Nafta-Gaz 2024, no. 2, pp. 91–95, DOI: 10.18668/NG.2024.02.03

Analysis of the influence of wave loads on offshore installations

Analiza wpływu obciążeń falowych na instalacje morskie

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ABSTRACT: Given that the loads affecting offshore installations exhibit a broad range of variability in both temporal and spatial parameters, these loads are among the least studied components in the consideration of offshore installations as integrated systems. The existing calculation models and approaches used in design are rather conditional. When determining loads affecting offshore installations, the most common error is the description of loads in terms of time parameters, which lead to a distortion of the dynamic behavior of offshore installations. This is primarily because dynamic effects on the structure clearly demonstrate feedback between the influence of loads and the system itself. These loads can be classified as external and internal. Internal loads include loads from installation and construction processes, as well as loads from auxiliary and technological equipment, and external loads include ice, seismic, snow and wind loads. There are several approaches to solving problems related to the impact of wind waves on offshore installations. For this reason, an analysis and comparison of these methods were conducted to improve modeling process of offshore installations. Taking into account the impact of wave loads is a critical aspect of in developing the calculation model for the operational assessment of the residual resource of offshore installations.

Key words: offshore installations, distortion, operating time, statistical data, state prediction, wave impact, wind waves, calculation models.

STRESZCZENIE: Biorąc pod uwagę, że obciążenia wpływające na instalacje morskie wykazują szeroki zakres zmienności, zarówno pod względem parametrów czasowych, jak i przestrzennych, obciążenia te są jednymi z najmniej zbadanych aspektów w rozważaniach nad instalacjami morskimi jako zintegrowanymi systemami. Istniejące modele obliczeniowe i koncepcje stosowane w projektowaniu są raczej uzależnione od warunków. Podczas określania obciążeń wpływających na instalacje morskie, najczęstszym błędem jest opis obciążeń w kategoriach parametrów czasowych, co prowadzi do zniekształcenia dynamicznego zachowania instalacji morskich. Dzieje się tak przede wszystkim dlatego, że dynamiczne oddziaływanie na konstrukcję wyraźnie wykazuje sprzężenie zwrotne między wpływem obciążeń a samym systemem. Obciążenia te można sklasyfikować jako zewnętrzne i wewnętrzne. Obciążenia wewnętrzne obejmują obciążenia związane z procesami instalacji i budowy, a także obciążenia związane z wyposażeniem pomocniczym i technologicznym, natomiast obciążenia zewnętrzne obejmują obciążenia spowodowane lodem, wstrząsami sejsmicznymi, śniegiem i wiatrem. Istnieje kilka koncepcji rozwiązywania problemów związanych z oddziaływaniem fal wiatrowych na instalacje morskie. Z tego powodu przeprowadzono analizę i porównanie tych metod w celu usprawnienia procesu modelowania instalacji morskich. Uwzględnienie wpływu obciążeń falowych jest krytycznym aspektem przy opracowywaniu modelu obliczeniowego do oceny operacyjnej pozostałych zasobów instalacji morskich.

Słowa kluczowe: instalacje morskie, zniekształcenia, czas pracy, dane statystyczne, przewidywanie stanu, oddziaływanie fal, fale wiatrowe, modele obliczeniowe.

Introduction

When designing models of offshore oil and gas installations, defining and classifying structural loads are crucial. Considering offshore installations as a system, the loads within such a system are not fully studied components. This is due to their wide range of variability in both temporal and spatial parameters. Moreover, the calculation models currently used in design practice are somewhat arbitrary.

One of the most common errors in the process of determining loads on offshore installations is their description in terms of temporal parameters. This approach can lead to a distorted representation of the dynamic behavior of offshore installations. Particularly during dynamic impacts on the structure, the feedback interaction between loads and the system itself, e.g., "structure-foundation", is clearly evident. While the load is a critical factor in describing the interaction of offshore installations with the environment, it is not the only one.

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Article contributed to the Editor: 14.08.2023. Approved for publication: 22.01.2024.

When studying offshore installations, loads can be classified as external and internal. However, such a definition is not exhaustive, since it does not reflect such environmental factors such as chemical interaction and, as a result, corrosion of individual elements of the system, as well as a change in the structural design during operation as a result of the destruction of individual bonds. The method of calculation by limit states used in modern practice suggests starting from the concepts of the normative load value and, accordingly, the calculated value. It is believed that the normative value of the load is determined by the design standards and, to some extent, corresponds to the maximum value permissible during the normal operation of offshore installations.

At the same time, one of the basic design conditions is not implemented, i.e., ensuring equal reliability of structures of the same classification, which are subjected to different loads, since the destruction of offshore installations does not require the influence of maximum load values if the reliability of its individual parts does not exceed 60% of the required.

Loads and impacts on offshore installations are diverse in nature and manifest quite specific forms. Observations of offshore installations enable the identification of general aspects for analyzing their effects on the structure as a whole. Such analysis can be grounded in reliability theory, as well as the application of methods of statics and dynamics in offshore installation calculations. Utilizing knowledge and experience of these areas facilitates the selection, modeling and determination of the structure's response to loads and other external and internal influences on offshore installations.

The disturbance of the surface of a body of water significantly impacts offshore installations. Gravitational waves, resulting from wind surges on the water surface, impose substantial loads on these installations.

These waves can be divided into:

- irregular waves, elements of which change randomly;
- regular waves, elements of which do not change at a given point in a body of water;
- traveling waves, visible form of which moves in space;
- standing waves, visible form of which does not move in space.

In design practice, a correlation has been established between the intensity of waves on the water surface in various points and the indicator of the wave height of 3% probability, $h_{3\%}$ (Table 1). In all variants, it is understood that the $r\%$ probability gives the calculated indicator of the wave height.

Currently, several approaches address the problem of wind wave impacts on offshore installations. The primary approach involves substituting the incoming irregular waves impacting the hydraulic structure with regular waves (Kim and Shin, 2003). However, this approach does not account for the random nature of the loading process. The second approach treats the wave action as a random process occurring over time, without clear, regulated intervals of action (Kim, 2008).

Table 1. Ocean wave characteristics
Tabela 1. Charakterystyka fal morskich

The degree of disturbance [points]	Wave power	Wave height, $h_{3\%}$ [m]
0	absent	0
I	low	0…0.002
II	moderate	0.002…0.020
III	significant	0.020…0.056
IV	significant	0.056…0.143
V	strong	0.143…0.440
VI	strong	0.440…1.286
VII	very strong	1.285…2.580
VIII	very strong	2.580…4.320
IX	exceptional	over 4.320

A fundamental result in the theory of wave motion in a liquid is considered the hypothesis of a small wave height, which states that the wave profile has a simple sinusoidal shape (Bateman et al., 2003).

$$\eta = \cos(kx - \omega t) \tag{1}$$

where:
$k = 2\pi/\lambda$ – the wave number,
λ – wave length,
η – wave amplitude,
x – the position along the wave,
ω – wave's angular velocity,
t – time.

This solution, often referred to as the Airy wave theory, could not explain many of the observed effects. The classical contributions of Stokes, who addressed the nonlinear problem of the so-called waves of finite height (second approximation), refined the wave profile (Stokes, 1880).

$$\eta = \cos(kx - \omega t) + \frac{k^2\left[2sh^2(k\sqrt{\mu}) - 3\right]}{4\omega^2 sh(k\sqrt{\mu})}\cos 2(kx - \omega t) \tag{2}$$

where:
$\mu = (H/\lambda)^2$ – the square of the relative depth of the water body (H – depth of the water body),
sh – hyperbolic sine.

This formula confirms all the main characteristics of constant waves depending on the depth of the water body. Therefore, it can be said that during waves, the wave height increases more than decreases relative to the calm surface of the water body. The value of the trough width is greater than

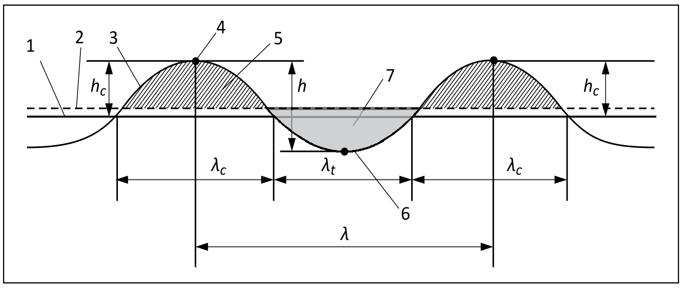

Figure 1. Wave profile and its elements: 1 – static level, 2 – average wave line, 3 – wave profile, 4 – wave top, 5 – wave crest, λ_c – crest length, λ_t – trough length, h – wave height, h_c – crest height

Rysunek 1. Profil fali i jego elementy: 1 – poziom statyczny, 2 – średnia linia fali, 3 – profil fali, 4 – wierzchołek fali, 5 – grzbiet fali, λ_c – długość grzbietu, λ_t – długość doliny, h – wysokość fali, h_c – wysokość grzbietu

that of the ridge width. This indicator tends to increase along with wave steepness (Figure 1).

It is noteworthy that soil particles from the bottom of the water body exhibit higher speeds at the crest than in the trough of the wave, and this difference increases as the depth of the water body decreases.

In this solution, for a water body depth exceeding 5 meters (Figure 2a), fluid particles at depth z rotate in a circle with a radius $h \cdot \exp \cdot (kz)$ and move horizontally with translational speed $h^2 k\omega \cdot \exp(2k)$ (Stokes flow). As the depth of the water body decreases, the trajectories of the circular motion of water particles become elliptical (Figure 2b). In this elliptical motion, the horizontal axis remains unchanged relative to the diameter of the circle, while a noticeable decrease in the vertical axis is observed.

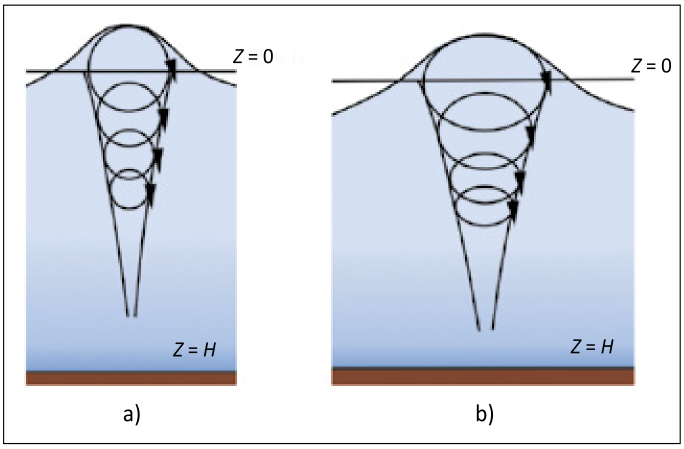

Figure 2. Structure of surface waves

Rysunek 2. Struktura powierzchni fali

The so-called Stokes theory satisfies the description of the observed phenomena at water body depths $H/\lambda \geq 0.1$. For water bodies with a shallower depth, sufficiently accurate results are given by the so-called theory of cnoidal waves by de Vries and Korteweg (Korteweg and Vries, 1895):

$$\eta = \eta_{\min} + hcn^2 (kx - \omega t, m) \quad (3)$$

where:

$\eta_{\min}$ –the deviation corresponding to the wave bottom,

h – wave height,

cn – Jacobi elliptic function with modulus m ($0 \leq m \leq 1$).

In water areas with shallow depths, where the theory of cnoidal waves is applied for calculations, the horizontal movement velocity of fluid particles predominates (Seyed and Fatemeh, 2017).

Research objectives

The aim of this paper is to analyze existing methods used for predicting various wave parameters, such as wave height, which are essential for modeling of offshore structures and improving their construction to increase their operating life. By comparing and understanding the applicability of these methods, it would be possible to simplify the modeling of wave loads on offshore installations.

Research results

In assessing the residual operational life of offshore installations, statistical methods that describe the level of waves require taking into account the complex nature of irregular waves, particularly when view as a random stationary process.

Key indicators of such statistical characteristics include average wave height $\bar{h}$, the average period $\bar{T}$, and the distribution function that determines the heights of the waves acting on the hydraulic structure and the probability of periods.

Calculating the distribution function makes it possible to estimate wave height $h_{i\%}$, which for the critical values can be calculated using the following formula:

$$h_{0.1\%} = 2.96\bar{h},\ h_{1\%} = 2.42\bar{h},\ h_{3\%} = 2.11\bar{h} \quad (4)$$

where: $h_{0.1\%}$, $h_{1\%}$, $h_{3\%}$ are wave heights with 0.1, 1 and 3% probability, respectively.

Due to unavailability of long-term statistical data on distribution functions, particularly for hydraulic structures without an owner, in accordance with SP38.13330.2018, the disturbance in the water body affecting a hydraulic structure can be determined using the so-called wave-forming criteria:

- relief of the bottom surface of the water body, considering changes in water surface elevations;

- size and shape of the wind-driven water body;
- time of wind impact on the surface of the water body and its speed.

In accordance with SP38.13330.2018, it is recommended to use the value of the acceleration or distance of the surface of the water surface covered by the wind, measured in the direction of the wind to the hydraulic structure in order to calculate the elements of wind waves. The average acceleration value for determining the elements of the wave is calculated using the following formula:

$$L = k_{vis} v / V_w \tag{5}$$

where:

k_{vis} – constant coefficient accepted equal to $5 \cdot 10^{11}$,

$v = 1.51 \cdot 10^{-5}$ m²/s – kinematic viscosity of air at 20°C,

V_w –the calculated wind speed at a height of 10 m above the sea level, which is accepted for hydraulic structures class I and II with a probability of 2%, i.e., 1 time in 50 years (GOST R 55260.1.6, 2012).

When making calculations for water bodies with zones deeper than 12 meters, the dimensionless indicator gL/V_w^2 is determined, according to which, using the graph (Figure 3), it is possible to determine the values of the average wave height $g\bar{h}_d/V_w^2$ and the dimensionless period $g\bar{T}/V_w$. The data was obtained as a result of systematization of the results of laboratory studies (SP38.13330.2018), field observations and indicators for it are calculated using the following formula:

$$\frac{g\dot{h}}{V_w^2} = 0.16\left\{1-\left[\frac{1}{1+0.006\left(\frac{gL}{V_w^2}\right)}\right]^2\right\} \cdot$$

$$\cdot\, th\left\{0.625 - \frac{\left(gL/V_w^2\right)^{0.8}}{1-\left[1/(1+0.006\left(\frac{gL}{V_w^2}\right)^{0.5}\right]^2}\right\} \tag{6}$$

Therefore, if the average period T is known, the average wavelength is calculated using the following formula:

$$\bar{\lambda}_d = \frac{g\bar{T}^2}{2\pi} \tag{7}$$

Other indicators, such as wave height h_i for shallow water bodies and h_{sur} for surf zones, are determined from the graphs and derived formulas specified in the SP38.13330.2018 standard.

After analyzing all the methods used for wave modeling, it is recommended to use all three methods according to their limitations (Figure 4).

Conclusions

The impact of wave loads can have a devastating effect on offshore installation structures if timely measures are not

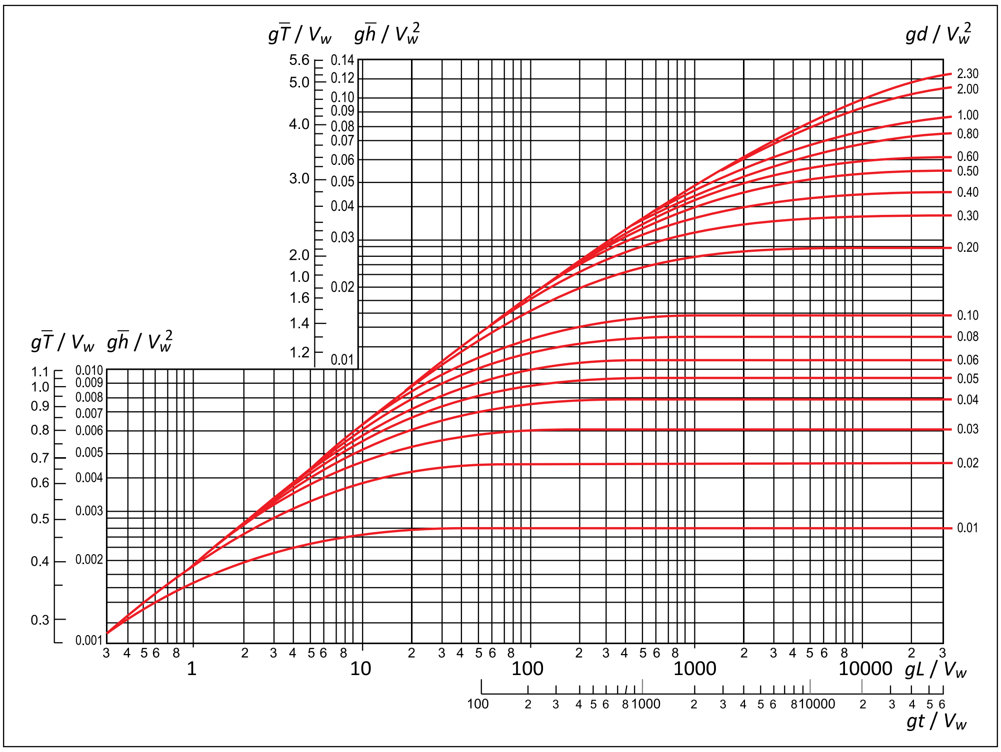

Figure 3. Graph for determining the elements of wind waves

Rysunek 3. Wykres do określania elementów fal wiatrowych

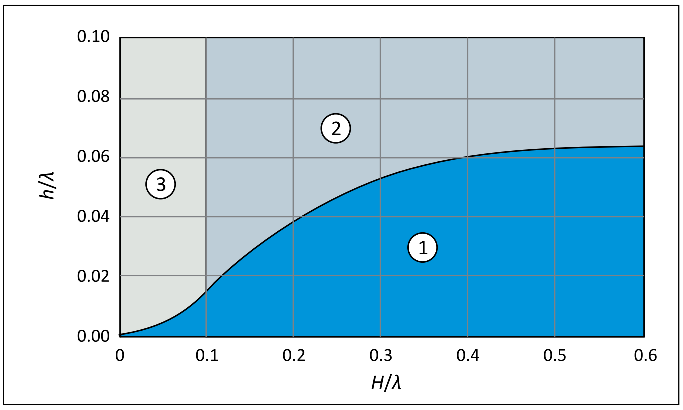

Figure 4. Diagram of applicability of: Airy wave theory (1), Stokes wave theory (2) and cnoidal waves (3)

Rysunek 4. Schemat zastosowania: teorii fal Airy'ego (1), teorii fal Stokesa (2) i fal knoidalnych (3)

taken to counteract them. The nature of this impact largely depends on the type of wave flows. Accurate prediction of wave heights enables taking appropriate measures such as reinforcing platform structures, securing equipment to ensure staff and equipment safety. Additionally, it allows to schedule maintenance and repair activities during periods of calmer wave, reducing the risk of accidents and enhancing overall reliability. Accounting for the impact of wave loads is a crucial aspect in developing calculation models for operational assessment of the residual resource of offshore installations.

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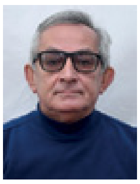

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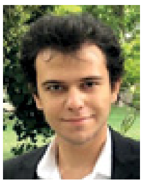

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