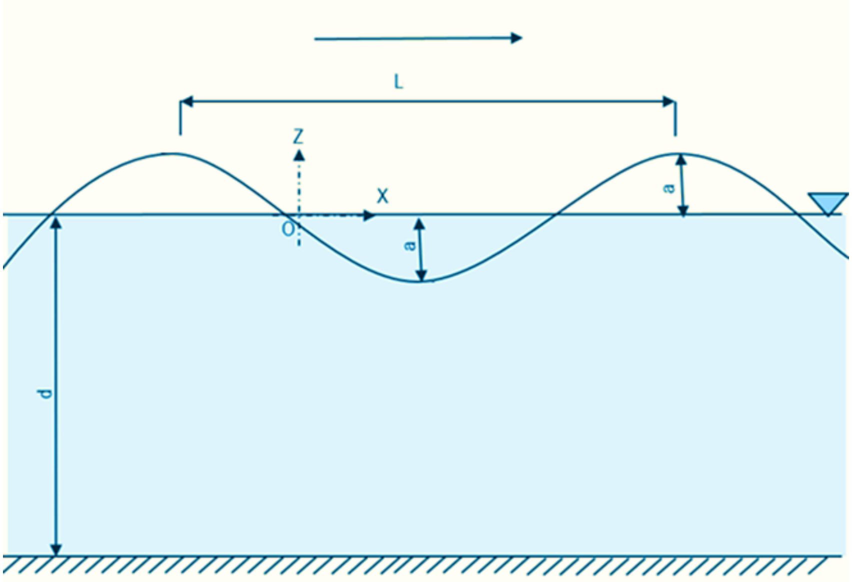

Figure 1. *Sinusoidal wave propagation*

$$\varphi(x,t) = a\,cos(kx - \omega t) \text{ whereas: } \begin{cases} k = 2\pi/L \\ \omega = 2\pi/T \\ c = \omega/k = L/T \end{cases} \tag{1}$$

In marine environment, the interrelation among the wavelength of the observed waves (L), wave period (T), and water depth (d) is articulated via a crucial equation (Equation 2).

$$L = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi d}{L}\right) \tag{2}$$

The bathymetric features of the study area, in combination with coastal protection structures and other factors, increase the accuracy and reliability of wave characteristic forecasts. The wave propagation formulas are related to the distance traveled by the wind over its fetch area and the wind speed, as shown in Equation 3. After applying the described transformations of the wind speed, the real wind speed data were converted into wind speeds using the following formulas:

$$\begin{cases} t = \dfrac{1609}{U_f} \\ U_{3600} = \dfrac{U_f}{\left(1.277 + 0.296 tanh\left[0.9 log(\frac{45}{t})\right]\right)} \\ U_A = 0.71 \cdot U^{1.23} \end{cases} \tag{3}$$

In cases where there is a fetch limit, the key parameters include the fetch (F) and wind speed. Based on these parameters, the significant wave heights and periods were like Equation (4):

$$\begin{cases} H_s = \dfrac{U^2}{g} \cdot 0.283\, tanh\left[0.0125\left(\dfrac{g \cdot F}{U_A^2}\right)^{0.42}\right] \\ T_s = \dfrac{2\pi \cdot U}{g} \cdot 1.2\, tanh\left[0.077\left(\dfrac{g \cdot F}{U_A^2}\right)^{0.25}\right] \end{cases} \tag{4}$$

The Morison equation was used to calculate the hydrodynamic forces acting on offshore structures [14,15]. Equation (5) represents the combination of inertial and drag forces acting on submerged offshore structures.

$$F_{total} = F_d + F_i \Rightarrow \begin{cases} F_d = 0.5 \cdot \rho \cdot C_d \cdot A \cdot V_r^2 = 0.5 \cdot \rho \cdot C_d \cdot D \cdot u \cdot |\mathrm{u}| \\ F_i = 0.5 \cdot \rho \cdot C_m \cdot A \cdot V_r = 0.25 \cdot \rho \cdot C_m \cdot \pi \cdot D^2 \frac{du}{dt} \end{cases} \tag{5}$$

The Morison equation is a method for determining the combined effects of both drag and inertial forces induced by wave action on a vertically submerged cylindrical structure at a certain depth of submergence (Figure 2). Adapting this equation to a circular column for load calculations is an important part of marine engineering and the design of coastal structures. This equation ensures that structures can operate safely and reliably in the presence of the dynamic forces produced by ocean waves (Equation 6 and 7).

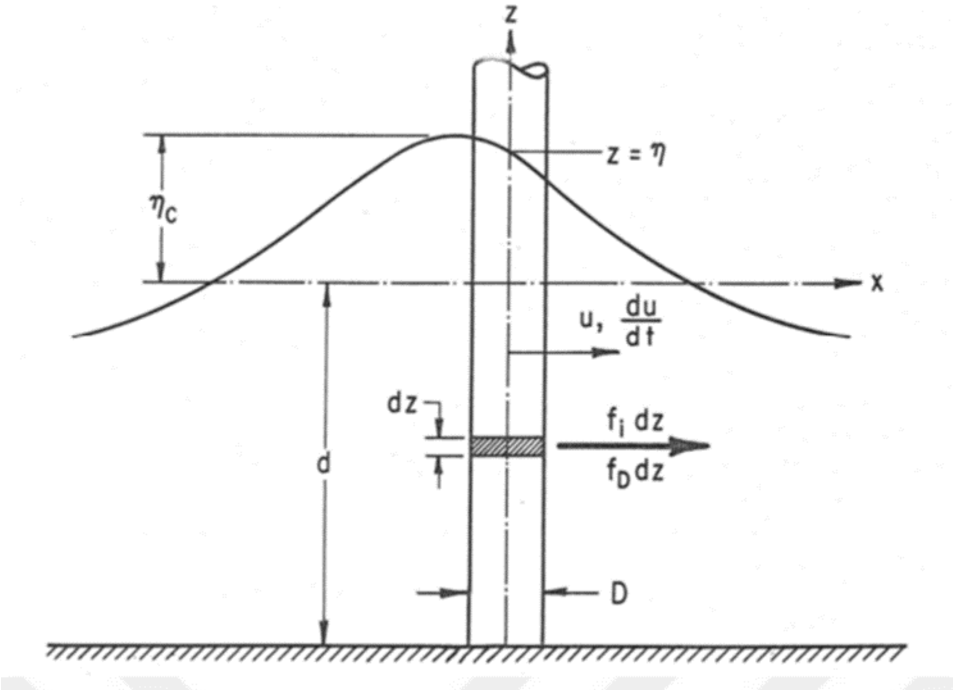

Figure 2. *Wave loads on a vertical cylinder*

$$F_{total} = F_d + F_i = \int_{-d}^{\eta} f_i dz + \int_{-d}^{\eta} f_D dz = -F_i sin\omega t + F_d cos^2 \omega t \tag{6}$$

$$\begin{cases} F_i = \frac{\pi}{4}\rho \cdot g \cdot C_m \cdot D^2 \cdot H \cdot K_i \\ F_D = \frac{1}{2} \cdot \rho \cdot C_d \cdot D \cdot H^2 \cdot K_D \end{cases}; \qquad \text{whereas,} \qquad \begin{cases} K_i = \frac{1}{2} tanh\, kd \\ K_D = \frac{1}{8}(1 + \frac{2kd}{sinh\, 2kd}) \end{cases} \tag{7}$$

III. Case Study

In this study, the wave load estimates were conducted using data from the Draugen Monopile Condeep platform (Figure 3). This platform was set to a depth of 250 m, with an embedment of 9 m into the seabed. The distance between the mean sea level and bottom surface of the deck of the platform is 30 m. The platform wall exhibits a diameter of 45 m at its most profound section, gradually tapering to 16 m at the elevation of still water. The thickness of the wall is intentionally specified to be 1.9 meters at the foundation of the structure, decreasing to 0.7 meters at its uppermost boundary [16].

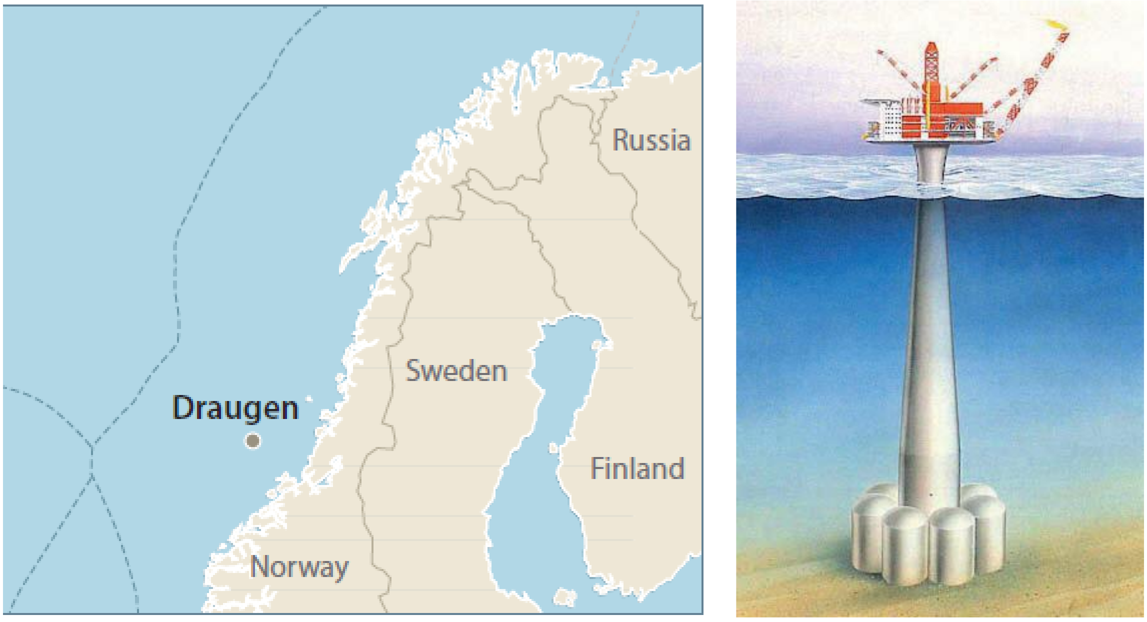

Figure 3. *Location plan and general overview of Draugen Monopile Condeep platform [17].*

This parametric analysis takes the annual wind speed of the region for the Draugen platform in Norway as a reference. The wind speed data for the past 10 years were obtained using the Meteoblue dataset API [18], with a focus on specific areas, as shown in Figure 4. Calculations with regard to wave load were therefore carried out using the highest wind speed values corresponding to the four main directions highlighted above. Another important parameter is the frictive wind velocity statistic, represented as U_f, which shows the maximum wind speed recorded within a given period. The data show that a maximum wind speed of 24 m/s was achieved from the north, while 20 m/s was achieved from the west. This was an extreme wind condition for ten years. By accepting the maximum wind speed, the calculations of the wave height and period were obtained using the previously mentioned formulae with consideration of the distance, from the coastline to the desired offshore platform location (Table 1) [19].

Tablo 1. Calculated wave parameters

Direction	F (km)	t (s)	U_{3600} (m/s)	U_A (m/s)	H_s (m)	T_s (s)
North	1380	57.5	19.21	26.91	6.51	10.57
West	985	49.25	15.79	21.14	4.88	8.89

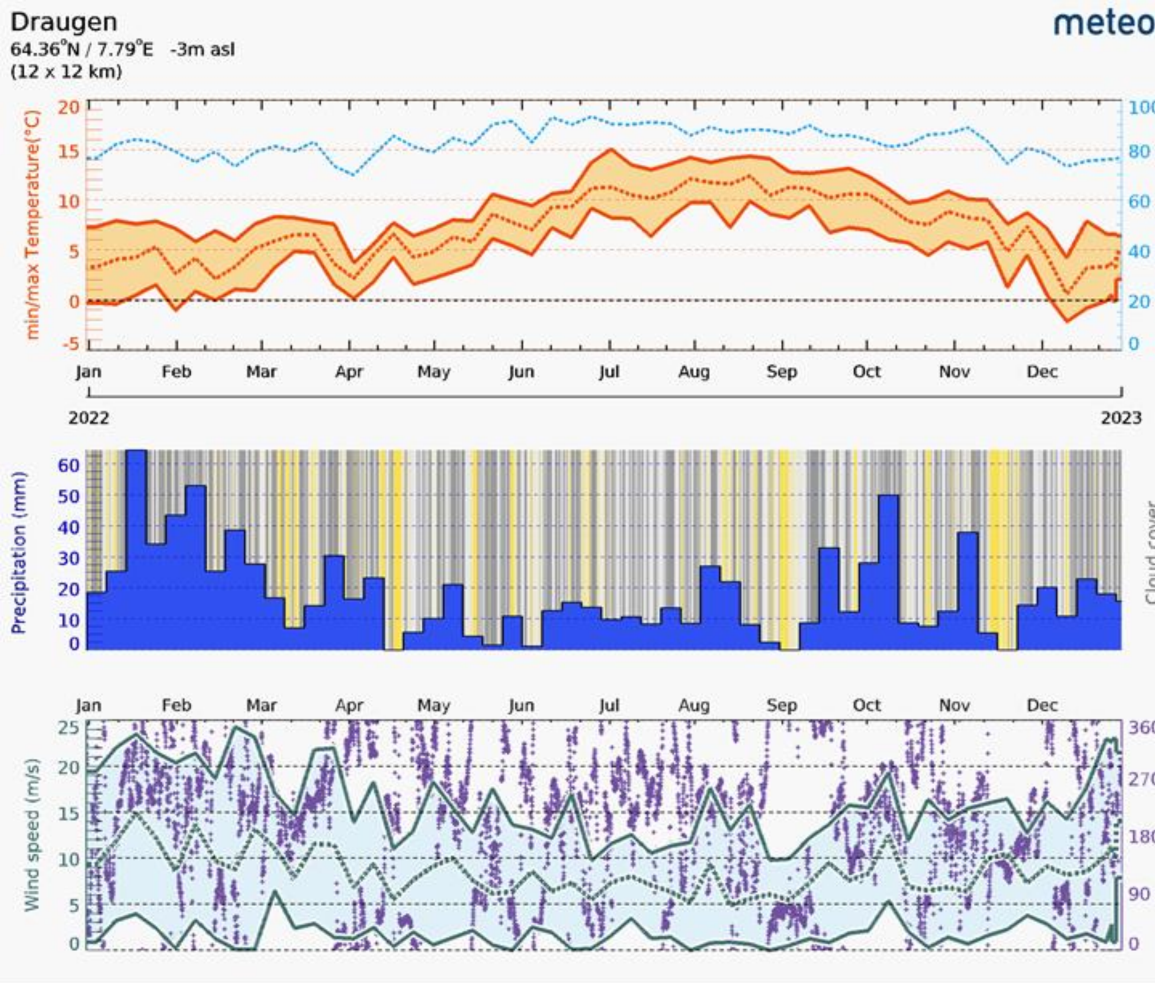

Figure 4. *Metrological statistics of Draugen platform [18]*

In this regard, calculations have primarily been made using small-amplitude wave theory to assess the wave parameters [20,21]. The result from such calculation provides the peak values that allow developing the significant wave height, H_s, and the significant wave period, T_s. Furthermore, in order to consider the design, analysis, and decision-making process through safety-oriented approach, extreme wave events are highlighted representing maximum values obtained from such calculations as H_s and T_s

$$\begin{cases} H_s = H = 6.51\ m \\ T_s = T = 10.57\ s \end{cases} \tag{8}$$

Because the actual situation places the Monopile Condeep platform at a depth of d=250 m, the wavelength was calculated using the proper equations of wave propagation in water.

$$L = \frac{gT^2}{2\pi} tanh\left(\frac{2\pi d}{L}\right) = \frac{9.81 \cdot 10.57^2}{2 \cdot 3.1415} tanh\left(\frac{2 \cdot 3.1415 \cdot 250}{L}\right) \qquad (9)$$

Consequently, after many iterations, the wavelength, was found to be 174.52 meters.

$$\frac{d}{L} = \frac{250}{174.52} > 0.5 \qquad (10)$$

It was then established that the waves fall into the category of deep-water waves; that is, these waves travel in a water body whose depth is greater than half the wavelength ($d > 0.5L$).

As a result, after evaluating all the necessary parameters, the final wave load for cylindrical support structure has been calculated using the Morison equation, as shown in Equations 6 and 7.

$$F_i = \frac{3.14}{4} \cdot 1025 \cdot 9.81 \cdot 2 \cdot \left(\frac{45 + 16.4}{2}\right)^2 \cdot 6.51 \cdot 0.5 = 4.843 \cdot 10^7 N$$
$$F_D = \frac{1}{2} \cdot 1025 \cdot 9.81 \cdot 0.7 \cdot \left(\frac{45 + 16.4}{2}\right) \cdot 6.51^2 \cdot 0.125 = 0.572 \cdot 10^7\ N \qquad (11)$$

$$F_{total} = -F_i sin\omega t + F_d cos^2\omega t = -F_i sin\omega t = -4.843 \cdot 10^7\ N\ = -48.43\ MN \qquad (12)$$
$$cos\omega t = 0 \quad \rightarrow \quad \omega t = \frac{\pi}{2}$$

IV. General reliability assessment of platform under wave load

Structures or their elements fail when subjected to excessive loads or when an interaction of the loads produces a sufficiently intense load effect to create an inappropriate failure mode in the structure. Such a failure condition can be an ultimate failure, where the structure cannot support the applied load, or serviceability failure, where the structure does not function appropriately.To address this problem, the size and consequences of such an event must first be predicted [22]. Furthermore, the strength and deflection under the load of each structural element should be evaluated using the available design information. Such a procedure requires probabilistic models that reflect uncertainties owing to the loading variables, as well as those of the structural resistance [23].

Although the load factor (LF) describes the magnitude and nature of the loads acting on a structure, it is important to determine its load-carrying capacity. The LF must be assessed together with the resistance factor (RF), which is representative of the strength and safety margins of the structure. If the structure is to be safe, LF and RF must be in balance on the right side of the figure so that the structure has a resistance equal to or greater than the expected load (Figure 5). All parameters affecting the structure related to a reliability assessment, such as moment capacity, shear force capacity, stress, and deformation, should be analyzed. Proper modeling and evaluation of these parameters will enable a realistic assessment of the performance of the structure. Proper comparison of the load and resistance parameters allows for more accurate conclusions regarding safety and durability.

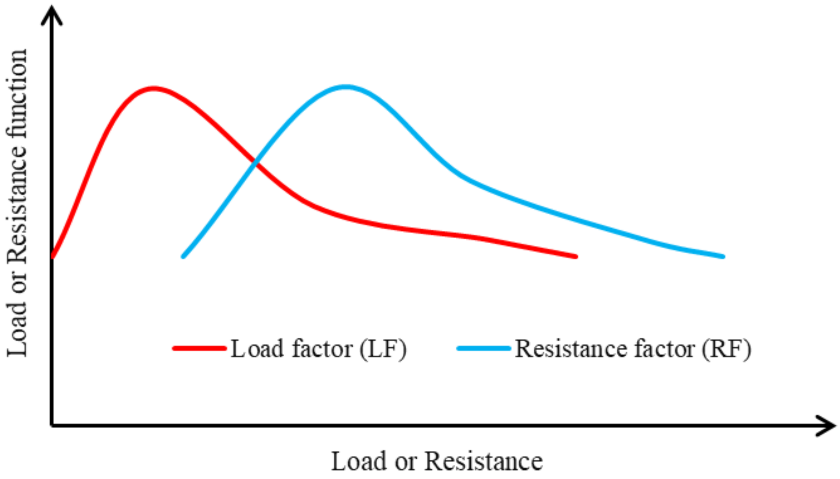

Figure 5. *Relationship between Load and Resistance factors in a reliable structure*

In this respect, in the case study of the Draugen Monopile Condeep platform, during the evaluation of the action of wave loads on the structure, the structural analysis model could be considered as a cantilever beam fixed to the ground. The wave load is lateral in nature and therefore exerts its most extreme effect at the support point, generating a large flexure moment ($\mathrm{M}_{\mathrm{flex.}}$). The magnitudes of the support moment and moment generated within the structure are related to stability and safety. To ensure safety in this respect, the support moment or the so-called Load Factor-LF of the structure at a certain point should be compared with the strength moment as RF designed by geometrical and material properties of the structure at a similar point. A structure is considered reliable if the support moment is less than or equal to the strength moment.

$$\mathrm{M}_{\mathrm{flex.}} - \mathrm{M}_{\mathrm{wave}} \geq 0 \tag{13}$$

In the computation of the unconditional failure probability for platform design, the failure probability corresponding to the platform for different wave heights is multiplied by the probability of occurrence of that particular wave height. This method considers the probabilities of different wave heights and their respective impacts on the platform, which enables failure risk evaluation for every possible scenario [24]. By aggregating all these probabilities of failure, the overall (unconditional) failure probability pertinent to the platform design can be derived. This approach facilitates a more dependable failure analysis by accounting for the potential risks that the platform might encounter under different wave conditions, thereby improving the precision of engineering designs.

$$E[p_F] = \int_H E[\langle p_F | H \rangle p_F]\, f_H(h) dh = \sum_H E[\langle p_F | H \rangle] P_H h \tag{14}$$

To perform these analyses and reliability calculations more accurately, one needs to develop proper probability models of the main load and resistance random variables beforehand. The characterization of the statistical distribution of structural materials and load conditions as accurately as possible is of crucial importance in the reliability study of engineering structures. The modeling of the probability distributions associated with the variables of load and resistance is important for understanding the nature of the uncertainties that structures are subjected to and to study the implications of these uncertainties on the safety of structures. In this context, the term "model" underlines the fact that the real behavior of structures is very complex, and any computational procedure relies on a number of idealizations to reduce this complexity. Idealization of structures is a basic necessity to make calculations possible; however, the accuracy and generality of the models employed directly influence the reliability of the results derived from the analysis. In addition, the development of 1D, 2D, or 3D models for structures using numerical analysis techniques and the assessment of these models for real loads and environmental effects allow the achievement of more realistic and reliable results [25]. Such models simulate how the structure will behave at both local and overall structural levels, thus enabling more realistic forecasts of structural performance. The execution of these analyses, considering also various loading conditions and environmental influences, provides sharper and more conclusive results regarding structural reliability and durability.

V. Conclusion

This study examined the wave load, representing one of the predominant forces exerted on marine and oceanic structures, and its implications for the reliability of such structures subjected to horizontal loads. This study used the small-amplitude wave theory in the calculation of the wave load, deriving a formula intended to quantify the wave impact on structures with cylindrical cross-sections. This equation was integrated into the standard Morison equation to develop a approach for calculating wave forces acting on cylindrical structures.

A case study evaluated the wave load on a Draugen Monopile Condeep platform installed in Norway. In the structural reliability analysis, the structure was modeled as a cantilever beam anchored to the seabed, for which the most important internal force was considered to be the moment generated at the anchorage to the seabed. This moment was compared with the moment induced by the wave load to quantify the general safety of the entire structure. Moreover, an explicit formula was provided to predict the structural failure due to the wave load. This highlights the need for an in-depth numerical analysis of the structural model to ensure safety. The results show that accurate calculations of wave forces acting on such structures should be performed, along with detailed preliminary scrutiny of the reliability of the structure.

The methodologies and formulae developed in the present study are expected to increase the calculation accuracy of the wave load and provide important guidelines for marine infrastructure design and safety evaluation. It is advisable that subsequent investigations prioritize more extensive numerical simulations to improve the safety of structures subjected to wave forces.

Notation

a : *Wave amplitude*
ω : *Angular frequency of the wave*
T : *Period of the wave*
c : *Singular wave speed*
k : *Wave number*
L : *Wave length*
d : *Water depth*

U_f : *Fastest wind speed*
U_{3600} : *1 hour average wind speed*
U_A : *Wind stress factor*
F : *Fetch distance*
H_s : *Significant wave height*
T_s : *Significant wave period*
F_{total} : *Total wave force*
F_d : *Drag force;*
F_i : *Inertial force;*
ρ : *Fluid density*
A : *Reference area (usually the front surface area of the cylinder)*
V_r : *Horizontal velocity perpendicular to the axis of the fluid particle*
D : *Cylinder diameter*
C_m & C_d : *Hydrodynamic coefficients*
$M_{flex.}$: *Flexural moment capacity*
M_{wave} : *Moment driven by wave forces*
$E[p_F]$: *Platform failure probability*
$f_H(h)$: *Pdf of the wave heights occurrence*
$P_H h$: *Occurrence probability*

Declaration

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