Research Article

Analytical and Experimental Study of Focused Wave Action on a Partially Immersed Box

Qinghe Fang ^{1,2,3} and **Anxin Guo** ^{1,2}

¹Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

²Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters of the Ministry of Industry and Information Technology, Harbin Institute of Technology, Harbin 1550090, China

³School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M13 9PL, UK

Correspondence should be addressed to Anxin Guo; guoanxin@hit.edu.cn

Received 28 March 2019; Accepted 15 May 2019; Published 11 June 2019

Academic Editor: Enrique Onieva

Copyright © 2019 Qinghe Fang and Anxin Guo. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Focused wave is a practical laboratory method for reproducing extreme waves that cause catastrophic damage to marine and coastal structures. This paper presents a simple and efficient analytical method for predicting the hydrodynamic pressure and wave forces acting on a partially immersed box when subjected to a focused wave group attack. The boundary value issue of the physical problem is first investigated to derive an analytical formula based on potential flow theory and the matching eigenfunction method. Thereafter, the test data from a hydrodynamic experiment is used to verify the accuracy of the proposed analytical model. Using the validated analytical model, a parametric analysis is conducted to gain insight into the effects of the structural configuration and wave properties on the pressure and wave forces. It is observed that the hydrodynamic pressure on the offshore side plate, horizontal wave force, and moment are notably influenced by the structure breadth and draft. A focused wave with a lower peak frequency and higher focused amplitude is found to exert greater wave forces on the partially immersed box. The paper shows the value of linear wave theory for wave loads prediction even for focused waves although with some limitations.

1. Introduction

Extreme waves on offshore and coastal structures have been the subject for long time and their importance is increasing due to climate change, which leads to more severe storm and sea level rise. Obviously, the action of the extreme waves on structures, such as wind turbine foundations, offshore platforms, floating vessels, and breakwaters, is an important aspect that should be considered in order to improve structure safety during service periods.

Both regular and irregular waves have been successfully generated in physical or numerical wave flumes or basins in different manners and have been used extensively by researchers to investigate wave actions on structures. Compared to the abovementioned water waves, the extreme wave exhibits the characteristics of sudden appearance and powerful concentrated energy with strong nonlinearities. The physical mechanisms of extreme waves in the ocean and

in a wave tank were reviewed by Kharif and Pelinovsky [1] and Chabchoub et al. [2], respectively. Based on dispersive focusing method, which focuses all (or part) of the wave component energy in a specific location simultaneously, unidirectional or directional focused wave [3] was generated in the wave flume or basin. Focused wave has been effectively utilized for research extreme wave action on structures experimentally or numerically. Cox and Ortega [4] observed wave impact and green water on a fixed deck. It was concluded that a focused wave could cause a greater amount of slamming on a structure than a regular wave. Bai and Taylor [5] investigated wave diffraction around a vertical cylinder by means of a higher-order boundary-element method. Their results indicated that the focus point influenced the maximum force direction. The wave force acting on a fixed horizontal cylinder was investigated by Hu et al. [6], using their in-house code. The New Year Wave was numerically regenerated by a linear [7] and, subsequently,

FIGURE 1: Schematic of boundary value problem.

nonlinear energy-focusing method [8] using the commercial finite volume package FLUENT in order to study the force acting on a semisubmerged horizontal cylinder.

In addition to single-structure members, focused wave action on marine and offshore structures has also been addressed by researchers. Weller et al. [9] reported experimental measurements of the complex motion of a floating body in a near-focused wave. It was found that the horizontal excursion of the float was over six times that of the vertical displacement during focused wave propagation. Using a constrained interpolation profile- (CIP-) based high-order finite-difference method, Zhao et al. [10] calculated floating body motion under a focused wave and compared the measurements with their previous experimental results. Furthermore, the response of a semi-submersible model under a focused wave was experimentally investigated by Banks and Abdussamie [11], in which the focused wave was found to be a reliable method for testing the dynamic response of offshore platforms.

Dealing with wave-structure interaction problem, the potential flow method has been proven to be a workable and efficient approach. Black et al. [12] investigated the radiation and scattering phenomenon of surface waves led by a floating rigid box. With a simple Green's function technique, Poul and He [13] calculated the added mass and damping coefficients of 2D structures in or below free surface. Subsequently, Williams [14] investigated the Froude-Krylov coefficients of rectangular body located close to free surface or seabed with linear diffraction solution. Furthermore, Wu et al. [15] analysed the wave excited response of an elastic floating box by the eigenfunction expansion-matching method. Inspired by existing successful application, the potential flow method is broadened to investigate the wave scattering and radiation problem of more complex structures, such as submerged decks [16, 17], complex rectangular floaters [18], rigid body with elastic plates [19], perforated walls [20], bottom step [21], and, most recently, T-shaped floating breakwater [22].

Besides, the potential flow method has also been extended to study the wave action on navigation lock sliding gate [23] and submerged wave energy converters [24], even the wave overwash of a step [25]. Except that, Baarholm and Faltinsen [26] solved the wave impact on a fixed deck under

the regular incident waves with the potential flow assumption by nonlinear boundary-element methods.

The geometry of ocean structures, such as ocean platforms, very large floating structures (VLFS), breakwater, and wave energy devices, can be simplified as rectangular bodies. It can be summarized that the focused wave generation methodologies in physical or numerical wave flumes have all been successfully developed based on the potential method. Therefore, as a simple means of gaining insight into the wave-structure interaction mechanism under a focused wave, it is possible to use the potential method for investigating wave action on this structure type. However, this issue has seldom been addressed by researchers.

Aiming at convenience and efficiency, this paper presents an analytical solution for focused wave action on an immersed box by applying the potential flow method to investigate the velocity field of focused wave. This paper is organised in five parts. A detailed analytical formula for the boundary value problem is derived firstly. The presented method is validated through comparison between the analytical and experimental results subsequently. Following this, a parametric study is conducted to check the effect of structure configuration and wave properties. Finally, concluding remarks are provided.

2. Analytical Formula

2.1. Boundary Value Problem. A schematic of the defined problem is provided in Figure 1. As illustrated in the figure, a rigid box with a breadth B and draft h is fixed in the water with uniform depth d . For the convenience of the following analysis, a 2D Cartesian coordinate system is defined, with the origin O coinciding with the box centre. The x -axis of the coordinate system is assumed to overlap with the still water level (SWL) and the z -axis is upward.

For a focused wave, the 2D free surface elevation $\eta(x, t)$ can be expressed as

$$\eta(x, t) = \sum_{i=1}^{N_f} a_i \cos(k_i x - \omega_i t + \phi_i), \quad (1)$$

where a_i is the amplitude of the i -th wave component with wave angular frequency $\omega_i = 2\pi f_i$ and initial phase ϕ_i , k_i is

the corresponding wave number, and N_f is the total number of wave frequency components. The wave angular frequency and wave number satisfy the dispersion relation:

$$\omega_i^2 = gk_i \tanh k_i d, \quad (2)$$

where g is the gravity acceleration and d is the water depth.

According to Longuet-Higgins [27], Rayleigh distribution can be used to describe the wave height of sea wave. The probability of occurrence of a freak wave in an irregular wave train can be estimated, about 3.35×10^{-4} taking the wave height of freak wave as two times of significant wave height. This means it will take very long time to obtain one freak wave in the irregular wave train. Besides, the occurrence time and location of the freak wave are difficult to define by users. One practical method to obtain freak wave in wave flume is dispersive focusing method.

If a focused wave is achieved at focus time t_b and focusing location x_b , the initial phase of wave component should satisfy the following equation:

$$\cos(k_i x_b - \omega_i t_b + \varphi_i) = 1. \quad (3)$$

Therefore, the initial phases can be obtained as

$$\varphi_i = -k_i x_b + \omega_i t_b + 2m\pi, \quad m = 0, \pm 1, \pm 2, \dots \quad (4)$$

Generally, m is taken as 0 and the wave elevation, as described in (1), becomes

$$\eta(x, t) = \sum_{i=1}^{N_f} a_i \cos(k_i(x - x_b) - \omega_i(t - t_b)). \quad (5)$$

A particular form of focused wave group generally used to represent extreme conditions [28] is given by

$$a_i = \frac{A_{\max} S_i(\omega) \Delta\omega}{\sum_{l=1}^{N_f} S_l(\omega) \Delta\omega} \quad (6)$$

in which $S_i(\omega)$ is the discretised energy spectrum, $\Delta\omega$ is the frequency resolution, and $A_{\max}$ is the maximum crest amplitude equalling the summation of a_i .

Based on linear wave theory, the velocity potential of the entire fluid domain under a focused wave can be expressed as the sum of the velocity potential of the different wave frequency components:

$$\Phi(x, z, t) = \mathbf{Re} \left[\sum_{i=1}^{N_f} \phi_i(x, z) e^{-j(\omega_i t - \varphi_i)} \right], \quad (7)$$

where ϕ_i is the velocity potential of the i -th wave component, $j = \sqrt{-1}$, and $\mathbf{Re}[\cdot]$ represents the real part of a complex expression. Moreover, the velocity potential of each single wave frequency component should satisfy Laplace's governing equation:

$$\frac{\partial^2 \phi_i(x, z)}{\partial x^2} + \frac{\partial^2 \phi_i(x, z)}{\partial z^2} = 0. \quad (8)$$

For each single wave frequency component, the boundary conditions at the free surface, seabed, and wet surface of the box can be expressed as follows:

$$\begin{aligned} \frac{\partial \phi_i}{\partial z} - \frac{\omega_i^2}{g} \phi_i &= 0 \quad (x \leq -b \text{ or } x \geq b, z = 0) \\ \frac{\partial \phi_i}{\partial z} &= 0 \quad (z = -d) \\ \frac{\partial \phi_i}{\partial z} &= 0 \quad (-b \leq x \leq b, z = -h) \\ \frac{\partial \phi_i}{\partial x} &= 0 \quad (x = \pm b, -h \leq z \leq 0). \end{aligned} \quad (9)$$

As indicated in Figure 1, the entire space domain can be divided into three subdomains, including the offshore open subdomain Ω_1 , onshore open subdomain Ω_3 , and interior subdomains Ω_2 , covered by the fixed box. At the interface of adjacent subdomains, the following continuity conditions should also be satisfied for the velocity potential and horizontal velocity:

$$\begin{aligned} \phi_i^1 &= \phi_i^2, \\ \frac{\partial \phi_i^1}{\partial x} &= \frac{\partial \phi_i^2}{\partial x} \quad (-d \leq z \leq -h, x = -b) \\ \phi_i^2 &= \phi_i^3, \\ \frac{\partial \phi_i^2}{\partial x} &= \frac{\partial \phi_i^3}{\partial x} \quad (-d \leq z \leq -h, x = b), \end{aligned} \quad (10)$$

where ϕ_i^1 , ϕ_i^2 , and ϕ_i^3 are the i -th wave component velocity potential of subdomains Ω_1 , Ω_2 , and Ω_3 , respectively.

2.2. Analytical Solutions. According to the eigenfunction expansion method, the velocity potentials of the three subdomains (denoted by superscripts) for the i -th wave component can be expressed as follows based on the boundary condition of corresponding subdomain [29, 30]:

$$\begin{aligned} \phi_i^1 &= -\frac{jga_i}{\omega_i} \left[\left(e^{jk_{i0}^1(x+b)} + A_{i0} e^{-jk_{i0}^1(x+b)} \right) Z_{i0}^1(z) \right. \\ &\quad \left. + \sum_{n=1}^{\infty} A_{in} e^{k_{in}^1(x+b)} Z_{in}^1(z) \right], \quad (x \leq -b, -d \leq z \leq 0) \end{aligned} \quad (11)$$

$$\begin{aligned} \phi_i^2 &= -\frac{jga_i}{\omega_i} \left[\sum_{n=0}^{\infty} B_{in} Z_{in}^2(z) \cosh k_{in}^2 x + C_{i0} Z_{i0}^2(z) x \right. \\ &\quad \left. + \sum_{n=1}^{\infty} C_{in} Z_{in}^2(z) \sinh k_{in}^2 x \right], \quad (-b \leq x \leq b, -d \leq z \leq -h) \end{aligned} \quad (12)$$

$$\phi_i^3 = -\frac{jga_i}{\omega_i} \left[D_{i0} e^{jk_{i0}^3(x-b)} Z_{i0}^3(z) + \sum_{n=1}^{\infty} D_{in} e^{-k_{in}^3(x-b)} Z_{in}^3(z) \right], \quad (b \leq x, -d \leq z \leq 0), \quad (13)$$

where A_{in} , B_{in} , C_{in} , and D_{in} are unknown coefficients; $k_{in}^{1,2,3}$ and $Z_{in}^{1,2,3}(z)$ are the corresponding wave numbers and eigenfunctions for each subdomain, respectively; and a_i is the amplitude of the i -th wave component referring to (6). For the velocity potentials of the offshore subdomain Ω_1 , the first item in (11) represents the incident velocity potential, the second denotes the reflected velocity potential, and the infinite series indicate the evanescent modes which only influence the local zone around the structure. For the velocity potentials of the onshore subdomain Ω_3 , the first item in (12) represents the transmitted velocity potential, and the infinite series indicate the evanescent modes that attenuate quickly along the positive x -direction.

In (11)-(13), the vertical eigenfunctions and corresponding eigenvalues of the offshore domains Ω_1 and onshore domains Ω_3 are identical and given by

$$Z_{in}^{1,3}(z) = \begin{cases} \frac{\cosh k_{i0}^{1,3}(z+d)}{\cosh k_{i0}^{1,3}d}, & n=0 \\ \frac{\cos k_{in}^{1,3}(z+d)}{\cos k_{in}^{1,3}d}, & n=1, 2, \dots, \end{cases} \quad (14)$$

with the corresponding eigenvalues of

$$(\omega_i)^2 = \begin{cases} gk_{i0}^{1,3} \tanh k_{i0}^{1,3}d & n=0 \\ -gk_{in}^{1,3} \tan k_{in}^{1,3}d & n=1, 2, \dots \end{cases} \quad (15)$$

For the box-covered subdomain Ω_2 , the vertical eigenfunctions are

$$Z_{in}^2(z) = \begin{cases} \frac{\sqrt{2}}{2}, & n=0 \\ \cos k_{in}^2(z+d), & n=1, 2, \dots \end{cases} \quad (16)$$

and the corresponding eigenvalues are

$$k_{in}^2 = \frac{n\pi}{(d-h_1)}, \quad (n=0, 1, 2, \dots). \quad (17)$$

The eigenfunctions expressed in (14) are orthogonal to one another in the corresponding subdomains of Ω_1 and Ω_3 , as follows:

$$\int_{-d}^0 Z_{in}^{1,3}(z) Z_{im}^{1,3}(z) dz = \begin{cases} 0 & (m \neq n) \\ \frac{(d/2 + \sinh 2k_{i0}^{1,3}d/4k_{i0}^{1,3})}{\cosh^2 k_{i0}^{1,3}d} & (m = n = 0) \\ \frac{(d/2 + \sin 2k_{in}^{1,3}d/4k_{in}^{1,3})}{\cos^2 k_{in}^{1,3}d} & (m = n \neq 0). \end{cases} \quad (18)$$

For the covered subdomains Ω_2 , the eigenfunctions also satisfy the following orthogonality:

$$\int_{-d}^{-h} Z_{in}^2(z) Z_{im}^2(z) dz = \begin{cases} 0, & (m \neq n) \\ \frac{(d-h)}{2}, & (m = n). \end{cases} \quad (19)$$

For the neighbouring subdomains Ω_1 and Ω_2 , the potential continuity at interface $x = -b$ can be expressed as follows, by substituting (11) and (12) into (10):

$$\begin{aligned} (1 + A_{i0}) Z_{i0}^1 + \sum_{n=1}^{\infty} A_{in} Z_{in}^1 \\ = \sum_{n=0}^{\infty} B_{in} Z_{in}^2 \cosh k_{in}^2 b - C_{i0} Z_{i0}^2 b \\ - \sum_{n=1}^{\infty} C_{in} Z_{in}^2 \sinh k_{in}^2 b \\ i k_{i0}^1 (1 - A_{i0}) Z_{i0}^1 + \sum_{n=1}^{\infty} k_{in}^1 A_{in} Z_{in}^1 \\ = - \sum_{n=1}^{\infty} k_{in}^2 B_{in} Z_{in}^2 \sinh k_{in}^2 b + C_{i0} Z_{i0}^2 \\ + \sum_{n=1}^{\infty} k_{in}^2 C_{in} Z_{in}^2 \cosh k_{in}^2 b. \end{aligned} \quad (20)$$

By multiplying the eigenfunctions $Z_{in}^2(z)$ and $Z_{in}^1(z)$ on both sides of the above two equations and integrating the equation within the scope of the water depth $(-d, -h)$ and $(-d, 0)$ for the first and second equations, respectively, two sets of linear equations are obtained after truncating n at N :

$$\begin{aligned} \{\mathbf{p}\} + [\mathbf{F}] \{A_i\} &= [\mathbf{G}] \{B_i\} - [\mathbf{H}] \{C_i\} \\ \{\mathbf{q}\} + [\mathbf{E}] \{A_i\} &= -[\mathbf{J}] \{B_i\} + [\mathbf{K}] \{C_i\}, \end{aligned} \quad (21)$$

in which the components $\{\mathbf{p}\}$, $[\mathbf{F}]$, $[\mathbf{G}]$, $[\mathbf{H}]$, $\{\mathbf{q}\}$, $[\mathbf{J}]$, and $[\mathbf{K}]$ in the vector and matrices are given in the appendix and $[\mathbf{E}]$ is the $(N+1) \times (N+1)$ -dimensional identity matrix.

Similarly for the interface $x=b$ between the neighbouring subdomains Ω_2 and Ω_3 , the continuity condition (10) can be expressed as

$$\begin{aligned} \sum_{n=0}^{\infty} B_{in} Z_{in}^2 \cosh k_{in}^2 b + C_{i0} Z_{i0}^2 b \\ + \sum_{n=1}^{\infty} C_{in} Z_{in}^2 \sinh k_{in}^2 b = D_{i0} Z_{i0}^3 + \sum_{n=1}^{\infty} D_{in} Z_{in}^3 \\ \sum_{n=1}^{\infty} k_{in}^2 B_{in} Z_{in}^2 \sinh k_{in}^2 b + C_{i0} Z_{i0}^2 \\ + \sum_{n=1}^{\infty} k_{in}^2 C_{in} Z_{in}^2 \cosh k_{in}^2 b = i k_{i0}^3 D_{i0} Z_{i0}^3 \\ - \sum_{n=1}^{\infty} k_{in}^3 D_{in} Z_{in}^3. \end{aligned} \quad (22)$$

FIGURE 2: Sketch diagrams of (a) experimental setup and (b) embedded pressure transducers, and (c) photo of the experimental setup.

The following two sets of linear equations can be obtained by applying the orthogonality of eigenfunctions and truncating n at N :

$$\begin{aligned} [\mathbf{L}] \{B_i\} + [\mathbf{O}] \{C_i\} &= [\mathbf{P}] \{D_i\} \\ [\mathbf{Q}] \{B_i\} + [\mathbf{R}] \{C_i\} &= [\mathbf{E}] \{D_i\} \end{aligned} \quad (23)$$

in which $\{L\}$, $\{O\}$, $\{P\}$, $\{Q\}$, $\{R\}$, $\{S\}$ are all $(N+1) \times (N+1)$ -dimensional matrices as defined in the appendix.

With the matrix equations, the unknown coefficients of the above linear equations can be solved separately, and A_{i0} and D_{i0} are the reflected and transmission coefficients of the i -th wave frequency component, respectively, satisfying

$$A_{i0}^2 + D_{i0}^2 = 1. \quad (24)$$

When the flow field potential has been determined, the pressure field contributed by the i -th wave frequency component can be obtained by Bernoulli's principle:

$$p_i(x, z, t) = \text{Re} \left[j\omega_i \rho \phi_i(x, z) e^{-j(\omega_i t - \varphi_i)} \right]. \quad (25)$$

The wave force acting on the partially submerged box, exerted by the i -th wave frequency component, can be calculated by integrating the pressure acting on the body surface. Therefore, the entirety of pressure and wave forces acting on the box can be obtained by summing all wave components:

$$p(x, z, t) = \text{Re} \left[\sum_{i=1}^{N_f} j\omega_i \rho \phi_i(x, z) e^{-j(\omega_i t - \varphi_i)} \right] \quad (26)$$

F_H

$$= \text{Re} \left[j\rho \sum_{i=0}^{N_f} \omega_i e^{-j(\omega_i t - \varphi_i)} \int_{-h}^0 (\phi_i^1(-b, z) - \phi_i^3(b, z)) dz \right] \quad (27)$$

$$F_V = \text{Re} \left[j\rho \sum_{i=0}^{N_f} \omega_i e^{-j(\omega_i t - \varphi_i)} \int_{-b}^b \phi_i^2(x, -h) dx \right] \quad (28)$$

M

$$\begin{aligned} &= \text{Re} \left[j\rho \sum_{i=0}^{N_f} \omega_i e^{-j(\omega_i t - \varphi_i)} \left(\int_{-h}^0 \phi_i^1(-b, z) \right. \right. \\ &\quad \cdot z dz - \int_{-b}^b \phi_i^2(x, -h) x dx - \left. \int_{-h}^0 \phi_i^3(b, z) z dz \right) \Big], \end{aligned} \quad (29)$$

where F_H , F_V , and M are the horizontal, vertical, and overturning moments relative to the point O , as shown in Figure 1, with positive in clockwise direction, respectively, and ρ is the water density.

2.3. Examination of Convergence. Shown in (11) to (13), the accuracy and convergence of the solutions are influenced by the truncation order of the evanescent modes in the velocity potentials. The convergence of the analytical solution is investigated by using a limited order of the evanescent modes. To achieve this, two cases with different wave parameters and structural configuration were checked by numerical simulation. The input peak frequency f_p was 0.6 Hz and maximum wave amplitude $A_{\max}$ was 5.0 cm for Case 1, while the configuration of the box, as shown in Figures 1 and 2(b),

TABLE 1: Convergence of pressure and wave forces acting on box.

(a) Case 1: $f_p = 0.6$ Hz, $A_{\max} = 5$ cm, $d = 0.5$ m, $h = 0.025$ m and $B = 0.6$ m

Truncation order	Pressure (kPa) at the position of						Wave force		
	P0	P1	P2	P3	P4	P5	F_x (N)	F_z (N)	M_y (N·m)
1	0.58	0.33	0.30	0.27	0.25	0.23	12.6	166.3	10.9
4	0.57	0.33	0.30	0.27	0.25	0.23	12.5	170.6	11.6
6	0.57	0.33	0.30	0.27	0.25	0.23	12.6	170.9	11.7
8	0.57	0.33	0.30	0.27	0.25	0.23	12.8	170.8	11.7
10	0.58	0.33	0.30	0.27	0.25	0.23	12.9	170.7	11.7
12	0.58	0.33	0.30	0.27	0.25	0.23	13.0	170.6	11.6
14	0.58	0.33	0.30	0.27	0.25	0.23	13.1	170.5	11.6
16	0.58	0.33	0.30	0.27	0.25	0.23	13.2	170.5	11.6

(b) Case 2: $f_p = 1.0$ Hz, $A_{\max} = 8$ cm, $d = 0.5$ m, $h = 0.15$ m and $B = 0.6$ m

Truncation order	Pressure (kPa) at the position of						Wave force		
	P0	P1	P2	P3	P4	P5	F_x (N)	F_z (N)	M_y (N·m)
1	0.79	0.27	0.23	0.20	0.16	0.13	139.6	124.0	2.8
4	0.78	0.25	0.22	0.19	0.16	0.13	142.8	121.2	2.2
6	0.80	0.25	0.22	0.19	0.16	0.13	143.7	120.7	2.0
8	0.80	0.25	0.22	0.19	0.16	0.13	143.7	120.8	2.0
10	0.81	0.25	0.22	0.19	0.16	0.13	143.8	120.6	1.9
12	0.81	0.25	0.22	0.19	0.16	0.13	143.9	120.6	1.9
14	0.80	0.25	0.22	0.19	0.16	0.13	143.9	120.5	1.9
16	0.80	0.25	0.22	0.19	0.16	0.13	144.0	120.5	1.9

is $d = 0.5$ m, $h = 0.025$ m, and $B = 0.6$ m. Case 2 was similar to Case 1 except $f_p = 1.0$ Hz, $A_{\max} = 8.0$ cm, and $h = 0.15$ m. Based on the proposed method, the simulation results of the pressure at certain position shown in Figure 2(b) and wave forces acting on the box with a different truncation order are listed in Table 1. It can be seen that the pressure of both two cases quickly converges to a stable value with six evanescent modes. However, the wave forces convergence is relatively slow until the truncated order N reaches 8. To balance the computational accuracy and efficiency, the truncated order is set to 12 in the following analysis.

3. Validation

3.1. Experimental Setup. A hydrodynamic experiment was conducted to measure focused wave action on a partially immersed box in the Hydraulics Laboratory at the University of Manchester in order to validate the proposed analytical method. The experiment was carried out in a 2D wave flume which is 17.0 m, 1.3 m, and 1.0 m in length, width, and depth, respectively. One force-feedback absorbing piston-type wavemaker is installed at one end of the wave flume to generate waves while an elliptical slope beach is equipped at another end to eliminate wave energy.

The experimental setup is illustrated in Figure 2. It can be seen that the box is 60 cm wide and 20 cm high, while the water depth and draft are 50 cm and 15 cm, respectively. The box is tightly clamped on the side wall of the wave flume

to make the support as rigid as possible. Free vibration test shows that the first mode frequencies are 36.3 Hz in the vertical direction and 20.3 Hz in the horizontal direction, which are abundantly higher than the wave frequencies.

In the experiment, the incident wave is periodic focused wave which was generated by running several focused wave group with the same focusing location but different focused time in the wave flume at the same time. Before installing the specimen, the periodic focused wave was firstly checked in the empty wave flume. The water surface elevation is measured at two positions, with a distance 7.3 m and 8.0 m to the wave maker, respectively. Figure 3(a) shows the undisturbed elevation recorded at the focusing location. It can be seen that the wave elevations are repetitive and generally agree well with theory except some difference existing at wave troughs. It has limit influence on the test results as only the pressure generated by the focused wave crest are concerned in this study. By shifting different focused time to the same temporal position, the repeatability can be much more clearly seen from Figure 3(b). Figure 3(c) shows the wave elevation at the point 7.3 m from wave maker (0.4 m in front of the box) during the test. It is clear that the reflection on the immersed box was measured by wave gauge as the elevation of first wave group is different with the following groups. Similarly, the disturbed wave elevation at 7.3 m is superimposed in Figure 3(d) to show the difference of all 6 focused wave groups. It can be observed from Figure 3(d) that there is some difference between the first focused wave

FIGURE 3: The comparison between the measured and theoretical wave surface elevations at focusing location with $A_{\max}$ 3.78 cm and f_P 0.7 Hz: (a) Periodic focused wave elevation in the empty flume, (b) superimposed focused wave elevations, (c) wave elevation at 0.4m before box, and (d) superimposed disturbed wave elevations.

group and the rest 2nd to 6th focused wave groups which is expected due to the reflection. Quite repetitive elevations can be found for the 2nd to 6th focused wave groups even some difference exists in the leading part which maybe results from imperfect absorption of wavemaker and the influence of previous groups. However, those differences can be neglected as only the pressure or force generated by the focused crest is concerned in this study. As shown in Figure 3(a), every incident wave trial has 6 focused group. Conscientiously, only the hydrodynamic pressure generated by the first three focused waves was considered in the following comparison to avoid the possible effects of the imperfect absorption of wavemaker and second reflection. Beside, wave run-up on the side plate can be observed during the test.

The test plan was designed to cover a range of peak frequency f_p and an appropriate maximum wave amplitude $A_{\max} = 3.5$ cm to avoid significant wave breaking and overtopping during the wave-structure interaction. Actually, measured wave amplitude has some difference compared to the designed value. The measured wave amplitude and

TABLE 2: Test plan for hydrodynamic experiment.

Peak frequency f_p (Hz)	0.7	0.8	0.9	1.0	1.1	1.2
Maximum wave amplitude $A_{\max}$ (cm)	3.78	3.74	3.24	3.05	3.16	3.33

peak frequency of the test is given in Table 2. All NewWave type focused wave groups with a JONSWAP spectrum but different peak frequencies f_p and maximum wave amplitudes $A_{\max}$ were verified in the empty wave flume prior to the tests, and the wave making files of all checked waves were saved for the wave-structure interaction test.

The hydrodynamic pressure acting on the offshore side plate and bottom was measured by 6 Druck® UNIK PTX5072 serial gauge type pressure transducers (Figure 2(b)). The sampling rate is 500 Hz while the maximum response frequency of the sensor is 3.5 kHz. An image of the experimental setup can be seen in Figure 2(c).

FIGURE 4: Comparison of calculated and measured time series of pressure acting on fixed box for wave trial $A_{\max} = 3.78$ cm and $f_p = 0.7$ Hz.

3.2. Comparison with Experimental Results. The checked wave profile at focusing location in the empty wave flume was used as the wave input for the proposed method. Figure 4 depicts the comparison between the calculated results and measured time series of the hydrodynamic gauge pressure generated by the first focused wave group of wave trial with $f_p = 0.7$ Hz and $A_{\max} = 3.78$ cm. It is observed that the maximum pressure measured by all sensors almost occurred at approximately 37 s, at which time the maximum wave crest of the focused wave reached the box submerged in water. Both the experimental and calculated results show that the time difference is less than 0.1 s. Taking the phase velocity of the peak frequency $f_p = 0.7$ Hz as the representing phase velocity of the focused wave, the time lag between the peak pressures of two neighboring sensors can be estimated to be 0.069 s, which is consistent with the measured and analytical results. During the wave propagation process across the box, the maximum pressure of the offshore side (P0) was found to be approximately twice that of the bottom side (P1). This difference between the peak pressure of P0 and P1 results

from the hydrodynamic pressure difference in the propagating wave field and the larger diffraction force on offshore side of the immersed box. Negative pressure was also measured during the wave trough propagating through the structure. Furthermore, the hydrodynamic wave pressure decreased gradually along the bottom deck. From the comparison between the calculated and measured results, it can be found that the present method overestimates the peak pressure in some extent, especially for the offshore side plate and the leading region of the deck. This phenomenon mainly results from the limitation of present method, which cannot effectively consider the nonlinear effects existing in the hydrodynamic experiment. However, from the engineering practice view, the present method can be adopted as a conservative approach to estimate the wave loads on the structures. In general, the simulation results agreed reasonably with the tested results, which demonstrates that the proposed method can effectively represent the hydrodynamic behaviour of a semisubmerged box subjected to focused wave action.

In order to investigate the effectiveness of the analytical method more thoroughly, a comparison between the maximum measured and calculated pressure is shown in Figure 5. In this figure, each pentagram represents the maximum measured pressure value during a single focused wave event in the wave trial, while the square indicates the calculated results. It can also be seen from the figure that the hydrodynamic pressure decreases gradually along the focused wave propagation direction for all wave conditions. In the case of lower peak frequency, the analytical method provides a relatively conservative pressure prediction, particularly at the offshore side plate and deck front area. With an increase in wave frequency, the analytical results are increasingly similar to the test results.

It is believed that the diffraction effect plays a dominant role when $B/L > 0.2$ [31]. Figure 6 shows the ratio B/L for all wave frequency components included in the wave trial shown in Figure 4. It can be observed from Figure 6 that B/L is smaller than 0.2 when wave frequency $f < 0.63$ Hz which means the immersed box is a small object for those frequency components. For the wave trial shown in Figure 4, the part of wave components with $f < 0.63$ Hz holds 12 percent wave energy of the whole wave spectrum. It should be noted that the proposed method may overestimate the loads acting on small box generated by focused wave with low peak frequency.

4. Parametric Study

The pressure and wave forces acting on the box are influenced by several parameters, including structural breadths, drafts, and focused wave properties. The wave force can be expressed as

$$F = f(\rho, g, A_{\max}, f_p, h, B, d), \quad (30)$$

where F represents the wave forces F_H , F_V , and M or wave pressure $P(x, z)$.

The wave forces may depend on a set of variables:

$$\left(\frac{F_Z}{\rho g B A_{\max}}, \frac{F_X}{\rho g h A_{\max}}, \frac{M}{\rho g h B A_{\max}}, \frac{P}{\rho g A_{\max}} \right) = f\left(\frac{B}{d}, \frac{h}{d}, f_p\right). \quad (31)$$

Parametric analysis is conducted based on the proposed analytical method to investigate the sensitivity of wave and geometrical parameters. In the following analysis, the dimensionless results of the hydrodynamic pressure and wave forces acting on the immersed structure are discussed for the instant when the focused wave fully generated and shaped at the focusing location.

4.1. Effect of Structural Breadth. To focus on the structural breadth effect, the other parameters are kept constant during the analysis, including $f_p = 1.0$ Hz, $A_{\max} = 5$ cm, $h = 15$ cm, and $d = 50$ cm. Figure 7 illustrates the pressure distribution on the offshore side plate and the deck bottom of the

partially immersed box with a varying breadth-depth ratio B/d between 0.20 and 1.2. It can be seen that the pressure acting on the offshore side plate decreases gradually along the immergence direction. This pressure distribution trend is identical for the entire structure breadth. Furthermore, it is observed that the structure breadth variation only slightly affects the pressure distribution along the immergence direction. For pressure acting on the deck bottom, it is observed that increased breadth would induce an obvious increase in pressure on the leading edge of deck, while strongly decreasing in the following region.

Based on the simulation results, the variation in dimensionless wave forces is shown in Figure 8, following (27) to (29). It is evident that the negative moment is significantly reduced and even reversed with the structure breadth ratio increase from 0.2 to 1.2. However, the vertical and horizontal wave forces almost remain stable about the change of breadth ratio except slight decrease and increase when the breadth ratio changes from 0.2 to 0.6, respectively. Actually, the increase of the breadth of the structure would induce large vertical force. Nevertheless, the increase of the breadth also leads to more reflection, which means the hydrodynamic pressure at the bottom of deck would decrease. In Figure 8, the dimensionless values include the effect of both factors. It can be concluded that the wider structure breadth ($B/d > 0.6$) leads to more severe reflection which exerts greater pressure on offshore side of the immersed box, but lower pressure on the bottom of the box. When the structure breadth ratio exceeds 0.6, the dimensionless horizontal and vertical wave forces are slightly influenced by the relative structure breadth.

4.2. Effect of Structural Draft. Using the same wave properties as the attack focused waves and water depth, the pressure acting on the partially immersed box is investigated with structure breadth $B = 0.6$ m and the relative draft h/d varying from 0.05 to 0.5. As shown in Figure 9, relative draft is a very important parameter affecting the pressure on side plate and deck bottom. With h/d varying from 0.05 to 0.5, the maximum pressure on the offshore side plate, which always occurs near free surface, is reduced by more than 20% while the pressure at the end of side plate drops from 1.25 to 0.41 significantly. The change of pressure on the offshore side plate is a result of the combination of stronger reflection led by thick box and pressure attenuation along vertical direction. Furthermore, it is found that the bottom deck hydrodynamic pressure decreases significantly with increasing structure draft, because the focused wave effects are obviously weakened. The pressure attenuation along the wave propagation direction becomes less obvious owing to the weakening of the wave energy density as the box being further submerged.

In order to gain direct insight into the structure draft influence, wave forces were calculated by integrating the structure surface pressure. As shown in Figure 10, the dimensionless horizontal wave forces increase slightly and then decrease gradually while the vertical wave forces show slow decline with increase of the draft h/d . It is well known that deeper draft leads to severer reflection which will result in

FIGURE 5: Comparison of the calculated and measured maximum pressure acting on fixed box generated by the first 3 focused wave groups.

FIGURE 6: A particular JONSWAP spectrum with peak frequency $f_p = 0.7$ Hz and maximum amplitude $A_{\max} = 3.78$ cm and the ratio of structural width ($B = 0.6$ m consistent with the experimental setup) to wavelength for wave components.

FIGURE 7: Pressure distribution along (a) offshore side plate and (b) deck bottom with varying breadth ratio B/d .

larger horizontal wave force but smaller vertical wave forces. However, the horizontal wave force declines gradually with the increase of draft ratio h/d , revealing the characteristic of the hyperbolic cosine pressure distribution along the water depth. Differently, the moment drops down noticeably from 1.47 to -0.1 with the draft h/d changing from 0.05 to 0.5. The moment contains the contribution of the pressure on both side plates and deck bottom. It can be concluded that the pressure on deck bottom plays a dominating role for small draft h/d cases and then changes to the pressure on offshore side plate as suggested by the negative moment when $h/d = 0.5$.

4.3. Effects of Wave Properties. The effects of the wave properties, such as peak frequency and focused amplitude, are investigated in this subsection. As the present analytical solution is a linear potential method-based model, the wave forces are linear about the maximum amplitude of the focused wave. Only the peak frequency is discussed in the following. The structure configuration remained constant, with $B = 60$ cm, $h = 15$ cm, and $d = 50$ cm. The influences of the peak frequency on the pressure distribution and wave forces are shown in Figures 11 and 12, respectively. Focused wave with a lower peak frequency contains more long-period wave components

FIGURE 8: Wave loads acting on box under focused wave with varying breadth ratio B/d . FIGURE 9: Pressure distribution along (a) offshore side plate and (b) deck bottom with varying draft ratio h/d .

with longer wavelengths. Therefore, for the offshore side plate, the influence of the focused wave peak frequency becomes stronger along the water depth. Due to the specific characteristics of the long-period waves, a focused wave with a lower peak frequency generates higher pressure on the deck bottom. Obviously, the dimensionless horizontal wave force first increases slightly and then decreases gradually with an increase in peak frequency, while the vertical force and moment only decline slightly, as illustrated in Figure 12. This means the focused wave with low peak frequency is much more dangerous for offshore structures.

5. Conclusions

Aiming at focused wave action, this paper presents an analytical method for analysing the hydrodynamic pressure and wave forces of a fixed submerged box, according to potential flow theory and the matching eigenfunction method. Following validation with the test data, the proposed method was used to investigate the influences of the structure configuration and wave properties by means of parametric analysis. It was found that the proposed method can effectively predict the hydrodynamic pressure on the wet surface

FIGURE 10: Wave loads acting on box under focused wave with varying draft ratio h/d . FIGURE 11: Pressure distribution along (a) offshore side plate and (b) deck bottom under focused wave with varying peak frequency f_p .

of a partially submerged box. The parametric analysis results indicate that the structural breadth significantly influences the hydrodynamic forces when it is smaller than 0.6. A large breadth ratio B/d leads to a higher horizontal wave force but lower vertical wave force and overturning moment. The dimensionless hydrodynamic forces gradually decline with the increase of structural draft. A focused wave with a lower peak frequency and larger focused amplitude would exert larger wave forces on the structure. It should be noted that the present method cannot consider nonlinear waves involving significant nonlinear effect, such as wave breaking and overtopping. The paper shows the value of linear potential method

for wave loads prediction even for focused waves even with some limitations existing.

Appendix

$$\mathbf{P} = \left\{ \frac{\int_{-d}^{-h} Z_{i0}^1 Z_{i0}^2 dz}{\int_{-d}^{-h} Z_{i0}^2 Z_{i0}^2 dz}, 0, 0, \dots, 0 \right\}_{(N+1) \times 1}^T \quad (\text{A.1})$$

$$\mathbf{F} = \left\{ \frac{\int_{-d}^{-h} Z_{in}^1 Z_{in}^2 dz}{\int_{-d}^{-h} Z_{in}^2 Z_{in}^2 dz} \right\}_{(N+1) \times (N+1)} \quad m, n = 0, 1, \dots, N \quad (\text{A.2})$$

FIGURE 12: Wave loads acting on box under focused wave with varying peak frequency f_p .

$$\mathbf{G} = \{\text{diag}(0, \cosh k_{i1}^2 b, \dots, \cosh k_{iN}^2 b)\}_{(N+1) \times (N+1)} \quad (\text{A.3})$$

$$\mathbf{H} = \{\text{diag}(b, \sinh k_{i1}^2 b, \dots, \sinh k_{iN}^2 b)\}_{(N+1) \times (N+1)} \quad (\text{A.4})$$

$$\mathbf{q} = \{-1, 0, 0, \dots, 0\}_{(N+1) \times 1}^T \quad (\text{A.5})$$

$$\mathbf{J}_{nm} = \begin{cases} 0 & n = 0, 1, 2 \dots N, m = 0 \\ \frac{jk_{im}^2 \sinh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{i0}^1 dz}{k_{i0}^1 \int_{-d}^{-h} Z_{i0}^1 Z_{i0}^1 dz} & n = 0, m = 1, 2 \dots N \\ \frac{k_{im}^2 \sinh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{in}^1 dz}{k_{in}^1 \int_{-d}^{-h} Z_{in}^1 Z_{in}^1 dz} & \text{other} \end{cases} \quad (\text{A.6})$$

$$\mathbf{K}_{nm} = \begin{cases} \frac{j \int_{-d}^{-h} Z_{i0}^2 Z_{i0}^1 dz}{k_{i0}^1 \int_{-d}^{-h} Z_{i0}^1 Z_{i0}^1 dz} & n = 0, m = 0 \\ \frac{jk_{im}^2 \cosh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{i0}^1 dz}{k_{i0}^1 \int_{-d}^{-h} Z_{i0}^1 Z_{i0}^1 dz} & n = 0, m = 1, 2 \dots N \\ \frac{\int_{-d}^{-h} Z_{i0}^2 Z_{in}^1 dz}{k_{in}^1 \int_{-d}^{-h} Z_{in}^1 Z_{in}^1 dz} & n = 1, 2 \dots N, m = 0 \\ \frac{k_{im}^2 \cosh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{in}^1 dz}{k_{in}^1 \int_{-d}^{-h} Z_{in}^1 Z_{in}^1 dz} & \text{other} \end{cases} \quad (\text{A.7})$$

$$\mathbf{L} = \{\text{diag}(\cosh k_{i0}^2 b, \cosh k_{i1}^2 b, \dots, \cosh k_{iN}^2 b)\}_{(N+1) \times (N+1)} \quad (\text{A.8})$$

$$\mathbf{O} = \{\text{diag}(b, \sinh k_{i1}^2 b, \dots, \sinh k_{iN}^2 b)\}_{(N+1) \times (N+1)} \quad (\text{A.9})$$

$$\mathbf{Q}_{nm} = \begin{cases} 0 & n = 0, 1, 2 \dots N, m = 0 \\ -\frac{jk_{im}^2 \cosh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{i0}^3 dz}{k_{i0}^3 \int_{-d}^{-h} Z_{i0}^3 Z_{i0}^3 dz} & n = 0, m = 1, 2 \dots N \\ \frac{k_{im}^2 \sinh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{in}^3 dz}{k_{in}^3 \int_{-d}^{-h} Z_{in}^3 Z_{in}^3 dz} & \text{other} \end{cases} \quad (\text{A.10})$$

$$\mathbf{K}_{nm} = \begin{cases} \frac{j \int_{-d}^{-h} Z_{i0}^2 Z_{i0}^3 dz}{k_{i0}^1 \int_{-d}^{-h} Z_{i0}^3 Z_{i0}^3 dz} & n = 0, m = 0 \\ -\frac{jk_{im}^2 \cosh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{i0}^3 dz}{k_{i0}^3 \int_{-d}^{-h} Z_{i0}^3 Z_{i0}^3 dz} & n = 0, m = 1, 2 \dots N \\ \frac{\int_{-d}^{-h} Z_{i0}^2 Z_{in}^3 dz}{k_{in}^3 \int_{-d}^{-h} Z_{in}^3 Z_{in}^3 dz} & n = 1, 2 \dots N, m = 0 \\ \frac{k_{im}^2 \cosh k_{im}^2 b \int_{-d}^{-h} Z_{im}^2 Z_{in}^3 dz}{k_{in}^3 \int_{-d}^{-h} Z_{in}^3 Z_{in}^3 dz} & \text{other.} \end{cases} \quad (\text{A.11})$$

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The first author would like to appreciate the host of Prof. Peter Stansby and the financial support from the China Scholarship Council during his 1-year visiting at the University of Manchester. The authors greatly appreciate the financial support provided by the National Natural Science Foundation of China (51725801, 51808172) and the project of China Postdoctoral Science Foundation (2018M641833).

References

- [1] C. Kharif and E. Pelinovsky, "Physical mechanisms of the rogue wave phenomenon," *European Journal of Mechanics - B/Fluids*, vol. 22, no. 6, pp. 603–634, 2003.
- [2] A. Chabchoub, N. P. Hoffmann, and N. Akhmediev, "Rogue wave observation in a water wave tank," *Physical Review Letters*, vol. 106, no. 20, p. 204502, 2011.
- [3] T. B. Johannessen and C. Swan, "A laboratory study of the focusing of transient and directionally spread surface water waves," *Proceedings of the Royal Society A Mathematical, Physical and Engineering Sciences*, vol. 457, no. 2008, pp. 971–1006, 2001.
- [4] D. T. Cox and J. A. Ortega, "Laboratory observations of green water overtopping a fixed deck," *Ocean Engineering*, vol. 29, no. 14, pp. 1827–1840, 2002.

- [5] W. Bai and R. Eatock Taylor, "Numerical simulation of fully nonlinear regular and focused wave diffraction around a vertical cylinder using domain decomposition," *Applied Ocean Research*, vol. 29, no. 1-2, pp. 55–71, 2007.
- [6] Z. Z. Hu, D. M. Causon, C. G. Mingham, and L. Qian, "Numerical simulation of floating bodies in extreme free surface waves," *Natural Hazards and Earth System Sciences*, vol. 11, no. 2, pp. 519–527, 2011.
- [7] N. Gao, J. Yang, W. Zhao, and X. Li, "Numerical simulation of deterministic freak wave sequences and wave-structure interaction," *Ships and Offshore Structures*, vol. 11, no. 8, pp. 802–817, 2016.
- [8] N. Gao, J. Yang, X. Tian, and X. Li, "A numerical study on the nonlinear effects in focused wave modelling and forces on a semi-submerged horizontal cylinder," *Ships and Offshore Structures*, vol. 12, no. 4, pp. 474–485, 2017.
- [9] S. D. Weller, T. J. Stallard, and P. K. Stansby, "Experimental measurements of the complex motion of a suspended axisymmetric floating body in regular and near-focused waves," *Applied Ocean Research*, vol. 39, pp. 137–145, 2013.
- [10] X. Z. Zhao, Z. T. Ye, Y. N. Fu, and F. F. Cao, "A CIP-based numerical simulation of freak wave impact on a floating body," *Ocean Engineering*, vol. 87, pp. 50–63, 2014.
- [11] M. Banks and N. Abdussamie, "The response of a semisubmersible model under focused wave groups: Experimental investigation," *Journal of Ocean Engineering and Science*, vol. 2, no. 3, pp. 161–171, 2017.
- [12] J. L. Black, C. C. Mei, and M. C. G. Bray, "Radiation and scattering of water waves by rigid bodies," *Journal of Fluid Mechanics*, vol. 46, no. 1, pp. 151–164, 1971.
- [13] P. Andersen and H. Wuzhou, "On the calculation of two-dimensional added mass and damping coefficients by simple Green's function technique," *Ocean Engineering*, vol. 12, no. 5, pp. 425–451, 1985.
- [14] A. N. Williams, "Froude-Krylov force coefficients for bodies of rectangular section in the vicinity of the free-surface and seabed," *Ocean Engineering*, vol. 21, no. 7, pp. 663–682, 1994.
- [15] C. Wu, E. Watanabe, and T. Utsunomiya, "An eigenfunction expansion-matching method for analyzing the wave-induced responses of an elastic floating plate," *Applied Ocean Research*, vol. 17, no. 5, pp. 301–310, 1995.
- [16] A. Guo, Q. Fang, and H. Li, "Analytical solution of hurricane wave forces acting on submerged bridge decks," *Ocean Engineering*, vol. 108, pp. 519–528, 2015.
- [17] J. Dong, B. Wang, X. Zhao, and H. Liu, "Wave forces exerted on a submerged horizontal plate over an uneven bottom," *Journal of Engineering Mechanics*, vol. 144, no. 6, p. 04018030, 2018.
- [18] W. L. Qiao, K.-H. Wang, and Y. Q. Sun, "Scattering of water waves by a floating body with two vertically attached porous walls," *Journal of Engineering Mechanics*, vol. 144, no. 2, p. 04017162, 2018.
- [19] Q. R. Meng and D. Q. Lu, "Wave-induced hydrodynamic responses of a rigid body connected with elastic plates floating on a two-layer fluid," *Journal of Fluids and Structures*, vol. 68, pp. 295–309, 2017.
- [20] Y. C. Li, G. H. Dong, H. J. Liu, and D. P. Sun, "The reflection of oblique incident waves by breakwaters with double-layered perforated wall," *Coastal Engineering Journal*, vol. 50, no. 1-2, pp. 47–60, 2003.
- [21] A. A. Kurkin, S. V. Semin, and Y. A. Stepanyants, "Transformation of surface waves over a bottom step," *Izvestiya - Atmospheric and Ocean Physics*, vol. 51, no. 2, pp. 214–223, 2015.
- [22] Z. Deng, L. Wang, X. Zhao, and Z. Huang, "Hydrodynamic performance of a T-shaped floating breakwater," *Applied Ocean Research*, vol. 82, pp. 325–336, 2019.
- [23] L. Cavallaro, C. Iuppa, P. Scandura, and E. Foti, "Wave load on a navigation lock sliding gate," *Ocean Engineering*, vol. 154, pp. 298–310, 2018.
- [24] L. Letournel, C. Chauvigné, B. Gelly, A. Babarit, G. Ducrozet, and P. Ferrant, "Weakly nonlinear modeling of submerged wave energy converters," *Applied Ocean Research*, vol. 75, pp. 201–222, 2018.
- [25] D. M. Skene, L. G. Bennetts, M. Wright, M. Meylan, and K. J. Maki, "Water wave overwash of a step," *Journal of Fluid Mechanics*, vol. 839, pp. 293–312, 2018.
- [26] R. Baarholm and O. M. Faltinsen, "Wave impact underneath horizontal decks," *Journal of Marine Science and Technology*, vol. 9, no. 1, pp. 1–13, 2004.
- [27] M. Longuet-Higgins, "On the statistical distributions of the heights of sea waves," *Journal of Marine Research*, vol. 11, no. 3, pp. 245–265, 1952.
- [28] P. S. Tromans, A. R. Anaturk, and P. Hagemeyer, "A new model for the kinematics of large ocean waves-application as a design wave," in *Proceedings of the The First International Offshore and Polar Engineering Conference*, International Society of Offshore and Polar Engineers, Edinburgh, UK, 1991.
- [29] Y. H. Zheng, Y. M. Shen, Y. G. You, B. J. Wu, and D. S. Jie, "On the radiation and diffraction of water waves by a rectangular structure with a sidewall," *Ocean Engineering*, vol. 31, no. 17-18, pp. 2087–2104, 2004.
- [30] H. Dhillon, S. Banerjee, and B. N. Mandal, "Water wave scattering by a finite dock over a step-type bottom topography," *Ocean Engineering*, vol. 113, pp. 1–10, 2016.
- [31] T. Sarpkaya and M. Isaacson, *Mechanics of Wave Forces on Offshore Structures*, vol. 96, Van Nostrand Reinhold Company, New York, NY, USA, 1981.