INDEX COPERNICUS INTERNATIONAL

ORIGINAL ARTICLE Bulletin of the Maritime Institute in Gdańsk

Numerical and experimental analysis of the wave induced forces on the tripod support structure. Laboratory study

Analiza numeryczna i eksperymentalna obciążeń falowych działających na konstrukcję wsporczą typu trójnóg. Badania laboratoryjne

Authors' Contribution:
A – Study Design
B – Data Collection
C – Statistical Analysis
D – Data Interpretation
E – Manuscript Preparation
F – Literature Search
G – Funds Collection

Kraskowski Marek[2ABDEF], Pastwa Katarzyna[2BEF], Kowalczyk Sebastian[2EF], Marcinkowski Tomasz[1CEG]

[1]Instytut Morski w Gdańsku,
[2]Centrum Techniki Okrętowej S.A.

Article history: Received: 31.08.2016 Accepted: 14.11.2016 Published: 03.01.2017

Abstract: The presented work was realized within the framework of the AQUILO project, aiming to create the base of knowledge for prospective future investments in offshore wind energy on the Baltic Sea. The presented part of the work is focused on the experimental validation of numerical method of evaluation of the wave-induced forces on the bottom-mounted support structure of the offshore wind turbine. The experimental setup and measurement equipment, including in-house developed 6-DOF (six freedom) dynamometer, are described. Comparison of performance of different methods of evaluation of wave loads for wide range of parameters is presented. The results of experiments and numerical analyses are consistent; the largest discrepancy occurred at lowest wave frequencies, i.e., largest wave lengths. This may result from increased relative error of measurements for long waves in a relatively short tank.

Keywords: offshore wind turbine, seakeeping, model basin experiment

Streszczenie: Prezentowana praca została wykonana w ramach projektu AQUILO, mającego na celu stworzenie bazy wiedzy dla przyszłych, potencjalnych inwestycji w energetykę wiatrową na akwenach Morza Bałtyckiego. W prezentowanej pracy wykonano empiryczną walidację numerycznej metody wyznaczania obciążeń falowych działających na konstrukcję wsporczą morskiej elektrowni wiatrowej. Przedstawiono i opisano fizyczny model doświadczalny oraz urządzenia pomiarowe, włącznie z wykonanym dla tego zadania dynamometrem o sześciu stopniach swobody (6 DOF). Zaprezentowano porównanie wyników obciążeń wywołanych falowaniem, otrzymanych różnymi metodami, dla szerokiego zakresu zmienności parametrów falowania. Wyniki uzyskane z przeprowadzonych doświadczeń oraz wyniki otrzymane z modelu numerycznego wykazują zadowalającą zgodność; największe rozbieżności wystąpiły dla częstotliwości najniższych, tj. dla fal najdłuższych. Przyczynę tych rozbieżności można tłumaczyć wzrostem względnego błędu pomiarowego dla bardzo długich fal w stosunkowo krótkim basenie

Słowa kluczowe: pełnomorskie konstrukcje wsporcze, obciążenia falowe, eksperymenty w basenie modelowym

Introduction

Experimental evaluation of the wave-induced forces on the support structures of bottom-mounted offshore wind turbines (OWTs) may seem straightforward due to simplicity of shape of analysed structure and simple experimental setup. However, interpretation of the results of experimental analyses, although free from simplifications of the mathematical flow models, can be problematic due to unrecognized scale effect. A simple semi-empirical method for evaluation of wave loads, based on Morison equation [1], is still the most common and most reliable method for evaluation of wave loads. The unquestionable advantage of the experiment is, however, the possibility of validation of numerical models.

In this paper, the applicability of diffraction theory for evaluation of wave loads on the bottom-mounted OWT support structure of tripod type was verified. The importance of diffraction effects for this structure is not obvious. Considering the accepted criterion for using the diffraction theory ($\pi D/L>0.5$, where D is the member diameter and L is the wave length, [2]), single members of the structure fall into this category for shorter harmonics of the wind wave spectra (in presented analysis, the value of this factor varied between 0.05 and 0.7). However, in Fig.1 and Fig.2, it can be seen that reducing the bottom part of the structure to independent slender members is too crude. The flow model based on diffraction theory does not consider the viscous drag, which makes it invalid for some cases; moreover, the scale effects does not occur in the results. The presented analysis allows checking the validity of diffraction theory for predictions of wave loads on selected type of support structure and assesses the importance of viscous effects.

The comparative experimental analyses in the paper included the measurements for both regular and irregular waves. As a summary, complete comparative analysis is presented.

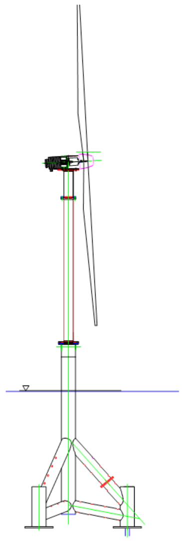

Fig. 1. Complete OWT – scheme

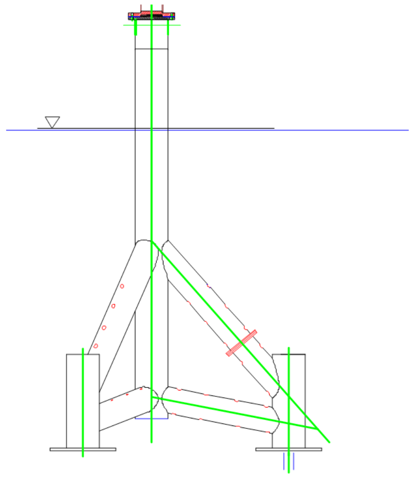

Fig. 2. OWT supporting tripod – side view

Overview of the analyses

The evaluation of wave loads was carried out for the bottom-mounted offshore wind turbine of tripod type, presented in Fig. 1. The design water depth is 60 m. The geometry does not represent an existing structure; it was designed for the AQUILO project, considering typical shapes of existing tripods and feasibility of manufacturing the physical model. Because the wave loads and wind loads are not coupled in case of bottom-mounted OWT support structures, it is possible to analyse the hydrodynamic loads separately. For that reason, the OWT rotor was not present in the analyses.

Experimental analyses

Measurements of the wave loads for the tripod were carried out in the auxiliary towing tank of Centrum Techniki Okretowej S.A. (65 m x 7 m x 3 m) for three wave directions (Fig. 5). The wave direction was changed by rotating the analysed structure. The model scale was 1:40, i.e., the design water depth in model scale is 1.5 m. For each direction, the following cases were analysed:

- series of regular waves of 3 cm height, covering entire range of frequency possible to achieve in the towing tank;
- series of regular waves of 1cm, the same frequencies;
- three irregular waves corresponding to storms in Baltic Sea of the return period of 1 year, 10 years, and 50 years, respectively.

The selection of wave heights for experimental analyses required a trade-off between the agreement with linear wave theory and signal-to-noise ratio. Two wave heights were used; the higher one gets closer to Stokes waves at higher frequencies, while for the smaller one, the results were expected to be somewhat noisy due to low values of measured forces. Executing the measurements for two wave heights allowed for improved control of the reliability of the results.

Although the auxiliary towing tank allows for changing the water depth from 0 to 3 m, in case of measurements in waves, the water depth must be set to optimum value from the point of view of wave maker capability (about 3 m). The water depth in the measurements does not correspond exactly to the design water depth.

The measured quantities were:

- reaction of the support structure foundation - 6 components (in this study, only the horizontal force in the wave direction was analysed);
- wave elevation near the analysed structure

Numerical analyses

The computational analyses were carried out with ANSYS AQWA software, based on diffraction theory ([4], [5]). The computations in AQWA were done for three depths of water, corresponding to design depth, infinite depth, and the depth corresponding exactly to the measurement conditions in the towing tank. Two directions of waves were considered - 1 and 2, according to Fig. 5. The computations based on diffraction theory were carried out only in frequency domain, which corresponds to measurements for series of regular waves.

Environmental conditions

The predictions of wave loads for the tripod were done for storm conditions in the Baltic Sea; three significant wave heights were considered, corresponding to the storm return period of 1 year, 10 years, and 50 years, respectively [6]. For the experiment, the wave conditions are idealised by assuming JONSWAP energy spectra. Parameters of the idealised wave spectra are listed in Tab. 1. Comparison of the experimental results with numerical results for irregular waves was done only for the highest wave, i.e., 50-year storm.

The spectral density of the wave energy for three considered conditions is presented in Fig. 3.

The analysis in regular waves was carried out to evaluate the transfer functions; this means the wave height must be minimized so as not to maintain the validity of the assumptions of linear wave theory. However, the wave height should be large enough to achieve sufficient signal to noise ratio. It was decided to use two heights of regular waves - 3 cm and 1 cm.

Tab. I. Wave spectra parameters

RETURN PERIOD	SIGNIFICANT WAVE HEIGHT HS [M]		WAVE PEAK PERIOD TP [S]		GAMMA g [-]
	Full scale	Model	Full scale	Model	
1 year	4.08	0.102	7.0	1.107	5.00
10 years	8.15	0.204	10.4	1.644	4.76
50 years	9.23	0.231	11.3	1.787	4.36

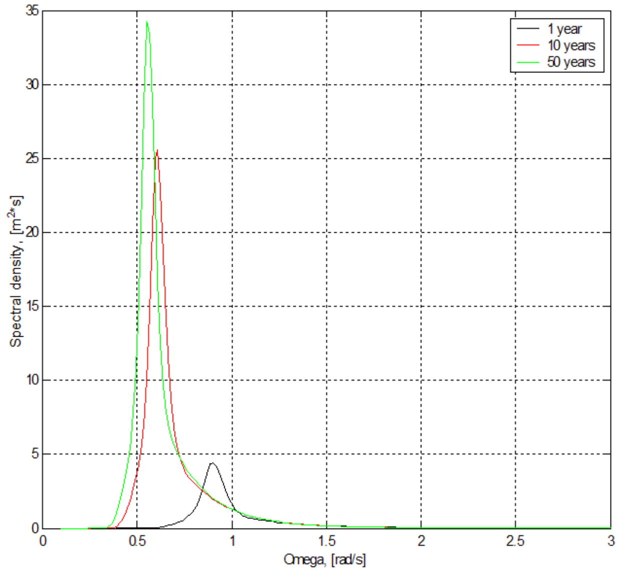

Fig. 3. Analysed wave spectra

Experimental setup

Installation

The depth of the towing tank does not correspond to actual design water depth for the analysed structure due to limitations of the wavemaker operability (the towing tank depth is 3 m, while the scaled design water depth for the tripod is 1.5 m). Location of the model relative to the free surface was then adjusted by using additional support structure mounted to the bottom of the towing tank (Fig. 4). Difference in water depth results in incorrect modelling of the wave kinematics; the proposed method of model tests is a necessary compromise, resulting from the limitations of the testing facility. To minimize the vertical motion of water particles near the tripod foundation, a circular flat plate was mounted below the model. The model is in the middle of the towing tank length. Analysed wave directions are presented in Fig. 5.

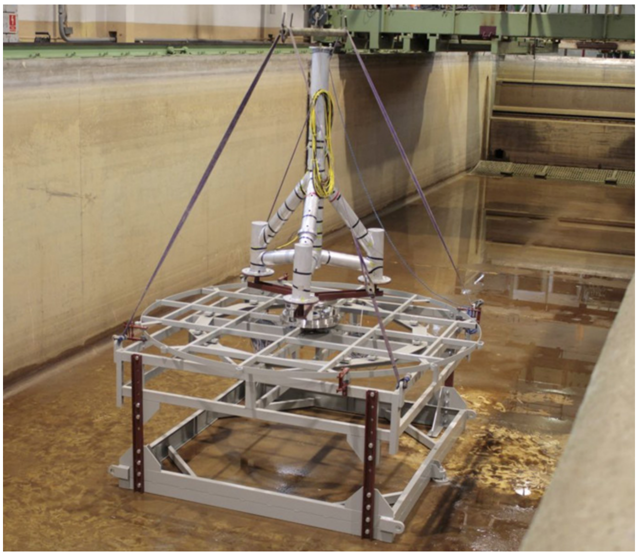

Fig. 4. Model installation in the towing tank

Measurement equipment

The wave elevation during the experiment was measured with a standard resistance wave probe.

To measure the foundation reaction, a specialized waterproof 6-DOF dynamometer was designed and manufactured in CTO S.A. It was theoretically possible to use three separate component load cells under each leg of the tripod and then calculate global reaction. However, such an approach has substantial drawbacks, i.e., individual setup for each analysed structure and very complex procedure of processing the results with high risk of errors. The 6-DOF dynamometer was designed to allow easy setup of the measurement stand, while maintaining compact size and high versatility of the device. This was achieved at the cost of a complex calibration procedure, resulting from coupling between all components of the meas-

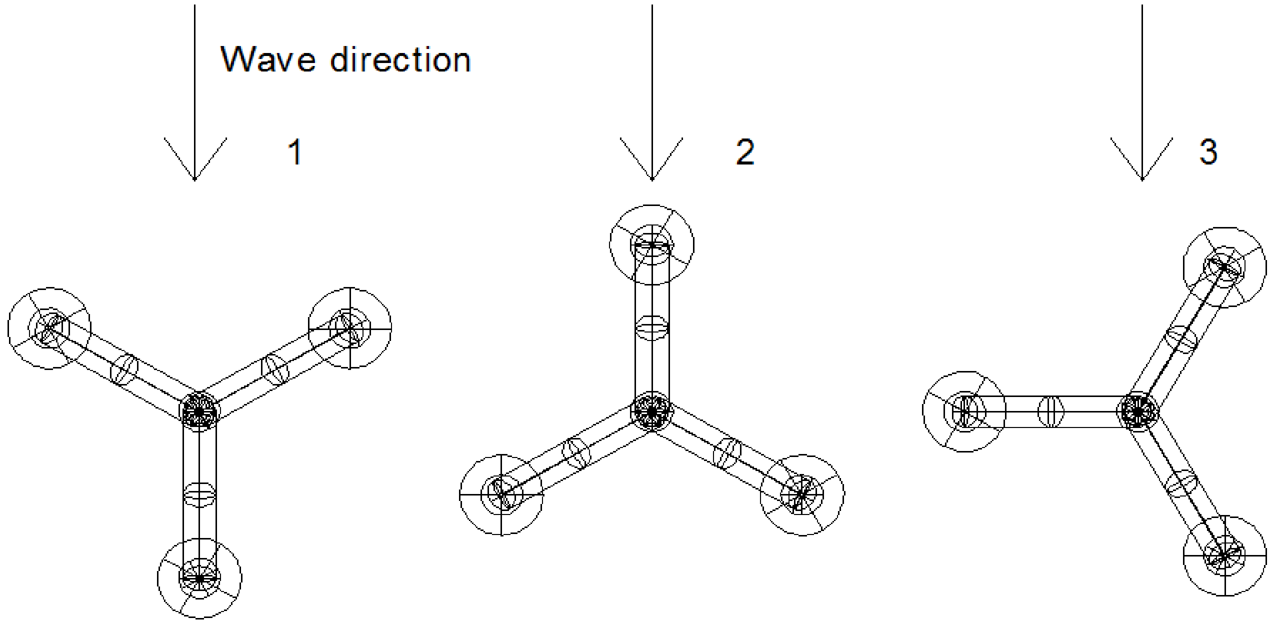

Fig. 5. Analysed wave directions

ured force (the construction of the dynamometer includes 6 load cells, and it is not possible to measure the reaction components separately - each component of the reaction is computed based on signals from all 6 load cells). The calibration procedure can be briefly described as follows:

- a variety of known load cases (708 in described case) was predefined and applied to the dynamometer;
- at each load case, the electric signal from each load cell was registered;
- the in-house software, developed based on mathematical models presented in [3], was used to evaluate the calibration matrix, i.e., a matrix of coefficients allowing for recalculation of the vector of load cell signals to the vector of six components of the load.

The dependency between the load vector and the vector of load cell signals, involving the calibration matrix, has the following form:

$$\begin{bmatrix} F_X \\ F_Y \\ F_Z \\ M_X \\ M_Y \\ M_Z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} \end{bmatrix} \cdot \begin{bmatrix} H_1 \\ H_2 \\ H_3 \\ V_1 \\ V_2 \\ V_3 \end{bmatrix}$$

where F_X - M_Z are six components of the load (forces and moments), H_1 - V_3 are the signals from load cells (horizontal and vertical ones), and a_{ij} are scalar coefficients.

Verification of the calibration procedure consists in comparing the force components for known load cases with force values computed using the evaluated calibration matrix. In the presented case, the calibration error did not exceed 1% in 95% load cases and 2% in 98% load cases. For single case, it reached up to 3.5%. The dynamometer is presented in Fig. 6 (design) and Fig.7 (actual device). The load cells in Fig.6 – three vertical and three horizontal ones – are marked with red.

Computational setup - diffraction theory

Due to neglecting the viscous forces in the computations based on diffraction theory (potential flow), the scale effect does not occur. The computations of wave loads were carried out at full scale, for three water depths:

- 60 m (design depth for the tripod);
- 120 m (corresponding to the depth of towing tank - 3 m at model scale);
- 1000 m (approximation of infinitely deep water conditions).

Repeating the analysis for different depths allows estimating the quantitative influence of changes in wave kinematics resulting from the change in water depth, which is important from the point of view of simplifications used in model tests and described above.

The mesh of app. 3000 elements was used; the computational model is presented in Fig. 8. The computations were carried out in frequency domain, i.e., for series of regular waves.

Results of primary analysis

The presented analysis is focused only on global axial force exerted by the waves on the tripod. The results are presented

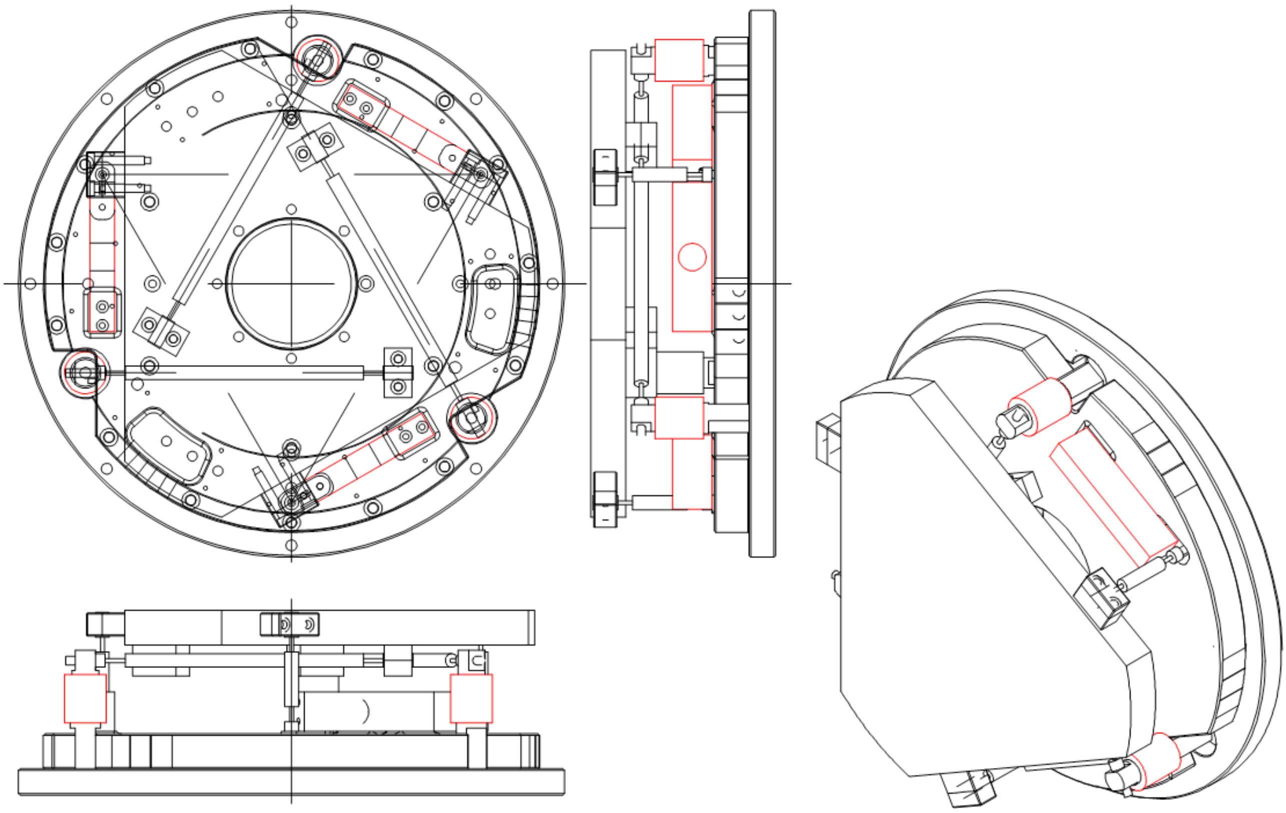

Fig. 6. 6-DOF dynamometer – design drawings

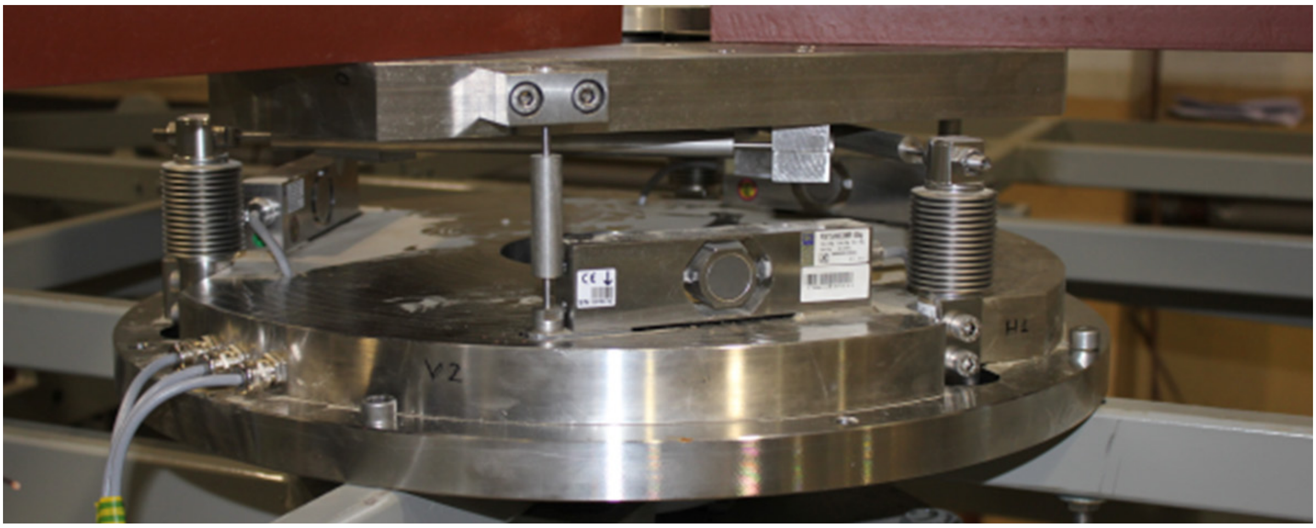

Fig. 7. 6-DOF dynamometer

primarily in graphs, showing the transfer functions (analyses in regular waves) and response spectra (analyses in irregular waves). Comparison of the predictions of significant amplitudes of the response is presented in a table. All values are presented for full scale structure, i.e., the experimental values were scaled according to Froude scaling law.

Results of experimental analyses in regular waves

Figure 9 shows the results of wave load measurements in regular waves, for wave directions 1 and 2. Fig. 10 shows the results for both wave directions. The results are presented in transfer functions,

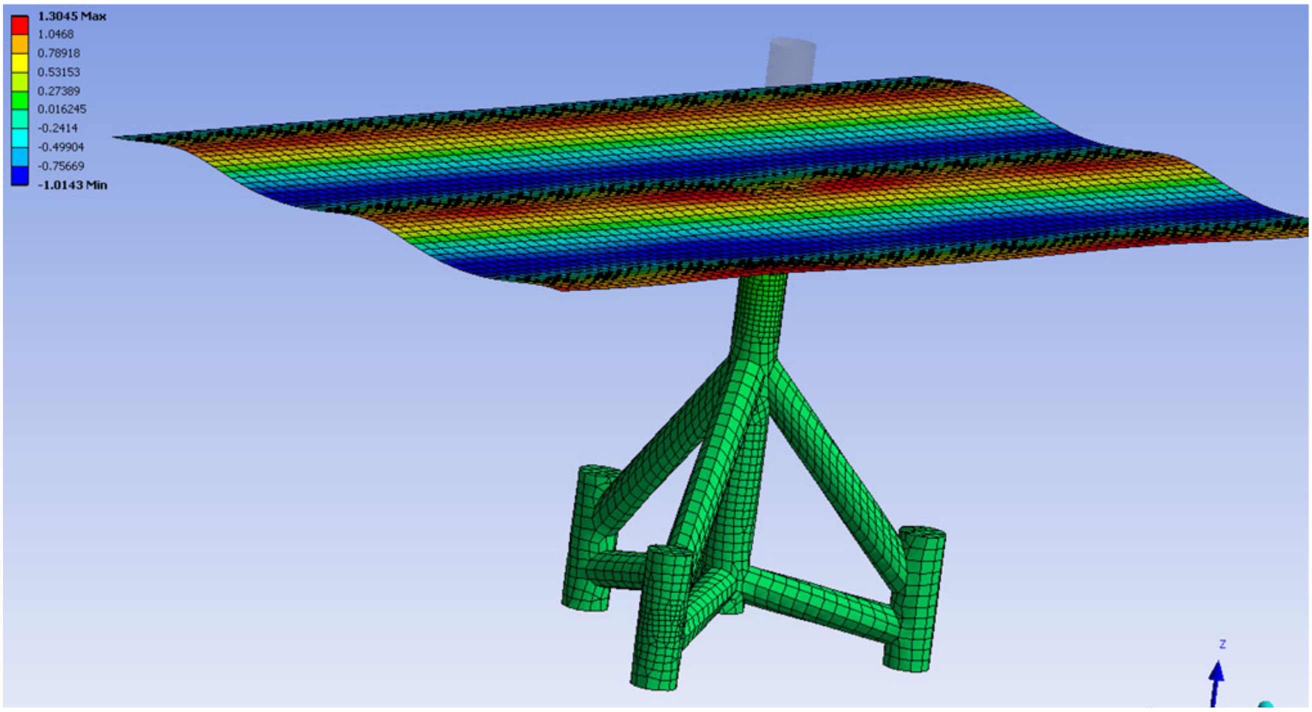

Fig. 8. Computational model – diffraction theory

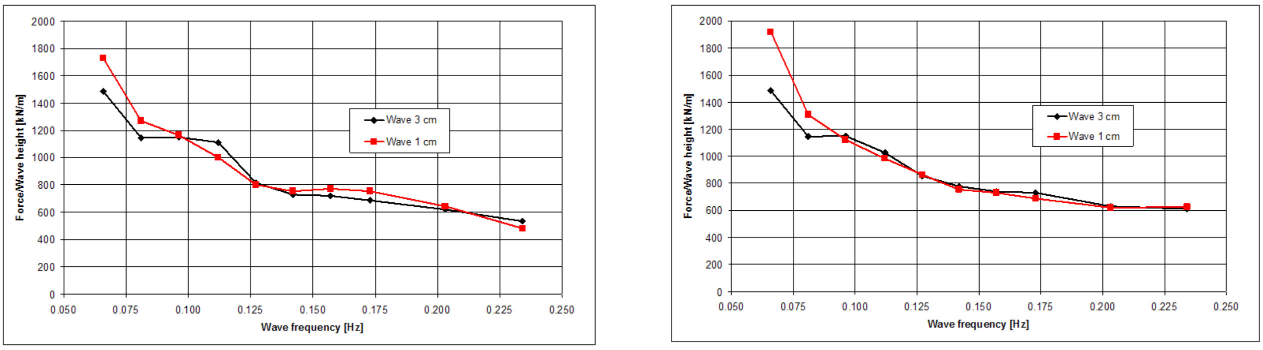

Fig. 9. Transfer functions - experiment, two wave heights, direction 1 (left) and direction 2 (right)

i.e., amplitude of axial force for unit wave amplitude vs. wave frequency. The values of transfer functions are obtained by dividing the double amplitude of resulting force by actual measured wave height. The measurements were carried out for two wave heights - 3 cm and 1 cm, to check the influence of wave height on the results. The results show minor differences in transfer functions evaluated for different wave heights. For high frequencies, the differences are negligible and may result mainly from interpretation of the results - the measured signals are not perfectly periodic, and selection of the best sample of the signal requires arbitrary decision. For lower frequencies (i.e., longer waves), larger differences are observed. Because the waves of larger height are closer to linear wave theory for low frequencies than for high frequencies (lower height to length ratio), the results for 3 cm wave should be more reliable due to larger absolute values of measured signals. The differences in wave loads for two considered wave directions are also small and result mainly from uncertainty of measurements and processing.

Results of numerical analyses - diffraction theory, regular waves

The computations carried out with ANSYS AQWA software show there is virtually no difference between the results for different wave directions. Only the results for direction 1 are presented here. Three water depths were considered to check its influence on resulting wave force: 1000 m (approximation of infinite depth), 60 m (design water depth) and 120 m (actual depth of the towing tank). Summary of the results is presented in Figure 11.

The results show the difference between tank depth and deep water conditions is small and virtually negligible from the point of view of prediction accuracy; however, large difference between the forces imposed by deep water waves and shallow water waves at low frequencies is visible. This confirms the need for adjusting the experimental conditions close to actual depth conditions; in the presented case, it was realized by ap-

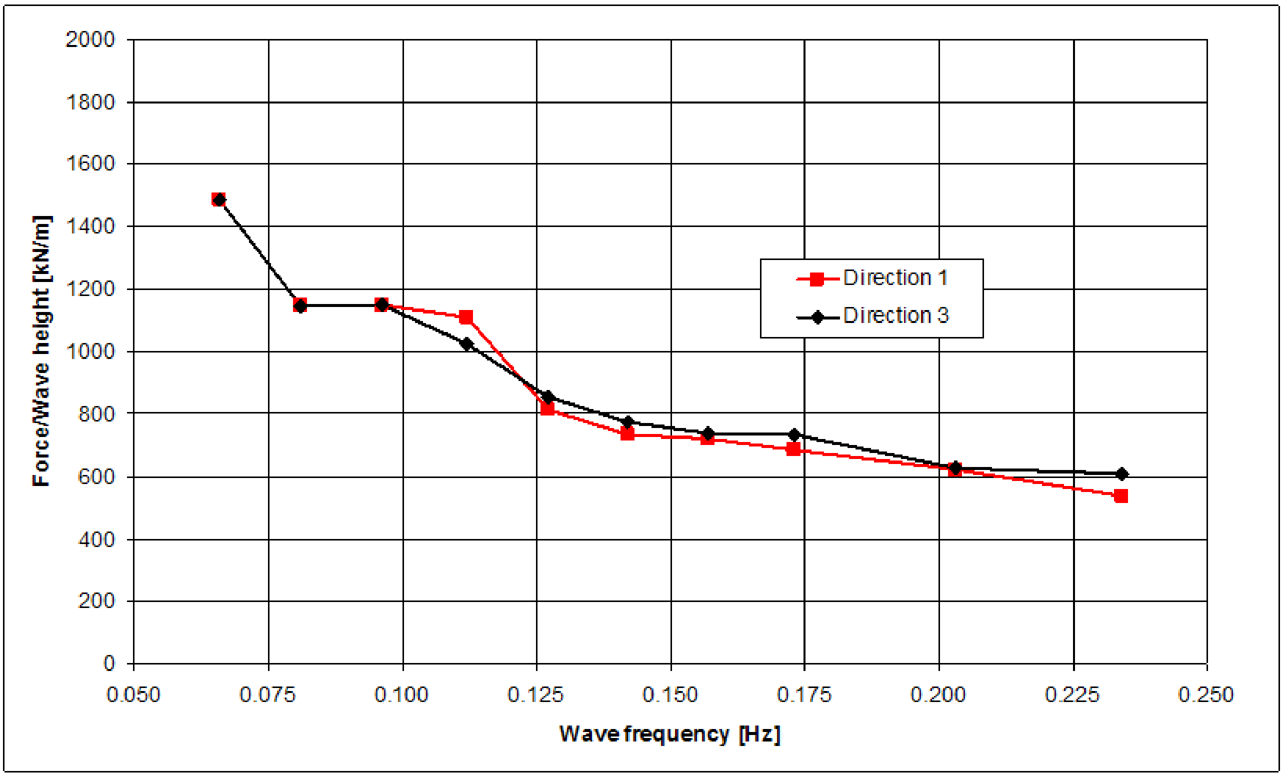

Fig. 10. Transfer functions – experiment, two wave directions

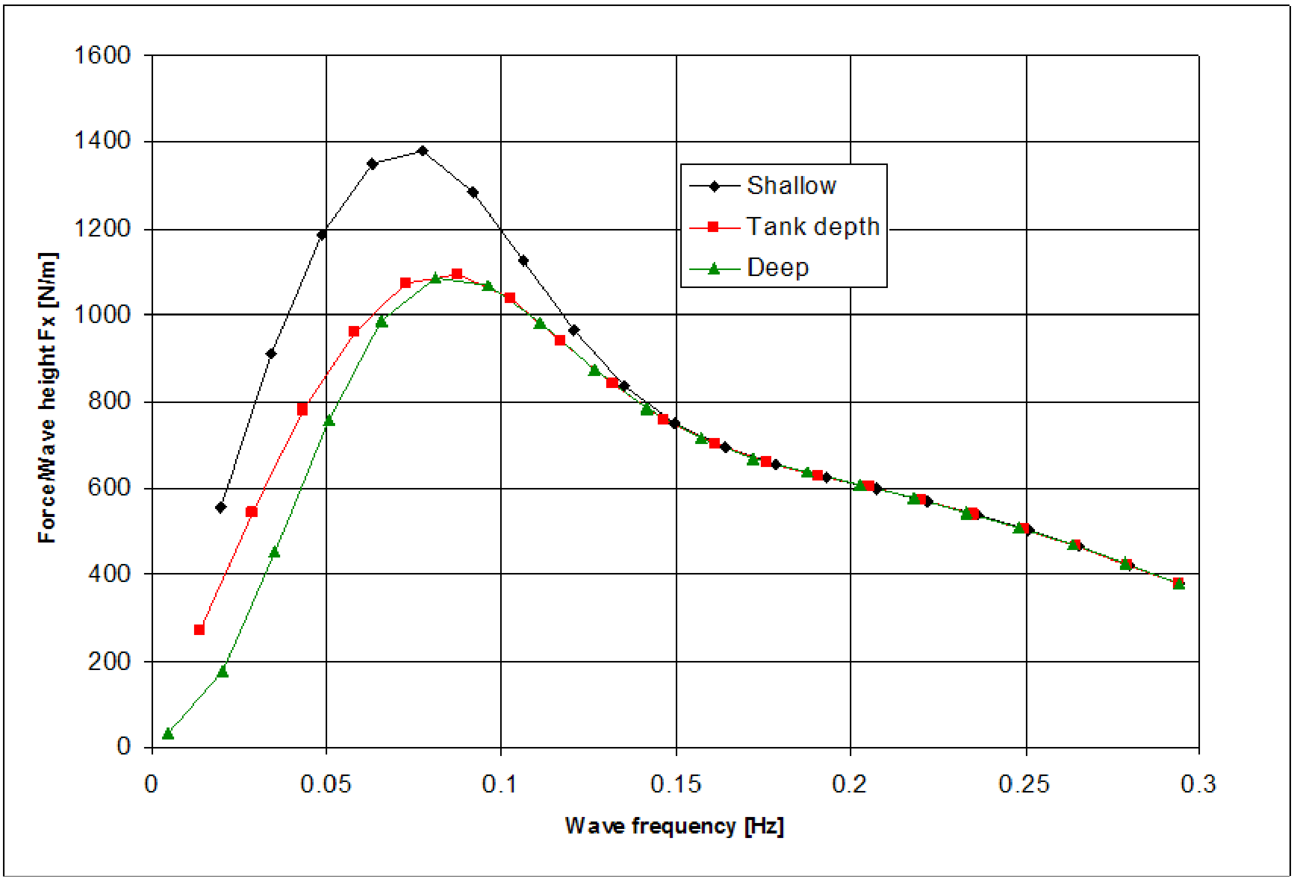

Fig. 11. Transfer functions – diffraction theory, different water depths

DOI: 10.5604/12307424.1224269

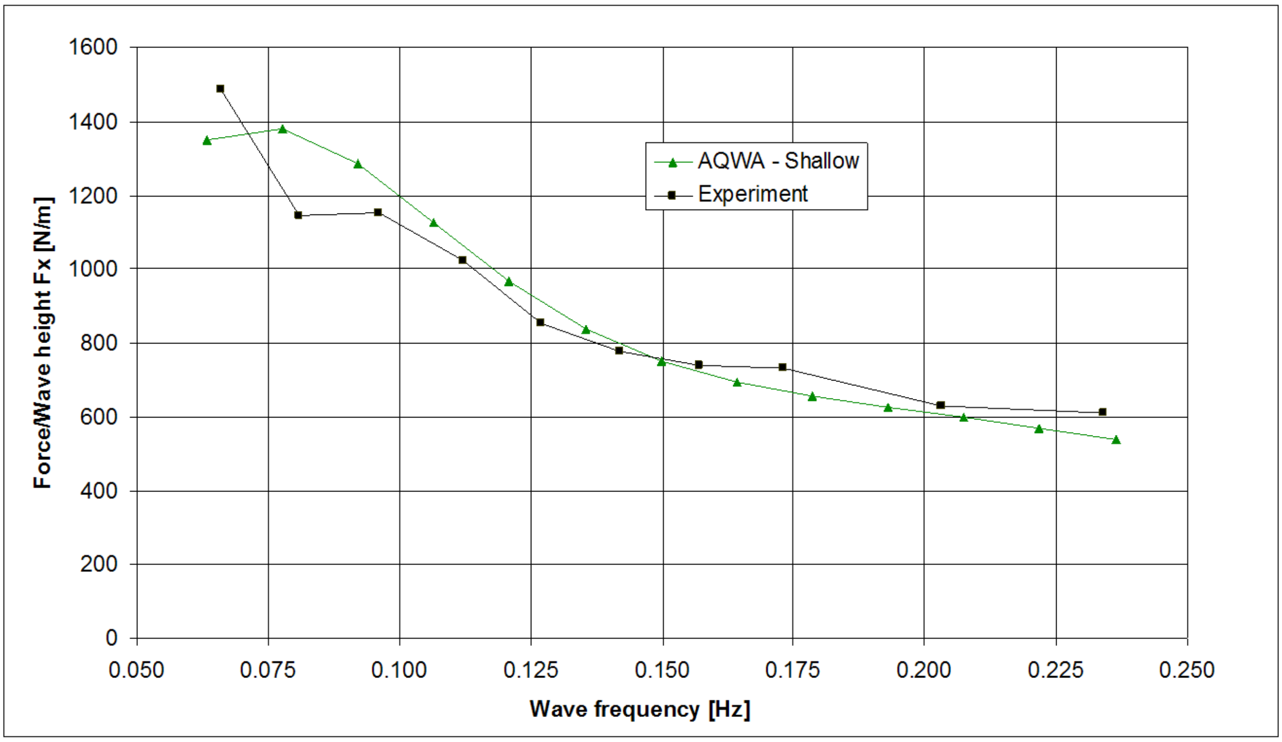

Fig. 12. Transfer functions - all methods

plying the flat plate below the analysed structure, at the level of actual seabed location.

Comparison of results for regular waves - experiment and diffraction theory

Fig. 12 shows the comparison of results for regular waves, obtained from all methods, i.e., experiment and diffraction theory.

The results obtained from AQWA (diffraction theory) are quite consistent with experimental results within analysed wave frequency range. Largest discrepancies were observed for lowest frequencies, at which the curve obtained from the experiment loses its monotonic character and tends to oscillate. The expected reason for that is the increase of relative error of measurements at low wave frequency, resulting mainly from increased influence of reflected wave in case when the wave length becomes comparable with the tank length. The presented comparison of transfer functions obtained from the experiment and from numerical analysis confirm the validity of the applied numerical model for evaluation of wave loads on analysed structure.

Summary

In Table 2, the results obtained from experiment and numerical methods are summarized by comparing one characteristic parameter - the root mean square (RMS) of the force imposed by the wave on the tripod. The presented analysis yields the following general conclusions:

Tab. II. Summary of the results

DESCRIPTION	FORCE RMS [KN]
Irregular waves – experiment	2650
Regular waves – experiment	2541
Diffraction theory	2368

- Largest discrepancy between diffraction theory and experiment occurred at lowest wave frequencies, which can result from lower accuracy of experimental predictions for largest wave lengths;
- The prediction based on diffraction theory is sufficiently close to experimental results, which reveals low contribution of viscous forces to total forces in the analyzed case;
- Taking the above into account, it can be expected that the wave load prediction based on both diffraction theory and direct Froude scaling of the experimental results at model scale can be close approximation of actual full scale load.

Acknowledgement

The environmental data used in the analyses were provided by the Maritime Institute in Gdansk. The presented work was realized within the framework of AQUILO project (PBS1/A6/8/2012), co-funded by The National Centre for Research and Development, and MareWint project under research area FP7-PEOPLE-2012-ITN Marie-Curie Action: "Initial Training Networks."

References:

[1] Morison J. R., O'Brien M. P., Johnson J. W., Schaaf, S. A., ***The force exerted by surface waves on piles***, Petroleum Transactions (American Institute of Mining Engineers) 189: 149–154, 1950

[2] Chakrabarti S. K.: ***Offshore structure modeling***, World Scientific, 1994

[3] Leung, S.Y.F, Link, Y.Y., ***Comparison and Analysis of Strain Gauge Balance Calibration Matrix Mathematical Models***, DSTO Aeronautical and Maritime Research Laboratory, 1999

[4] Faltinsen O. M., ***Sea loads on ships and ships and offshore structures***, Cambridge University Press, Cambridge, 1996.

[5] Garrison C.J., ***Hydrodynamic Loading of Large Offshore Structures: Three-Dimensional Source Distribution Methods***, Numerical Methods in Offshore Engineering, John Wiley, 87-140, 1978

[6] Marcinkowski T., ***Morskie elektrownie wiatrowe. Oddziaływanie środowiska: wiatr, falowanie morskie, prądy morskie***, Maritime Institute in Gdańsk, AQUILO project, 2013

[7] Kraskowski M, ***CFD modelling of the dynamics of moored structures***, Hydronav 2012, Iława

Word count: 2660 Page count: 9 Tables: 2 Figures: 12 References:7

Scientific Disciplines: Other

DOI: 10.5604/12307424.1224269

Full-text PDF: www.bullmaritimeinstitute.com/fulltxt.php?ICID=1224269

Cite this article as: Kraskowski M., Pastwa K., Kowalczyk S., Marcinkowski T.: Numerical and experimental analysis of the wave induced forces on the tripod support structure. Laboratory study: BMI, 2017; 32(1): 21-29

Competing interests: The authors declare that they have no competing interests.

Corresponding author: Autor do korespondencji: Tomasz Marcinkowski; Instytut Morski w Gdańsku, Polska, tel.: +48 58 301-16-41 w. 30; e-mail: tomasz.marcinkowski@im.gda.pl

Ministerstwo Nauki i Szkolnictwa Wyższego The goals are financed according to the agreement 591/P-DUN/2017 from the funds of the Ministry of Science and Higher Education for science promotion.