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IMPACT OF NONLINEAR STANDING WAVES UNDERNEATH A DECK

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A theoretical approach was applied to investigate the impact of nonlinear standing waves underneath a horizontal deck. A solution was achieved by applying a boundary element method. The model was applied to predict impact pressure underneath a deck. The results show that the wave impact is a very complex momentary process. The influence of initial boundary conditions, wave parameters and deck clearance on impact pressure are analysed. The analysis shows that purely sinusoidal waves of very small amplitude may cause an impact pressure several orders of magnitude higher than a pressure arising from typical applications of a linear wave theory. The analysis shows that all these non-intuitive outcomes arise from the complexity of a wave impact process and its enormous sensitivity to initial conditions what indicates serious difficulties in a reliable prediction of a wave impact for complex wave fields or other structures. Laboratory experiments were conducted to validate theoretical results.

Keywords: Wave impact, Impact pressure, Coastal structures, Offshore structures

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1. INTRODUCTION

The modelling of wave interaction with maritime structures is essential for the prediction of wave loads, wave agitations in harbours and resonance problems. In fact, the modelling and an accurate prediction of wave and pressure fields is indispensable for most wave-induced phenomena in coastal and offshore engineering. An important and challenging phenomenon, from the modelling point of view, is an accurate prediction of wave and pressure field for the problem of wave impact on coastal and offshore structures. Coastal and offshore structures such as jetties, breakwaters, oil platforms are often exposed to extreme wave impacts [1, 2]. Failures of many structures, including some recent unexpected failures of several maritime constructions as well as many ship accidents, are believed to be caused by wave impact. A better understanding of this phenomenon is essential for safety of coastal and offshore structures and for the improvements in ship constructions.

The studies conducted on wave action on a structure located above the still water level focus mainly on impact forces. Decks of jetties or platforms, elements of balustrades, superstructures of breakwaters, parapets are typical horizontal elements of maritime structures located above the still water level which are subject to wave attack and, in consequence, large impact forces. Simplified approaches to assess impact forces were proposed by [3, 4, 5, 6]. These approaches were based on momentum and energy considerations or approximate formulas. [7] proposed a set of equations to calculate wave forces on a platform, which are often applied in design. Numerical modelling of wave action on a horizontal deck have been conducted by [8, 9, 10, 11, 12, 13, 14]. The modelling is based on the application of a finite element method, a boundary element method, a volume of fluid method and has been focusing on the estimation of the impact of progressive waves.

Experimental data and theoretical investigations showed that a wave impact on a coastal or offshore structure is a very complex process. The problem is that knowledge on wave impact and its physics is still very limited. Our limited knowledge on the process of impact is mainly due to complex wave kinematics preceding the moment of impact, which makes this process difficult to be described with sufficient accuracy [15]. In fact, wave impact is usually a result of an attack of extreme or breaking waves and it is difficult to predict wave kinematics, especially, that a successful prediction of wave impact requires precise information regarding wave and velocity fields. The situation additionally complicates a complex response of a structure at the moment of impact. An analysis of various wave-impact phenomena conducted by [11, 12] indicated that a good insight into wave impact processes can be achieved for waves of moderate steepness for which wave kinematics can be predicted with sufficient precision [16]. This provides an opportunity to describe and analyse an impact process and its effects with a fairly good accuracy, which motivated present studies.

In this work, a theoretical approach is applied to investigate the impact of nonlinear waves underneath a horizontal deck. First, a theoretical model is applied to predict wave propagation and the formation of standing waves to get a desired wave field at the position of the deck. Then, the wave impact underneath the deck is investigated. This study omits the air cushion appearance. The results are analysed with emphasis on phenomena associated with wave impact and the origin of large pressure induced at the bottom of the deck by small amplitude waves. Finally, the non-intuitive results are addressed and conclusions are specified.

2. THEORETICAL FORMULATION

2.1. STATEMENT OF THE PROBLEM

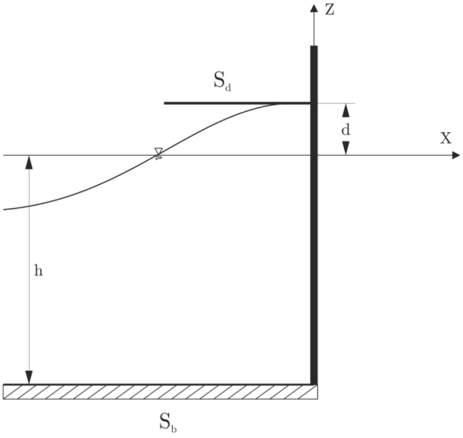

Fig. 1. Definitions sketch and coordinate system.

The situation considered for analysis is the impact of standing waves underneath a horizontal deck as shown schematically in Fig. 1. It is assumed that the water depth is h, the sea bottom (S_b) and the deck (S_d) are impervious. Moreover, it is assumed that

- The fluid is inviscid and incompressible.
- The motion is irrotational.
- The excitation is induced by normally incident waves.

According to the assumptions the fluid velocity vector, **V**, has a potential function, $\Phi(x, z, t)$, such that $\mathbf{V}=\nabla\Phi(x,z,t)$. The fluid motion is governed by the classical set of equations for the irrotational motion of incompressible and inviscid fluid, namely, the Laplace equation:

$$\nabla^2\Phi=0 \tag{2.1}$$

and the Bernoulli equation:

$$\frac{\partial\Phi}{\partial t}+\frac{1}{\varrho}P+gz+\frac{1}{2}|\nabla\Phi|^2=0 \tag{2.2}$$

where ϱ is the fluid mass density, P is the pressure and g is the acceleration due to gravity.

The velocity potential, $\Phi(x,z,t)$, has to satisfy the Laplace equation (2.1) with boundary conditions:

$$\nabla^2\Phi=0 \tag{2.3a}$$

$$\frac{\partial\eta}{\partial t}+\frac{\partial\Phi}{\partial x}\frac{\partial\eta}{\partial x}-\frac{\partial\Phi}{\partial z}=0, \quad z=\eta(x,t) \tag{2.3b}$$

$$\frac{\partial\Phi}{\partial t}+g\eta+\frac{1}{2}|\nabla\Phi|^2=0, \quad z=\eta(x,t) \tag{2.3c}$$

$$\frac{\partial\Phi}{\partial n}=0, \text{ on } S_b \text{ and } S_d, \tag{2.3d}$$

where n is outward normal vector. Moreover, the velocity potential has to satisfy boundary conditions at infinity and initial conditions [17].

It is very difficult to find a velocity potential that satisfies the boundary-value problem, (2.3), because the free-surface boundary conditions contain nonlinear terms. Moreover, the boundary conditions must be applied on the free surface $\eta(x,t)$ that is an unknown and is a part of a solution. The boundary-value problem was solved by applying the Direct Differentiation Approach to Boundary Element Method [18].

2.2. SOLUTION TECHNIQUE

The boundary-value problem (2.3) is solved to predict the propagation and transformation of nonlinear waves and wave impact underneath a deck. The solution of the boundary-value problem is achieved by adopting the Green's second identity. Accordingly, the following integral equation is solved in the fluid domain:

$$0.5\Phi(p)=\int_S\left[G(p,q)\frac{\partial\Phi(q)}{\partial n(q)}-\Phi(p,q)\frac{\partial G(p,q)}{\partial n(q)}\right]dS \tag{2.4}$$

$$G(p,q)=\frac{1}{2\pi}\ln r,\quad r=\sqrt{(p_x-q_x)^2+(p_y-q_y)^2} \tag{2.5}$$

where it is assumed that the fluid domain, its boundary S, and the function Φ satisfy the condition for which the fundamental solution given by (2.5) is valid, and r is the distance between the point p on the boundary and a field point q [19]. Eq. (2.4) is written in a general form and may also be applied to calculate a velocity potential inside the fluid domain. Eq (2.4) is solved numerically by discretizing the boundary S, into linear elements. The solution procedure leads to a linear algebraic system of equations whose solution is applied to determine the velocity potential on the boundary and in the fluid domain. The kinematic and dynamic boundary conditions, (2.3b) and (2.3c), are applied as boundary conditions and to determine free-surface elevation and velocity potential at a next time level. This is a standard approach typically applied in the modelling of the propagation and transformation of nonlinear water waves. The solution obtained by [10] is similar to that proposed in this paper but don't include vertical wall at the aft end of a horizontal plate. The time-step was of the order of 10^{-4} s during the impact to capture the peak of the pressure. The stability criterion tied up the surface boundary element length to be of the order of 10^{-4} m.

3. RESULTS

The derived solution was applied to predict and investigate impact of nonlinear standing waves underneath a horizontal deck located above the still water level ($\eta=0$). The wet surface is growing from the aft end of the plate without air cushion. This is assured by a sufficiently large angle between undisturbed water surface and horizontal deck on one time-step before the impact. Similar assumption was used by [14]. The wave impact process is investigated with emphasis on wave-induced pressure and loads on the deck. The analysis is conducted for linear and nonlinear waves and several basic parameters of the problem including wavelengths, wave heights, location of the deck above the still water level. The derived solution is first applied to predict wave-induced pressure at the first stage of wave impact underneath the deck for simplified initial conditions. The prediction of wave impact is based on the initial conditions derived from the linear wave theory. A typical pressure record predicted for the impact of waves underneath a horizontal is presented in Fig. 2. The results are plotted versus $t\sqrt{g/h}$ for A/h=0.1 and the ratio of the wavelength to the water depth equal to L/h=2.917 and the ratio of deck clearance to water depth d/h=0.033. The wave-induced pressure is presented in a dimensionless form. The pressure is made dimensionless to facilitate the analysis of results and to demonstrate the importance and complexity of an impact problem because in typical wave diffraction problems the value of dynamic pressure presented in this form is expected to be around one.

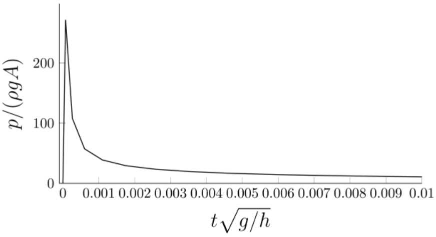

Fig. 2. Calculated dimensionless pressure.

The plot in Fig. 2 shows that the model predicts a characteristic rapid increase and then a decrease of pressures. Moreover, an extremely high pressure at the moment of wave impact is fairly well predicted. In fact, a similar pressure distribution is observed in laboratory experiments conducted in wave flumes. Father applications of the model indicate that a very large pressure can be induced even by waves of very small steepness. This phenomenon is also observed in laboratory experiments. The results clearly demonstrate an impulsive character of a wave impact as well as indicate potential difficulties in a reliable prediction of this phenomenon for complex wave fields and serious problems in the modelling of wave impact on maritime structures of complex shapes. There are several parameters affecting wave impact underneath the deck. The wave height is one of the most important parameters for this problem. High waves are expected to cause high impact pressure and, in consequence, high loads on a deck. The effect of wave amplitude on impact pressure is presented in Fig. 3.

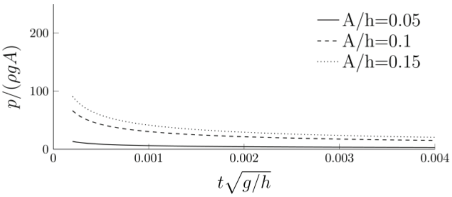

Fig. 3a. The effect of wave amplitude on impact pressure for initial conditions derived from linear wave theory.

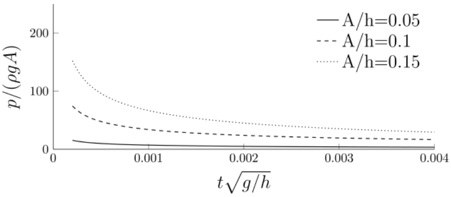

Fig. 3b. The effect of wave amplitude on impact pressure for initial conditions derived from Stokes wave theory.

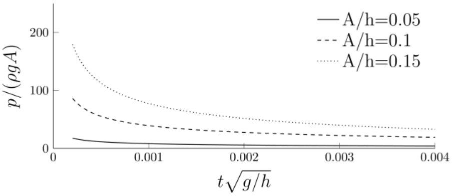

Fig. 3c. The effect of wave amplitude on impact pressure for initial conditions correct up two second order.

The results are plotted versus $t\sqrt{g/h}$ for d/h=0.047 for waves of low, moderate, and high steepness, corresponding to A/h=0.05, A/h=0.1, and A/h=0.15, respectively. Initial conditions were derived from linear wave theory (Fig. 3a), the second-order Stokes wave theory (Fig. 3b), and the second-order Stokes wave theory with a second-order correction of velocity potential arising from a need to apply boundary conditions on the deforming free surface (Fig. 3c).

The results in Fig. 3 show that a wave height has a significant effect on wave impact underneath the deck, as expected. The plots show that impact pressure increases with increasing wave height. An impact pressure increases in a strongly nonlinear manner with increasing a wave height even if attacking waves are purely sinusoidal. The effect of wave height on impact pressure is more pronounced for nonlinear waves. The second-order correction of velocity potential arising from a need to applying boundary condition on the free surface has practically no effect on impact pressure. This is a surprising result because this correction increases, often substantially, the vertical velocity component in comparison with the velocity derived from the second-order Stokes wave theory. A wavelength is the next important parameter for the problem of wave impact underneath the deck. This is because the impact of water waves strongly depends on wave kinematics and a wavelength must be included in the analysis of wave impact phenomenon due to a significant effect of a wavelength on wave kinematics. The effect of wavelength on an impact pressure is presented in Fig. 4. The results are plotted versus $t\sqrt{g/h}$ for three wavelengths 0.5L, L, 1.5L. The results in Fig. 4 show that the wavelength has a relatively low effect on wave impact underneath the deck. The effect of the wavelength on impact pressure is more pronounced when nonlinear wave kinematics are taken into account, however, this effect is still fairly low. A low effect of a wavelength on impact pressure is a surprising result because it is known that a wave impact strongly depends on wave kinematics and, in consequence, impact pressure is expected to depend on a wavelength. This is why the results presented in Fig. 4 are surprising, especially that the magnitude of vertical velocity component for the wavelength 0.5L is more than two times higher than in the case of the wavelength 1.5L. These results imply a need to validate the applicability range of a slamming pressure formula $p_s=0.5v^2C_S$ that predicts a substantial decrease of an impact pressure with increasing the wavelength from 0.5L to 1.5L. The plots presented in Fig. 4 demonstrate significant effects of initial conditions on wave-induced pressure and indicate the complexity of the problem of wave impact on maritime structures.

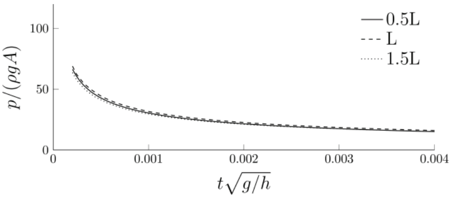

Fig. 4a. The effect of wavelength on impact pressure for initial conditions derived from linear wave theory.

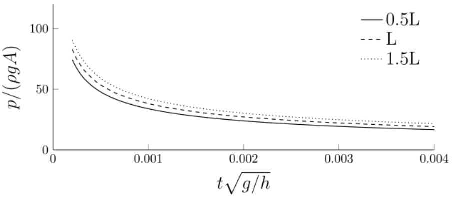

Fig. 4b. The effect of wavelength on impact pressure for initial conditions derived from Stokes wave theory.

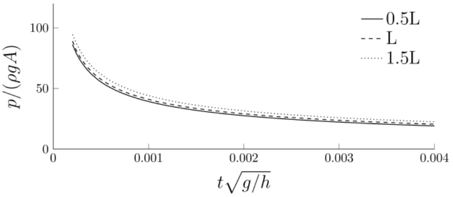

Fig. 4c. The effect of wavelength on impact pressure for initial conditions correct up two second order.

The location of a deck above the still water level is one of the most important geometrical parameters for the problem of wave impact underneath the deck. This is because the impact of water waves underneath the deck is expected to strongly depend on its distance above the still water level and this parameter must be included in the analysis of wave impact phenomenon and impact-induced loads. A typical dependency of impact-induced pressure on the distance of the deck above the still water level is presented in Fig. 5. The results are plotted versus $t\sqrt{g/h}$ for wavelength 0.5L and for three ratios of the distance d to the water depth h. The results in Fig. 5 show that the distance of a deck above the still water level has a very significant effect on wave impact underneath the deck, as expected.

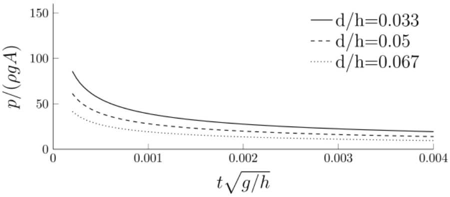

Fig. 5a. The effect of deck location on impact pressure for initial conditions derived from linear wave theory.

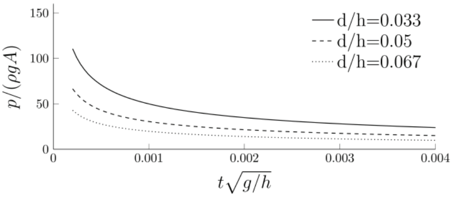

Fig. 5b. The effect of deck location on impact pressure for initial conditions derived from Stokes wave theory.

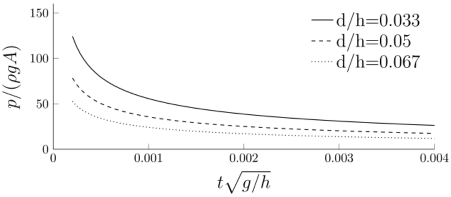

Fig. 5c. The effect of deck location on impact pressure for initial conditions correct up two second order.

The location of the deck has significant effect especially on wave-induced pressure and loads. The plots show that impact pressure increases with decreasing the distance of a deck from the still water level. This effect is more pronounced for nonlinear waves where an impact pressure increases more rapidly with decreasing the distance of a deck from the still water level. The effect of wave nonlinearities on impact pressure is becoming less pronounced when the distance of a deck from the still water level increases and is practically negligible for decks located far above the still water level. Additional information regarding the effect of the distance of the deck above the still water level, the wave amplitude and the wavelength on an impact pressure can be obtained from Figs. 6, 7 and 8 that shows impact pressure at the representative time $t\sqrt{g/h}$=0.001 for series of d/h parameter, wave amplitudes and wavelengths.

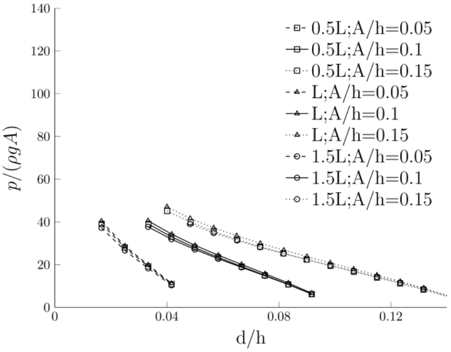

Fig. 6. Pressure at the representative time $t\sqrt{g/h}$ for different locations of the deck for initial conditions derived from linear wave theory.

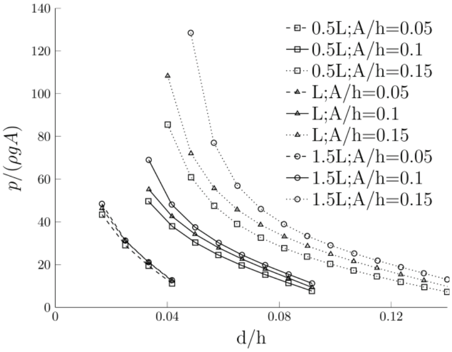

Fig. 7. Pressure at the representative time $t\sqrt{g/h}$ for different locations of the deck for initial conditions derived from Stokes wave theory.

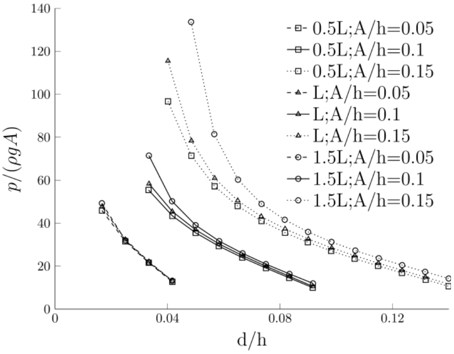

Fig. 8. Pressure at the representative time $t\sqrt{g/h}$ for different locations of the deck for initial conditions corrected up two second order

4. COMPARISON WITH EXPERIMENTS

Laboratory experiments were conducted in the wave flume at the Institute of Hydro-Engineering, Polish Academy of Sciences, Gdansk. The wave flume at the Institute of Hydro-Engineering is 64 m long and is equipped with a programmable piston wave generator and a porous wave absorber (Fig. 9).

The physical model is shown schematically in Fig. 10. The elements of the rectangular box were made from plexiglass plates stiffened by ribs. The model of the deck was supported by pre-stressed strings and springs. The physical model represents an elastically supported system. The deck can be considered as a rigid body. The construction of the deck and vertical wall as the specific suspension system were selected intentionally to study wave impact phenomenon for different locations of the deck with respect to the still water level. The selected construction and suspension system are the results of previous studies and analyses [1, 12] which indicated a need to investigate wave impact problem for a wide range of parameters affecting impact processes.

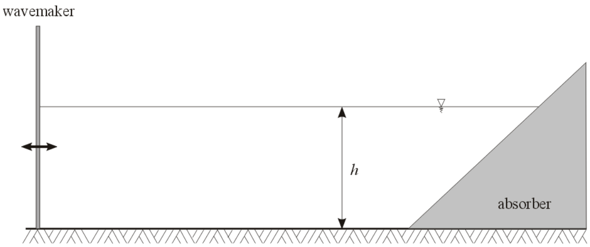

Fig. 9. Wave flume.

Four accelerometers were installed in the model to measure accelerations. The accelerometers were located close to the edges of the deck. The positions of accelerometers denoted by A1, A2, A3, and A4 are shown in Fig.11 . Moreover, eight pressure gauges were used to measure pressure. The pressure gauges were installed in the bottom of the deck. The positions of pressure gauges installed in the bottom of the deck, P1, …, P8 are shown in Fig. 11.

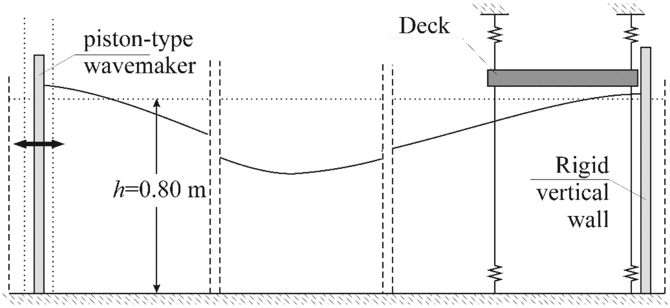

Fig. 10. Side view of the wave flume with the deck.

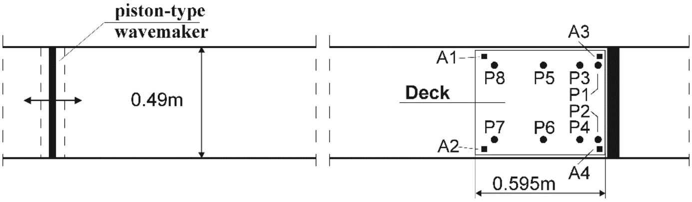

Fig. 11. Location of pressure gauges and accelerometers

The model of the deck was installed in the wave flume as it is shown schematically in Fig. 10. Then, the deck was exposed to the attack of wave trains. The wavemaker was programmed to generate trains of waves of different frequencies. A complementary series of experiments were conducted to assess the effect of wave steepness on the wave impact underneath the deck. Different wave steepness's were achieved by changing the amplitude of the wavemaker motion. The measurements of free-surface elevation, pressure and acceleration were conducted for each wave train for about 100 s and were sampled at the rate up to 20000 Hz.

The results obtained by the application of the model and the experimental data were compared in Fig. 12. The plots present theoretical results obtained for standing waves of estimated amplitude A=0.14 m and experimental data measured by the pressure gauge installed near the corner of the deck, P1. The comparison is conducted for the first stage of wave impact for which a large pressure is expected due to a wave impact. The plots in Fig. 12 present filtered numerical data compared to experimental results and show that the model predicts a characteristic rapid increase and then a decrease of pressures. Moreover, an extremely high pressure at the moment of wave impact is fairly well predicted. A similar pressure distribution with a characteristic rapid increase and then a decrease of pressures is observed in laboratory experiments. The model predicts fairly well high pressure at the first stage of wave impact and describes an impulsive character of a wave impact phenomenon. The pressure recorded in laboratory experiments is not expected to precisely follow theoretical results predicted by the model probably due to side effects of the pressure measuring system or simplifications applied in the derivation of the solution that is based on the theory of ideal fluid. There are no doubts that some effect on the discrepancies between the theoretical results and experimental data possess wave damping and a small content of air in water. This is because water waves in the wave flume are exposed to wave damping while the solution applied in the present study was derived by neglecting damping. Moreover, it is known that a very small content of air in water has substantial effects on pressure during wave impact [20]. In fact, there are more potential reasons of the discrepancies between theoretical results and experimental data. Further analysis indicates that the discrepancies between theoretical results and experimental data may be due to some side effects of the pressure measuring system, fluid compressibility, structure flexibility, cross waves in the wave flume.

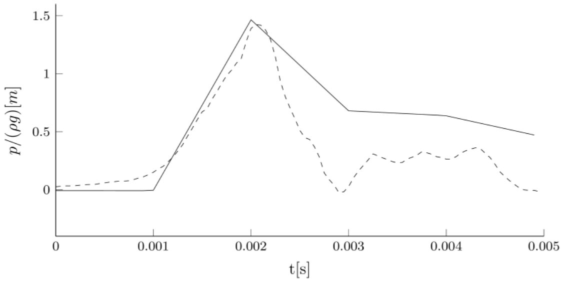

Fig. 12. Predicted and measured pressure at the moment of wave impact; – – experimental data, ——theory.

The derived theoretical model provides results with sufficient accuracy for engineering applications. The discrepancies between theoretical results and experimental data are likely due to complexity of the impact process and its enormous sensitivity to initial conditions. The analysis of experimental data supports conclusions derived in theoretical investigations regarding the complexity of an impact process. Laboratory experiments confirm that the wave impact on a horizontal deck, wave-induced pressure and loads are very complicated processes. The complexity and sensitivity of these phenomena well illustrate plots in Fig. 13 which show records of pressure measured by two pressure gauges located symmetrically with respect to wave flume middle line. Substantial differences between these two pressure records indicate the sensitivity and complexity of a wave impact phenomenon. The designed laboratory experiments allowed to achieve a good repeatability of the consecutive test with differences similar to those presented in Fig. 13. This also implies a need to conduct more fundamental studies and experimental investigations on the problem of wave impact on maritime structures.

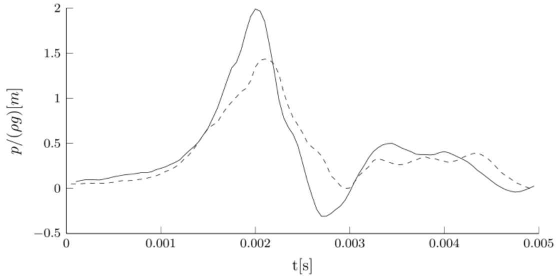

Fig. 13. Records of pressure measured by two gauges located symmetrically with respect to wave flume middle line; – – P1, —— P2.

5. SUMMARY

A theoretical approach was applied to investigate the impact of nonlinear standing waves underneath a horizontal deck. A solution was achieved by applying a Boundary Element Method. Initial conditions were derived from linear wave theory, the second-order Stokes wave theory, and the second-order Stokes wave theory with a second-order correction of velocity potential arising from a need to apply boundary conditions on the free surface. The model was applied to predict impact pressure due to the attack of standing waves underneath a deck and the results were analysed with emphases on the effect of basic parameters of the problem including wave heights, wavelengths, location of the deck above the still water level on the pressure during the first stage of wave impact. The results show that the wave impact is a very complex momentary process. The analysis shows that a significant effect on wave impact underneath the deck has a wave height and a deck distance from the still water level. An impact pressure increases in a strongly nonlinear manner with increasing a wave height even for linear or weakly nonlinear wave attack. Moreover, an impact pressure increases, usually in a strongly nonlinear manner, with decreasing the distance of the deck from the still water level. Wave nonlinearities have complex, often non-intuitive effects on an impact pressure. Some results are non-intuitive or even surprising. The analysis shows that purely sinusoidal waves of very small amplitude may cause an extremely high impact pressure, which is a non-intuitive result, especially that the predicted pressure may be several orders of magnitude higher than a pressure arising from typical applications of linear or nonlinear wave theories. Another unexpected result is a low effect of a wavelength on an impact pressure. This is because it is known that a wave impact strongly depends on wave kinematics and changes in a wavelength imply changes in velocities. Additionally, the analysis shows that the nonlinear correction of velocity at the free surface has practically no effect on an impact pressure. This is also a non-intuitive result because this correction substantially changes a velocity on the free surface and is also expected to substantially affect an impact pressure. These non-intuitive outcomes arise from the complexity of a wave impact process and its enormous sensitivity to initial conditions and indicate serious potential difficulties in a reliable prediction of a wave impact for complex wave fields or maritime structures of complicated shapes. Laboratory experiments were conducted in the wave flume to validate theoretical results. A special effort was devoted to data recorded in laboratory experiments and accompanying procedures because a wave impact is a very complex momentary process and standard laboratory procedures cannot be applied. The comparisons show that the theoretical results are in reasonable agreement with experimental data.

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LIST OF FIGURES AND TABLES:

Fig. 5a. The effect of deck location on impact pressure for initial conditions derived from linear wave theory.

Rys. 5a. Wpływ wysokości zawieszenia pokładu na ciśnienie uderzenia dla warunków początkowych wyznaczonych z teorii liniowej falowania.

Fig. 5b. The effect of deck location on impact pressure for initial conditions derived from Stokes wave theory.

Rys. 5b. Wpływ wysokości zawieszenia pokładu na ciśnienie uderzenia dla warunków początkowych wyznaczonych z teorii falowania Stokesa.

Fig. 5c. The effect of deck location on impact pressure for initial conditions correct up two second order.

Rys. 5c. Wpływ wysokości zawieszenia pokładu na ciśnienie uderzenia dla warunków początkowych z poprawką do drugiego rzędu.

Fig. 6. Pressure at the representative time $t\sqrt{(g/h)}$ for different locations of the deck for initial conditions derived from linear wave theory.

Rys. 6. Ciśnienie w charakterystycznej chwili $t\sqrt{(g/h)}$ dla różnych wysokości zawieszenia pokładu dla warunków początkowych wyznaczonych z teorii liniowej falowania.

Fig. 7. Pressure at the representative time $t\sqrt{(g/h)}$ for different locations of the deck for initial conditions derived from Stokes wave theory.

Rys. 7. Ciśnienie w charakterystycznej chwili $t\sqrt{(g/h)}$ dla różnych wysokości zawieszenia pokładu dla warunków początkowych wyznaczonych z teorii falowania Stokesa.

Fig. 8. Pressure at the representative time $t\sqrt{(g/h)}$ for different locations of the deck for initial conditions correct up two second order.

Rys. 8. Ciśnienie w charakterystycznej chwili $t\sqrt{(g/h)}$ dla różnych wysokości zawieszenia pokładu dla warunków początkowych z poprawką do drugiego rzędu.

Fig. 9. Wave flume.

Rys. 9. Kanał falowy.

Fig. 10. Side view of the wave flume with the deck.

Rys. 10.Kanał falowy z modelem pokładu, widok z boku.

Fig. 11. Location of pressure gauges and accelerometers.

Rys. 11. Rozmieszczenie czujników ciśnienia i przyśpieszenia.

Fig. 12. Predicted and measured pressure at the moment of wave impact; – – experimental data, ——theory.

Rys. 12. Obliczone i zmierzone ciśnienie w chwili uderzenia fali; – – dane pomiarowe, ——teoria.

Fig. 13. Records of pressure measured by two gauges located symmetrically with respect to wave flume middle line; – – P1, —— P2.

Rys. 13. Zapis pomiaru ciśnienia przez dwa czujniki rozmieszczone symetrycznie do osi kanału; – – P1, —— P2.

IMPACT OF NONLINEAR STANDING WAVES UNDERNEATH A DECK

Słowa kluczowe: Uderzenie fali, Impuls ciśnienia, Budowle brzegowe, Budowle morskie

STRESZCZENIE

Zbadano proces uderzenia nieliniowych, stojących fal wodnych w spód poziomego pokładu. Wykorzystano podejście teoretyczne, którego rozwiązanie opiera się na Metodzie Elementów Brzegowych. Za pomocą modelu wyznaczono ciśnienia generowane uderzeniem fal wodnych. Wyniki wskazują na to, że proces jest bardzo złożony i ma charakter impulsowy. Analizowano wpływ początkowych warunków brzegowych, parametrów fali oraz wysokości zawieszenia pokładu nad powierzchnią spokoju na generowane ciśnienia. Wyniki pokazują, że nawet fale sinusoidalne, o małej amplitudzie mogą wywołać ciśnienia kilkukrotnie większe niż ciśnienia wynikające z typowych zastosowań teorii liniowej falowania. Pokazują również, że często nieintuicyjne wnioski wynikają ze złożoności procesu uderzenia fali i jego dużej czułości na początkowe warunki brzegowe. Wskazuje to na poważne trudności w wiarygodnym modelowaniu procesu uderzenia dla złożonych pól falowych oraz skomplikowanych układów geometrycznych budowli. Przeprowadzono również pomiary laboratoryjne w celu uzyskania danych do walidacji modelu numerycznego. Opracowany model zapewnia wyniki z dokładnością umożliwiającą zastosowanie go w zadaniach inżynierskich.

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