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Numerical and Experimental Study on the Hydrodynamic Performance of a Sloping OWC Wave Energy Converter Device Integrated into Breakwater

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Abstract: This study presents numerical and experimental investigations on an oscillating water column (OWC) wave energy device integrated into a sloping breakwater. Regular waves were generated in a physical wave tank to investigate the hydrodynamic performance and extraction efficiency of the small-scale nested OWC device. Simultaneously, to complement various scenarios, numerical simulations were conducted using the open-source computational fluid dynamics platform OpenFOAM. The volume of fluid (VOF) method was employed to capture the complex evolution of the air–water interface, and an artificial source term (Forchheimer flow region) was introduced into the Navier–Stokes equations to replace the power take-off (PTO) system. By analyzing wave reflection properties, energy absorption efficiency, and wave run-up, the hydrodynamic characteristics of the inclined OWC device were explored. The comparison between the numerical and experimental results indicate a good consistence. A smaller front wall draft broadens the high-efficiency frequency bandwidth. For relatively long waves, increasing the air chamber width enhances energy conversion efficiency and reduces wave run-up. The optimal configuration was achieved with the following dimensionless parameters: front wall draft $a/h = 1/3$, air chamber width $d_1/h = 2/9$, and slope $i = 2$. Due to the sloped structure, when compared with a vertical OWC, long waves can more easily enter the chamber. This causes the efficient frequency bandwidth to shift towards the low frequency range, allowing more wave energy to be converted into pneumatic energy. As a result, wave run-up is reduced, enhancing the protective function of the breakwater.

Keywords: wave energy; oscillating water column; energy capture width ratio; wave hydrodynamics; wave run-up



Citation: Tao, T.; Deng, Z.; Li, M.; Cheng, P.; Luo, W. Numerical and Experimental Study on the Hydrodynamic Performance of a Sloping OWC Wave Energy Converter Device Integrated into Breakwater. *J. Mar. Sci. Eng.* **2024**, *12*, 2318. <https://doi.org/10.3390/jmse12122318>

Academic Editors: Kostas Belibassakis, Eugen Rusu and George Lavidas

Received: 19 November 2024

Revised: 12 December 2024

Accepted: 15 December 2024

Published: 17 December 2024



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1. Introduction

Energy issues have been a constant companion to human development, and clean, renewable energy is particularly important for sustainable development and environmental protection [1]. Ocean wave energy has higher energy flux density when compared with other renewable sources and has garnered significant attention. Currently, researchers have proposed various wave energy conversion (WEC) devices, including oscillating water columns, oscillating buoys, and overtopping devices [2,3]. The oscillating water column (OWC) wave energy converter, known for its simple structure, high conversion efficiency, and adaptability, is one of the most promising wave energy extraction devices [4]. Generally, OWC devices can be categorized into fixed and floating types [5]. By as early as 1998, Japan had installed the Mighty Whale, a floating OWC device, near Gokasho Bay [6,7], with a total power capacity of 110 kW. Subsequently, many countries have conducted related research, such as that associated with Australia’s MK3 device. However, high construction and maintenance costs have consistently hindered the development of floating OWC

devices. Compared with floating OWCs, fixed OWC devices are more economical and easier to maintain. They are often integrated with coastal structures like breakwaters [8,9], exemplified by the LIMPET OWC plant on Islay Island, Scotland [10]. Integrating OWC systems with breakwaters can help share construction costs and space [11].

The concept of oscillating water column (OWC) wave energy generation was first proposed by Masuda and Miyazaki [12], who successfully conducted experimental tests. However, early research focused mainly on theoretical analysis. Evans [13] simplified the water column in the air chamber to a weightless piston under the assumption of linear wave theory, deriving an approximate analytical solution for wave energy absorption efficiency. In complex engineering studies, the effects of simplified elements in theoretical analysis cannot be ignored, making physical model experiments more reasonable and effective. Currently, numerical simulations and small-scale model experiments are the primary methods for studying OWC devices. He and Huang [14] investigated the shapes of openings, simulating the PTO through tank experiments. They note that the relative thickness of the upper wall of the air chamber significantly influenced the oscillating airflow when the top opening shape was a narrow slit. With the development of computational simulation technology, numerical simulations of wave–structure interactions have become an important research method. Deng, Wang et al. [15] proposed a fixed OWC device with a horizontal bottom plate and studied the effects of the opening ratio of the small holes, length of the horizontal bottom plate, relative opening of the bottom inlet, and water depth on its hydrodynamic performance through a combination of model experiments and numerical simulations.

Numerical simulations and model experiments are equally significant for the study of integrated OWC breakwaters. Many researchers have conducted studies about it. Evans [16] first investigated the wave pressure of OWC integrated with breakwaters using linear wave theory and proposed a simple relationship between OWC pressure distribution and energy absorption. Zanuttigh [17] analyzed the wave reflection coefficient of the OWC device using two-dimensional experimental results. Their experimental findings indicate that the reflection coefficient decreases with increasing wavelength, consistent with the chamber width. Harikrishnan [18] combined an L-shaped OWC device with a lightweight floating breakwater, demonstrating advantages such as wave energy absorption and wave attenuation. Under optimal conditions for a model with three floating breakwaters, the OWC efficiency reached 30%. Zhang et al. [19] conducted physical experiments and numerical simulations on an integrated OWC breakwater, incorporating the device with a set of porous plates, to investigate the effects of wave nonlinearity on hydrodynamic efficiency and wave forces. Zhao [20] studied a multi-chamber OWC breakwater device and found that implementing a multi-chamber design expanded the effective frequency bandwidth of the OWC breakwater. Compared with traditional breakwaters, multi-chamber OWC breakwaters exhibited better wave attenuation performance in longer waves. However, optimization studies on integrated OWC breakwater structures remain limited, even though geometric configurations significantly impact OWC performance.

The main objective of this study is to investigate the hydrodynamic characteristics of a sloped OWC integrated into a breakwater using experimental and numerical methods. By combining these two devices, the aim is to enhance the safety performance of the breakwater while extracting wave energy and reducing transmitted wave energy. Our research also examines the effects of structural parameters, such as draft of the front wall, chamber width, slope, and other relevant factors, on the protective performance and energy extraction efficiency of the sloped OWC device and to provide references for optimizing the device from a structural perspective. This paper is organized as follows: Section 2 introduces the experimental setup, operating conditions, and methods for calculating hydrodynamic parameters; Section 3 focuses on the numerical model setup; experimental and numerical results will be discussed in Section 4; and Section 5 provides a summary of the entire work.

2. Experiments

The experiments were conducted at the Ocean Engineering Laboratory of Zhejiang University. The wave tank dimensions were 35 m in length, 0.6 m in width, and 0.8 m in height, with glass sides and bottom for easy observation of the interior. A piston-type wave generator was installed at one end of the tank and was equipped with an active absorption system. The other end featured a porous medium slope of 1:8 and which was approximately 4 m long. This served as a dissipation zone to eliminate the effects of reflections at the tank's end on the experiments.

2.1. The Physical Model

The OWC device used in this experiment consists of two plates on top of each other, with a cover on top to form an air chamber, as shown in Figure 1. The supporting structure is made of steel, with acrylic adhesive used at the joints to ensure structural stability. The model has a total height of 0.85 m, a width of 0.58 m, and a slope of 2.0. As shown in Figure 2, the bottom of the rear slope is submerged, and the sides are bonded to the tank walls with silicone sealant to prevent water from penetrating through the structure.

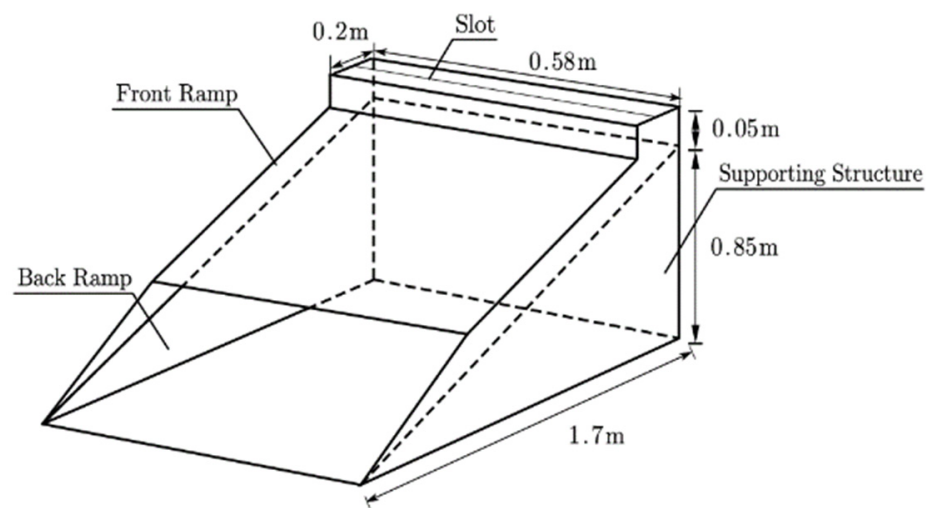


Figure 1. A sketch of the OWC device.



Figure 2. Physical model of the OWC device.

The experiments employed the Froude scaling law to determine the scaling ratio. To compare with the numerical simulation, the model width was set equal to the wave tank width, resulting in a scaling of 1:20. Figure 3 illustrates the installation of the OWC device in the wave tank. The OWC model is constructed from transparent acrylic, with the thickness of the two inclined plates being 12 mm and the other sections having a thickness of 8 mm. The height of the top cover is 0.05 m, with a width equal to the horizontal distance between the two plates. It features a narrow slit-type opening measuring 2 mm in width, with a porosity ratio of 1% to simulate a PTO system. The experimental research by Elhanafi and Kim [21] indicates that a porosity rate of 1% results in optimal wave energy conversion efficiency. The experimental setup is shown in Figure 4. The OWC model is positioned 15.25 m from the wave generator, with waterproof adhesive sealing the gap between the device and the tank wall. The front wall draft is determined by the water depth—at a depth of 0.4 m, the front wall draft is 0.1 m, and at a depth of 0.45 m, it is 0.15 m.



Figure 3. The OWC device in the wave flume.



Figure 4. Detail view of the orifice.

A total of eight capacitive wave gauges were used to monitor the water level changes inside and around the OWC. Wave gauge G1 is placed 6 m from the wave generator to monitor any anomalies in the incident wave height. According to Goda and Suzuk's [22] method, three wave gauges, G2, G3, and G4, are positioned 4.08 m in front of the OWC model to separate incident and reflected waves. A wave gauge, G5, is fixed on the front wall to measure wave run-up. Additionally, three wave gauges, G6, G7, and G8, are installed in the center of the air chamber to measure instantaneous water level inside the chamber, and the average value of three gages was used to represent the mean water level within the chamber. The ranges of G6, G7, and G8 are 1000 mm, while others are 600 mm. The accuracy of all wave gauges is 0.3% of their respective ranges.

The top cover of the OWC has two threaded holes to secure two pressure sensors, S1 and S2, which monitor the relative pressure inside the air chamber. Based on the monitoring data, the wave energy conversion efficiency, wave reflection characteristics, and responses of the front and rear wall run-up for different operating conditions of the sloping OWC device can be determined.

2.2. Test Conditions Setup

To evaluate the performance of the OWC model under different draft conditions, regular wave experiments were conducted under two water depths of 0.4 m and 0.45 m.

This setup ensured that the water level remained above the upper edge of the inclined plate in the chamber, maintaining an airtight condition except for the opening. Additionally, the effects of varying wave periods and heights were considered. Due to equipment limitations, experiments were not conducted for the incident wave height of 0.07 m at a water depth of 0.4 m to ensure that the wave gauge inside the chamber could capture trough data. Table 1 presents all of the operating conditions for the experiments.

Table 1. A summary of test conditions in the experiment.

Parameters	Value							
Depth h (m)	0.40							
Wave height H_i (m)	0.03	0.05						
Period T (s)	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
Wavelength λ (m)	1.4637	1.9362	2.3928	2.8359	3.2691	3.6950	4.1155	4.5320
Wave steepness H_i/λ ($H_i = 0.03$ m)	0.0205	0.0155	0.0125	0.0106	0.0092	0.0081	0.0073	0.0066
Wave steepness H_i/λ ($H_i = 0.05$ m)	0.0341	0.0258	0.0403	0.0176	0.0152	0.0135	0.0121	0.0110
Parameters	Value							
Depth h (m)	0.45							
Wave height H_i (m)	0.03	0.05	0.07					
Period T (s)	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
Wavelength λ (m)	1.4923	1.9978	2.4884	2.9640	3.4281	3.8837	4.3329	4.7773
Wave steepness H_i/λ ($H_i = 0.03$ m)	0.0201	0.0150	0.0121	0.0101	0.0088	0.0077	0.0069	0.0063
Wave steepness H_i/λ ($H_i = 0.05$ m)	0.0335	0.0250	0.0201	0.0168	0.0145	0.128	0.0115	0.0104
Wave steepness H_i/λ ($H_i = 0.07$ m)	0.0469	0.0350	0.0281	0.0236	0.0204	0.0180	0.0161	0.0146

Before commencing the official experiments, the wave generation accuracy of the wave tank was validated. In the absence of the OWC device, wave gauges recorded the stabilized water level data, capturing five cycles to calculate the average measured wave height. A comparison between the measured wave height and the target wave height indicated that the maximum error did not exceed 2.37%.

2.3. Data Analysis

Calculate the efficiency P_{owc} of the OWC device when converting wave energy to pneumatic energy within a single wave period as follows:

$$P_{OWC} = \frac{1}{T} \int_T^{t+T} p(t)u(t)A_0 dt \quad (1)$$

where $u(t)$ is the vertical velocity of the water surface in the air chamber, $p(t)$ is the pressure fluctuation in the air chamber caused by the oscillation of the water surface, and A_0 is the cross-sectional area of the air chamber. Neglecting the effects of air compressibility, the pressure fluctuation $p(t)$ in the air chamber is taken as the average of the data collected by sensors S1 and S2. The vertical velocity, $u(t)$, can be obtained by differentiating the average oscillatory displacement of the water surface.

The wave energy absorption efficiency is used to quantify the pneumatic power conversion efficiency of the wave energy device. Its expression is given as follows:

$$\xi = \frac{P_{OWC}}{E_i C_g} \quad (2)$$

where $E_i = \rho g H^2 / 8$ represents the wave energy per unit area of the incident wave and C_g is the group velocity of the incident wave.

According to the two-point method proposed by Goda and Suzuk [22] for separating reflected and incident waves, the formula for calculating the reflection coefficient is as follows:

$$C_r = A_r / A_i \quad (3)$$

where A_i represents the amplitude of the reflected wave. To quantitatively describe the energy loss caused by vortices and surface oscillations during the energy conversion process, the energy dissipation coefficient is defined as follows:

$$C_l = \sqrt{1 - \xi - C_r^2} \quad (4)$$

3. Numerical Modeling

In numerical simulations, the direction of the incident wave is defined as the x axis, and the vertical direction is defined as the y axis. In OpenFOAM v1912, the number of grid cells in the z axis direction is set to 1, representing a two-dimensional simulation. The entire computational domain is set to be consistent with the experimental setup.

3.1. Governing Equations

The numerical model is based on the open-source CFD platform OpenFOAM, employing the Reynolds-averaged Navier–Stokes (RANS) equations as the governing equations for water–air two-phase flow. The viscosity of water is considered, while the compressibility effects of the fluid are neglected. The governing equations can be expressed as follows:

$$\nabla \cdot \vec{U} = 0 \quad (5)$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot (\rho \vec{U} \vec{U}) - \nabla \cdot (\mu_{eff} \nabla \vec{U}) = -\nabla p^* - \vec{g} \cdot \vec{X} \cdot \nabla \rho + \nabla \vec{U} \cdot \nabla \mu_{eff} + \sigma \kappa \nabla \alpha \quad (6)$$

where ρ denotes the fluid density, $\vec{U}$ is the velocity vector of the fluid particle, g is the gravitational acceleration, P^* is total pressure and represents the dynamic pressure, $\sigma \kappa \nabla \alpha$ represents the model considering surface tension, σ is the surface tension coefficient, and κ is the interfacial curvature. $\mu_{eff} = \mu_f + \mu_t$ is the effective dynamic viscosity coefficient; here, μ_f is the molecular dynamic viscosity and μ_t is the turbulent dynamic viscosity. We

used the following $k - \omega$ turbulence model [23] to provide a closure for describing the effects of turbulence on the mean flow:

$$\frac{\partial \rho k}{\partial t} + \nabla \cdot (\rho \vec{U} k) = \rho P_k - \rho \beta^* k \omega + \nabla \cdot [(\mu_f + \sigma^* \mu_t) \nabla k] \quad (7)$$

$$\frac{\partial \rho \omega}{\partial t} + \nabla \cdot (\rho \vec{U} \omega) = \rho P_\omega - \rho \beta \omega^2 + \rho \frac{\sigma_d}{\omega} \nabla k \cdot [\nabla \omega]^T + \nabla \cdot [(\mu_f + \rho \sigma \frac{k}{\omega}) \nabla \omega] \quad (8)$$

where k and ω represent the specific turbulent kinetic energy and the characteristic eddy frequency; σ , σ_d , σ^* , β and β_* are model parameters; and P_k and P_ω are the production terms of k and ω , respectively. Mayer and Madsen [24] proposed that, when P_k and p_ω have the following expressions,

$$\begin{aligned} p_k &= \mu_t (\nabla \times \vec{U}) \cdot (\nabla \times \vec{U})^T \\ p_\omega &= \frac{\omega}{k} P_k \end{aligned} \quad (9)$$

it is possible to suppress the abnormal growth of turbulent viscosity and turbulent kinetic energy. The turbulent dynamic viscosity μ_t is then determined as follows:

$$\mu_t = \frac{\rho k}{\max\{\omega, C_{\lim} \sqrt{\frac{2S:S}{\beta^*}}\}} \quad (10)$$

According to the suggestions of Wilcox [25], the values for the above parameters are set as follows: $\beta = 0.072$, $\beta^* = 0.09$, $\sigma_\omega = 0.5$, $\sigma_d = 0.856$, $\sigma_* = 0.6$ and $C_{\lim} = 0.875$.

The numerical simulation uses the volume of fluid (VOF) method [26] to capture the free surface of the water–air two-phase flow. In this method, the volume fraction of the fluid in a cell is denoted as α . When $\alpha = 1$, the cell is filled with liquid and the cell is filled with air when $\alpha = 0$. Cells with intermediate values of α represent the interface cells [27]. The volume fraction of water α should satisfy the advection equation. By introducing artificial compressibility $\nabla \cdot U_r \alpha (1 - \alpha)$ [27,28], its expression is as follows:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\vec{U} \alpha) + \nabla \cdot U_r \alpha (1 - \alpha) = 0 \quad (11)$$

Here, U_r represents the compressive velocity perpendicular to the air–water interface. Additionally, the volume fraction α can be used to calculate the density and dynamic viscosity of the interface element, the subscripts 1 and 0 represent water and air.

$$\mu = \alpha_i \mu_1 + (1 - \alpha_i) \mu_0 \quad (12)$$

$$\rho = \alpha_i \rho_1 + (1 - \alpha_i) \rho_0 \quad (13)$$

3.2. Wave Generation and Absorption

The numerical wave generation and dissipation utilize the wave generation tool wave2Foam [29] in OpenFOAM. Wave2Foam employs a relaxation zone model for numerical wave generation, which also prevents reflections at the inlet and outlet boundaries. Its principle is based on adjusting the momentum equations using spatial weighting factors of the actual and target solution values to achieve the specified wave properties. The expression is as follows:

$$\phi = \chi \phi_c + (1 - \chi) \phi_t \quad (14)$$

where ϕ_c is the computed value, ϕ_t is the target value, and χ is the relaxation factor defined as follows:

$$\chi(\zeta) = 1 - \frac{\exp(\zeta^{3.5} - 1)}{\exp(1) - 1} \quad (15)$$

Here, ζ represents the coordinate value in the local spatial coordinate system, where $\zeta = 0$ indicates the interface between the relaxation zone and the non-relaxation zone, and $\zeta = 1$ represents the end walls of the wave tank.

3.3. Porous Media Model

Using the orifice as the PTO for the OWC device is relatively straightforward in experiments. However, in numerical simulations, capturing the geometric features often requires very fine mesh grids, and the high flow velocities between the perforated plates demand smaller time steps to meet the CFL number condition. These two aspects can significantly increase the computational load of the simulations. Hang et al. [14] proposed introducing artificial source terms and using an artificial Forchheimer flow region to replace the orifice as the PTO for the OWC device.

OpenFOAM is equipped with the porous media solver porousSimpleFoam, which can be used for simulating fluid flow through porous media. By selecting specific regions and adding source terms to the momentum equations, porous media flow can be simulated. The solver utilizes the Darcy–Forchheimer model [30], and the expression for the source term is as follows:

$$S_m = -\left(\mu D + \frac{1}{2}\rho|U|F\right)U \quad (16)$$

Under the assumption of the negligible compressibility of air, the pressure drop within the air chamber can be calculated using the following expression:

$$\Delta P = \mu D|u|\Delta x + \frac{1}{2}F \cdot \Delta x \rho u|u| \quad (17)$$

where F represents the nonlinear porosity parameter, D is the linear porosity parameter, and Δx is the thickness of the porous medium layer. The research of Huang, Huang et al. [31] indicates that the pressure drop, ΔP , is not sensitive to variations in thickness, Δx , and, by neglecting the nonlinear terms [14], nonlinear fitting of the expression (17) was performed based on the simulation results of the OWC device with the orifice. The nonlinear porosity parameter D was set to 3.6×10^5 .

3.4. Mesh Setup and Convergence Verification

In this study, an unstructured mesh was used to cover the entire computational domain. First, a layer of mesh with a resolution of $1.8 \text{ cm} \times 1.0 \text{ cm}$ was formed across the domain. The mesh was refined within a range of 14.0 cm above and below the still water level to accurately capture the free surface. Additionally, under the testing conditions of $H_i = 0.45 \text{ m}$, $h = 0.03 \text{ m}$, $T = 1.4 \text{ s}$, three different mesh resolutions were set around the OWC model to verify convergence, as shown in Figure 5.

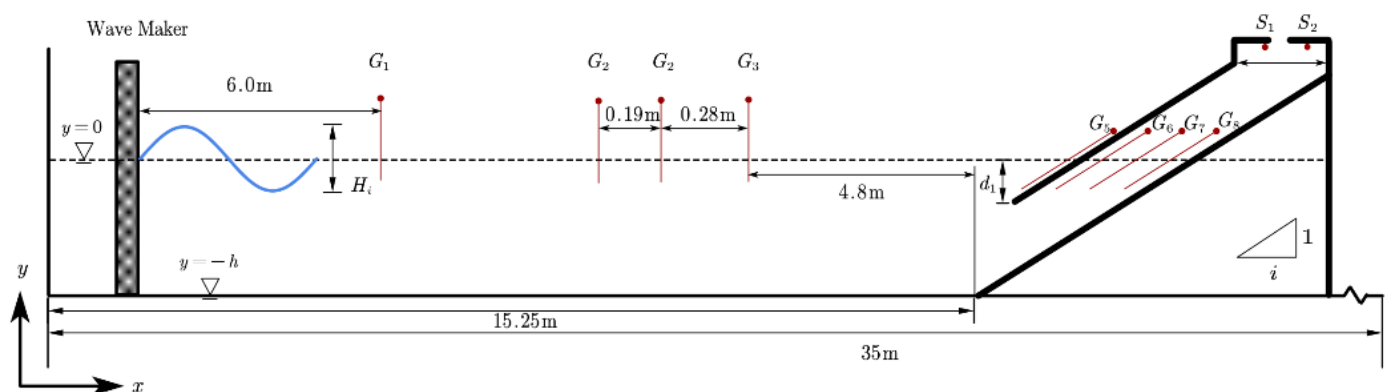


Figure 5. Experimental setup.

The monitoring results of the free liquid surface elevation and relative pressure in the OWC air chamber under three different mesh sizes are shown in Figure 6. It can be observed that the average liquid elevation and relative pressure in the chamber are quite similar for the medium and fine meshes. In contrast, the coarse mesh yields higher results. Considering both computational efficiency and accuracy, the medium mesh size was selected as the resolution for the mesh surrounding the OWC.

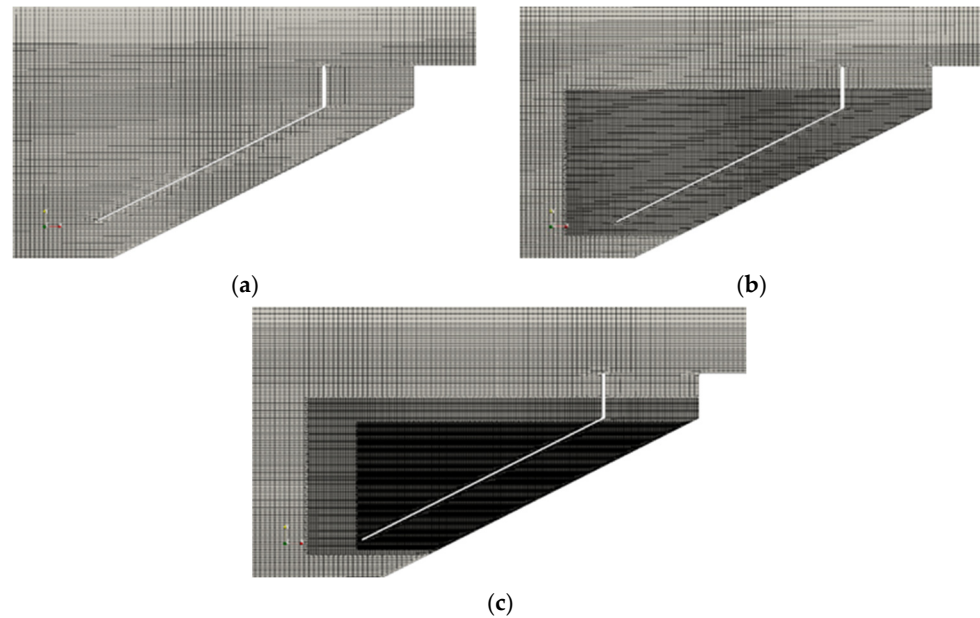


Figure 6. The grid discretization scheme around the structure. (a) Coarse, (b) medium, and (c) fine.

By comparing the numerical calculation results using the porous media model with the experimental results, as observed in Figure 7, we find that the numerical simulation of the wave climbing process is relatively accurate, and that the characteristics of the oscillating free surface are also reflected. When $H_i = 0.03$ m and $T = 1.0$ s, there is a certain deviation in the peak and trough values of the pressure curve in the air chamber. This is due to the relatively low pressure in the chamber, making the pressure fluctuations caused by experimental errors more pronounced at this point.

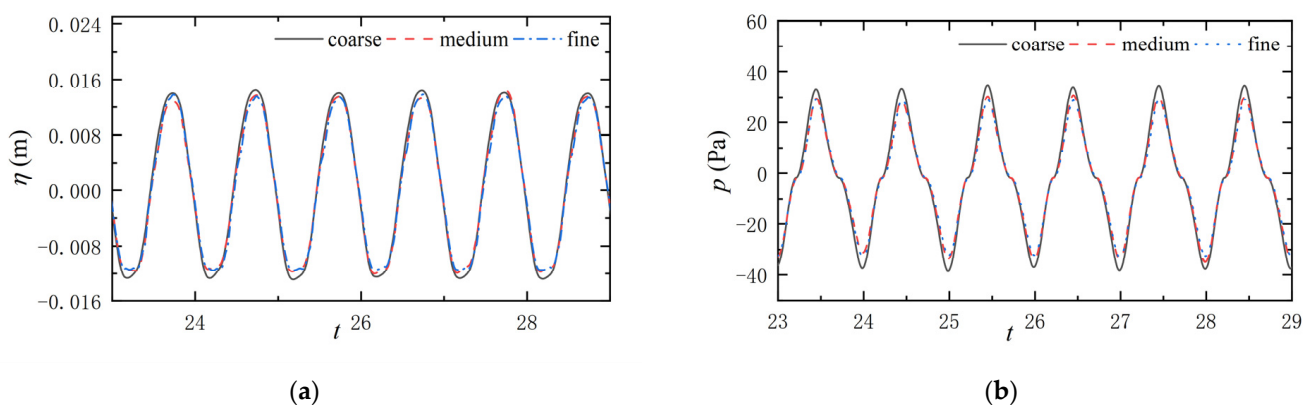


Figure 7. The variation of the free surface (a) and the corresponding pressure values (b) in the air chamber under different grids.

4. Experimental and Simulation Results

This section analyzes the effects of incident wave height and period on the hydrodynamics around the OWC using an experimental and a numerical approach. The dimensionless parameters studied include the wave energy absorption rate, ζ ; reflection coefficient, C_r ; peak and trough values of the free surface oscillations at the front wall, R_{u_front}/H_i ; and peak and trough values at the rear wall R_{u_back}/H_i .

4.1. Comparison of Hydrodynamic Parameters

Figure 8 illustrates the variation of hydrodynamic performance parameters of the sloped OWC device under different incident wave conditions. From Figure 8a, it can be observed that, when the water level is 0.40 m and the dimensionless frequency $\omega^2 g/h \leq 0.63$, higher wave heights result in lower wave energy conversion efficiency, while the opposite is true for $\omega^2 g/h > 0.63$. Figure 8b shows that, when $\omega^2 g/h \leq 0.82$, the wave height has little effect on wave reflection; however, when $\omega^2 g/h > 0.82$, larger wave heights lead to a smaller reflection coefficient. This phenomenon indicates that stronger nonlinear waves result in more severe wave breaking, leading to greater energy loss.

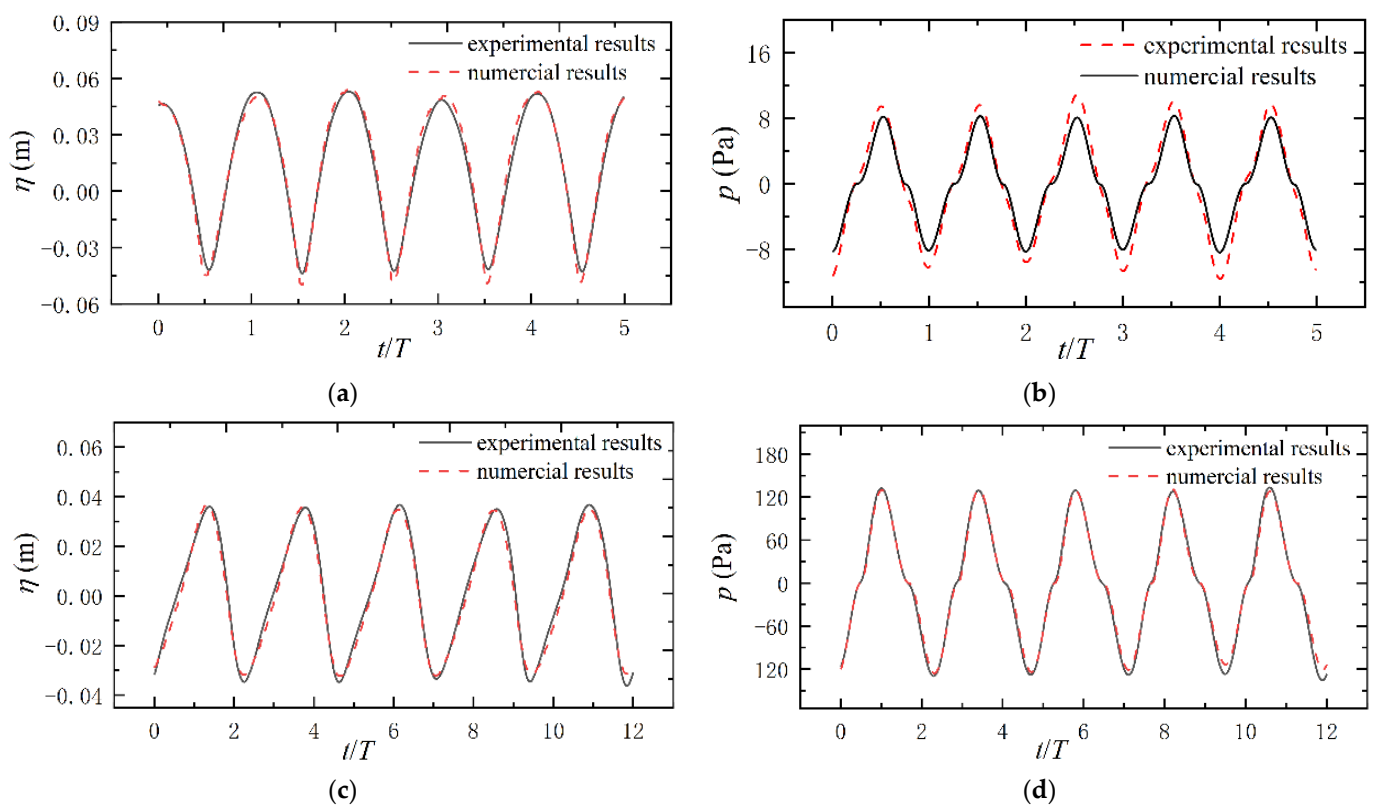


Figure 8. The comparison of numerical values of the free surface at the front wall of the OWC device and the relative pressure in the air chamber with experimental results. (a) Surface elevation, (b) pressure drop ($H_i = 0.03$ m, $T = 1.0$ s), (c) surface elevation, and (d) pressure drop ($H_i = 0.03$ m, $T = 2.4$ s).

Figure 9c reveals that the air damping at the top of the chamber does not affect the trend of hydrodynamic parameter changes at the front wall. Within the studied frequency range, the incident wave height has a minimal effect on the relative increase at the front wall. When $\omega^2 g/h \leq 0.63$, the wave height has little impact on the trough values of the front wall's free surface, while for $\omega^2 g/h > 0.63$, stronger nonlinearities in the incident waves cause the troughs at the front wall to rise closer to the bottom of the front wall. From Figure 9d, the peak and trough values of the free surface changes at the rear wall can be approximately considered symmetric about the x axis and are insensitive to the

strength of the incident wave's nonlinearity. When $\omega^2 g/h \leq 0.82$, larger wave heights lead to smaller relative amplitudes at the rear wall's free surface. Notably, although in some conditions higher incident wave heights correspond with smaller relative amplitudes of the free surface, the actual amplitudes are always relatively large.

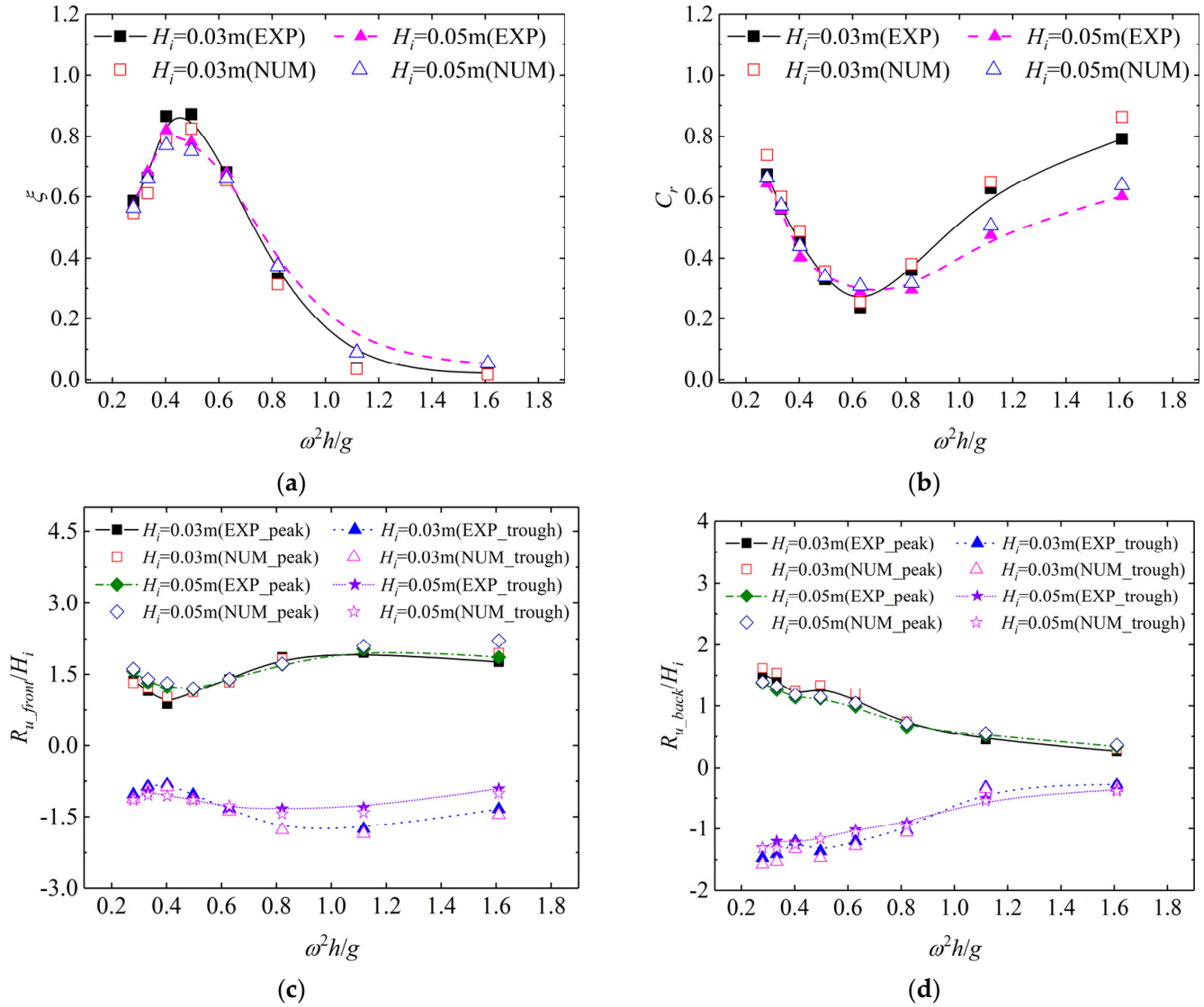


Figure 9. Comparison between experimental and numerical results for the OWC device. (a) Wave energy absorption efficiency, (b) reflection coefficient, (c) peak and trough values of the free surface oscillations at the front wall, and (d) peak and trough values of the free surface oscillations at the back wall ($h = 0.40$ m).

As shown in Figure 10, when the water level is 0.45 m, the overall trend is similar to that at a water level of 0.40 m. The critical frequency for wave energy conversion efficiency decreases from 0.63 to 0.56, while the boundary frequency for the reflection coefficient increases from 0.63 to 0.71. The critical frequency for the wave height's trough values at the front wall changes from 0.63 to 0.45. The critical frequencies for the peak and trough values of the free surface changes at the rear wall shift from 0.82 to 0.71. The differences in critical frequencies caused by changes in water level are attributed to the different drafts of the front wall, which in turn affect the resonance frequency of the water column between the two plates.

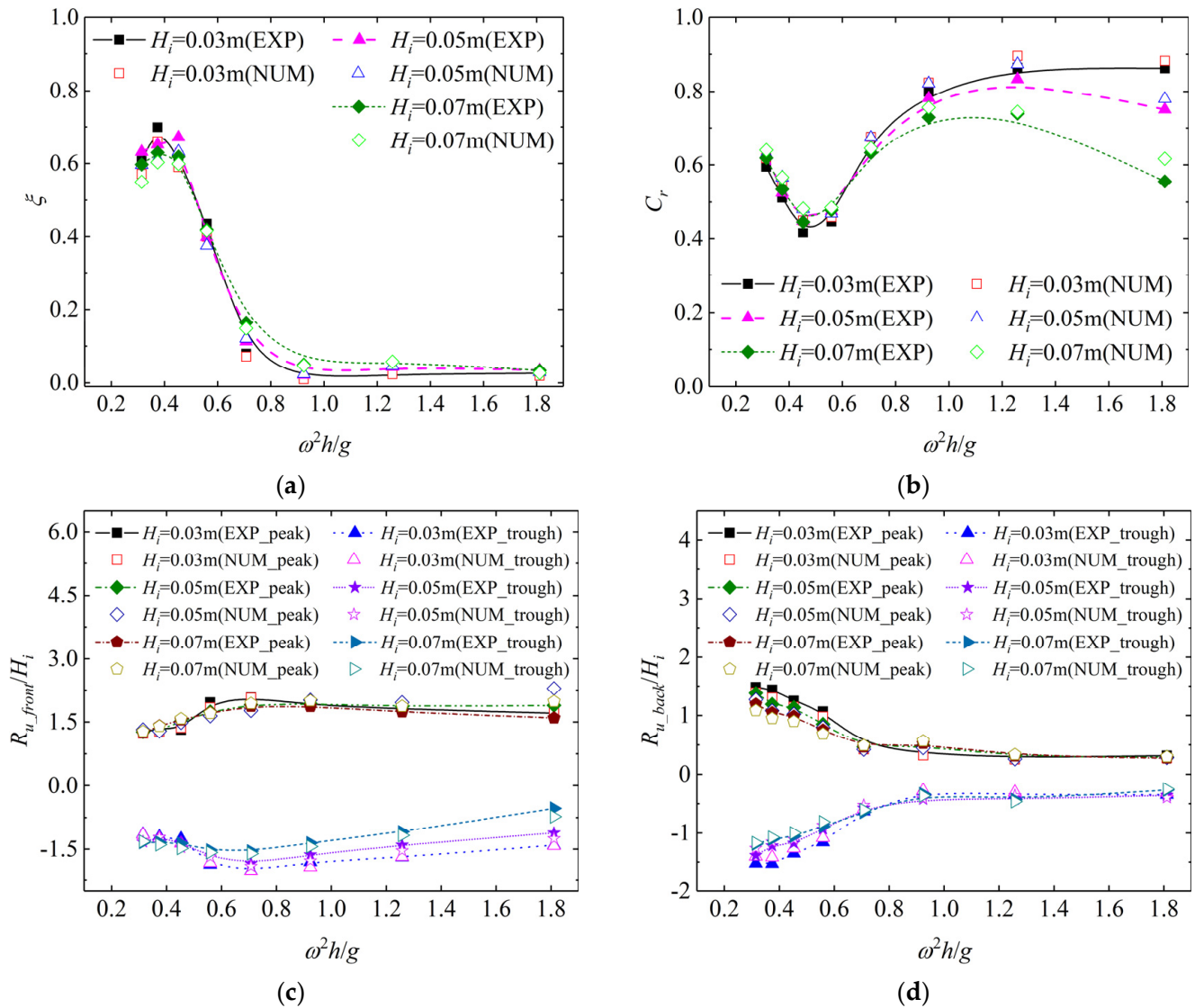


Figure 10. Comparison between experimental and numerical results for the OWC device. (a) Wave energy absorption efficiency, (b) reflection coefficient, (c) peak and trough values of the free surface oscillations at the front wall, and (d) peak and trough values of the free surface oscillations at the back wall ($h = 0.45\text{ m}$).

Both the peak values of the curves and the effective frequency bandwidth indicate that the sloped OWC device has a significantly better capacity to capture wave energy at lower water levels. This is because, at lower water levels, the draft of the front wall is smaller, allowing wave energy to enter the air chamber more easily. It is worth noting that, compared with the condition with a water depth of 0.45 m , the smaller front wall draft at a water depth of 0.4 m allows more energy to enter the chamber near the resonance frequency. This leads to intensified oscillations of the liquid surface inside the device, resulting in significant vortex dissipation at the bottom of the front wall and increased wave breaking at the rear wall. This portion of energy cannot be captured by the device, causing a deviation between the non-dimensional frequency corresponding with the maximum reflection coefficient and that of the maximum efficiency, as shown in Figure 9.

4.2. Supplementary of Numerical Results

In Section 4.1, we see a total of 240 data points composed of 40 groups and 6 hydrodynamic parameters, with 90.4% of the data showing an error of no more than 10%. There are discrepancies between the experimental and numerical results, attributed to factors such as the limited precision of the monitoring instruments, the impact of three-dimensional effects on the results, errors introduced by using the porous media model, and the numerical model's inability to accurately capture turbulent energy dissipation. Overall, the hydrodynamic characteristics of the sloped OWC device indicated by both the experimental and numerical results are consistent. The numerical simulation effectively illustrates the hydrodynamic response of such structures, and this section will use numerical simulations to supplement the experimental results. The meanings of the symbols to be used below are as follows: C_l represents energy dissipation coefficient, $|\Delta p|_{\max}$ represents the maximum pressure difference on both sides of the front wall, and H_{column}/H_i represents the relative amplitude of the water column in the air chamber.

4.2.1. Impact of the Draft at Front Wall

The incident wave height H_i is set to 0.05 m, the chamber width a is 0.2 m, the front wall thickness b is 0.01 m, the slope $i = 2$, and the depth of the rear wall is equal to the water depth. The draft of the front wall is set to 0.05 m, 0.10 m, 0.15 m, and 0.20 m. Figure 11 illustrates the impact mechanism of different front wall draft depths on the hydrodynamic characteristics of the sloped OWC device. From Figure 11a,b, it can be observed that a shallower draft of the front wall results in a smaller reflection coefficient and a higher wave energy conversion efficiency. This is because a deeper draft obstructs wave energy from entering the air chamber. As the wave period increases, the influence of the front wall draft on wave reflection diminishes, and the conversion efficiency tends to become consistent. The peak frequency corresponding with the absorption efficiency decreases with an increasing draft depth, indicating that the velocity resonance frequency of the water column decreases as well.

In actual sea conditions, wave frequencies typically fall within a range rather than being a specific single frequency. It is evident that a shallower draft of the front wall leads to a broader effective frequency bandwidth. However, considering that too shallow a draft may cause direct communication between the gas in the air chamber and the external air at the front wall, resulting in air leakage that is detrimental to wave energy conversion, the subsequent design fixes the front wall draft at 2/9 h.

Comparing Figure 11c,d, it is observed that the energy dissipation coefficient and the maximum pressure difference on both sides of the front wall exhibit a synchronous variation pattern. The difference in pressure between the two sides of the front wall is attributed not only to the phase difference in the oscillation of the water on either side but also to the generation of vortices at the bottom. This suggests that a significant portion of energy dissipation is due to the vortices formed at the base of the front wall.

From Figure 11e, the relative amplitude of the water column in the air chamber increases as the frequency decreases, indicating that the displacement resonance frequency of the water column occurs at lower frequencies. Combining the analysis from Figure 11a,f, it is found that, when wave energy absorption efficiency is higher, the relative increase at the front wall is smaller. This indicates that coupling the wave energy absorption device with the breakwater helps reduce wave impact.

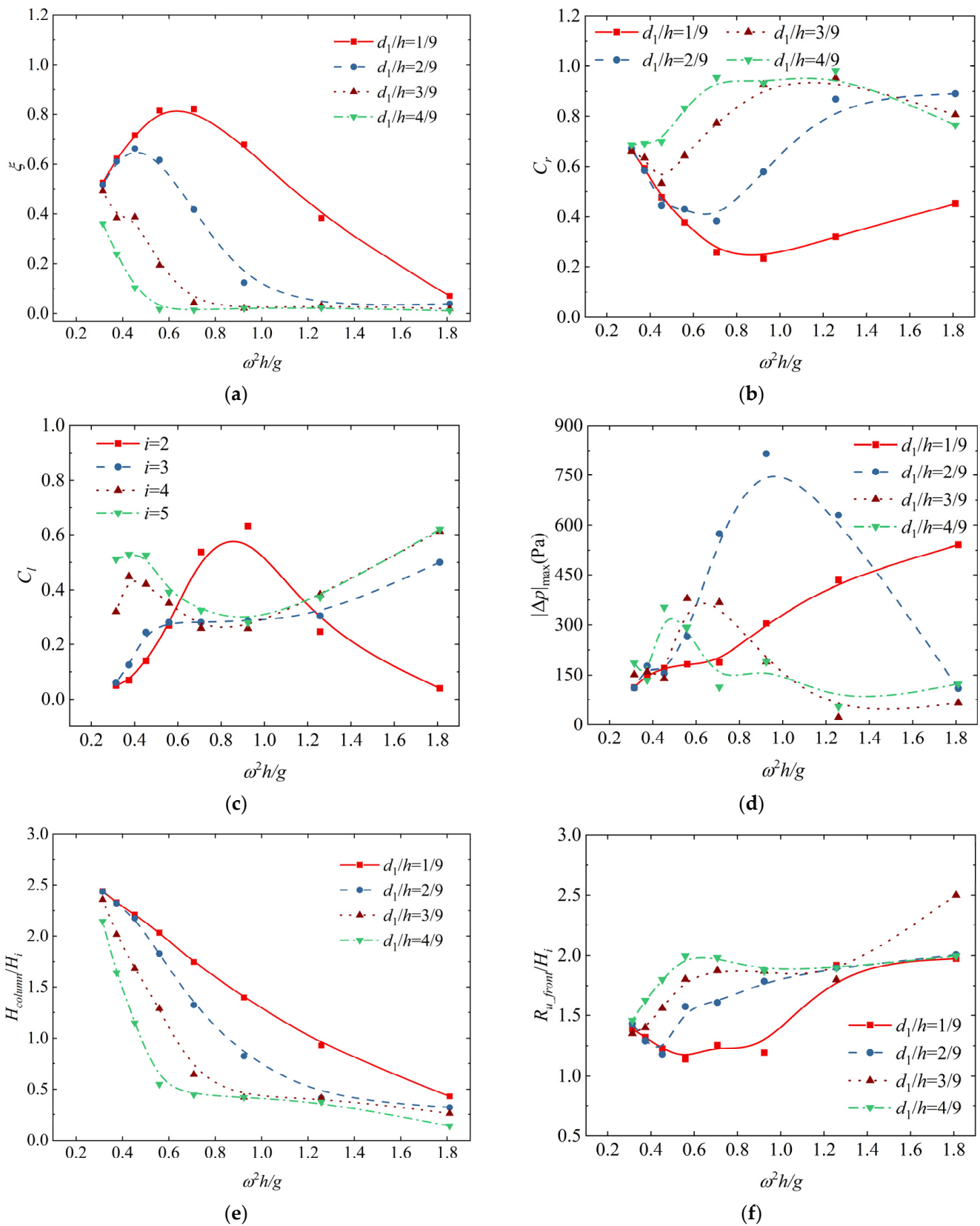


Figure 11. The impact of the front wall draft depth on the hydrodynamic characteristics of the sloped OWC device. (a) Wave energy absorption efficiency, (b) reflection coefficient, (c) energy dissipation coefficient, (d) maximum pressure difference on both sides of the front wall, (e) relative amplitude of the water column in the air chamber, and (f) relative wave run-up at the front wall.

4.2.2. The Impact of Chamber Width

The incident wave height H_i is set to 0.05 m, the draft of the front wall d is 0.1 m, the front wall thickness b is 0.01 m, the slope i is 2, and the depth of the rear wall is equal to the water depth. Figure 12 illustrates the impact mechanism of different chamber widths on the hydrodynamic characteristics of the sloped OWC device.

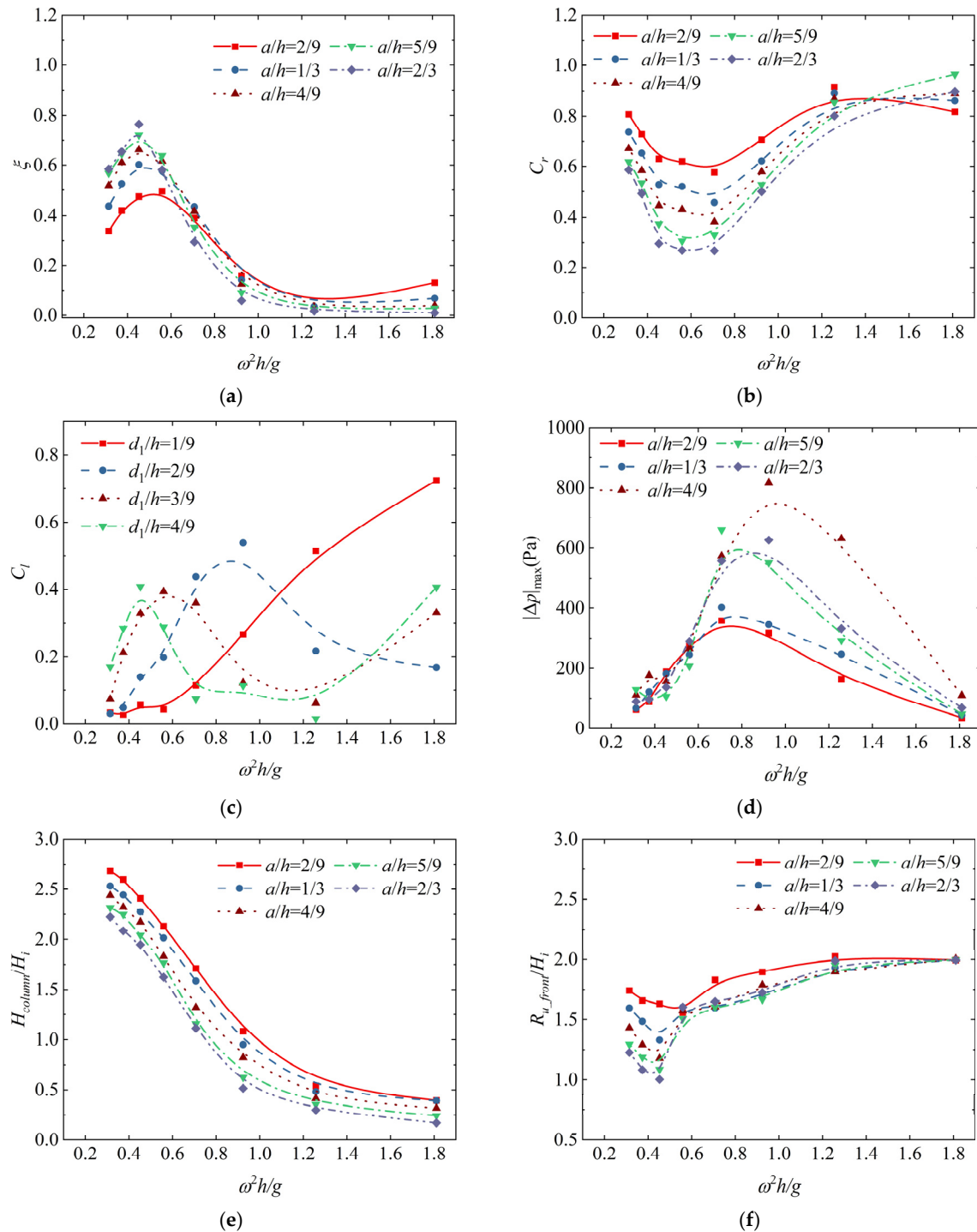


Figure 12. The impact of chamber width on the hydrodynamic characteristics of the sloped OWC device. (a) Wave energy absorption efficiency, (b) reflection coefficient, (c) energy dissipation coefficient, (d) maximum pressure difference on both sides of the front wall, (e) relative amplitude of the water column in the air chamber, and (f) relative wave run-up at the front wall.

A portion of the incident wave energy is absorbed by the OWC device, another portion is converted into reflected wave energy, and some is dissipated due to viscosity. From Figure 12a,b, it can be observed that the wave energy absorption efficiency first increases and then decreases as the period increases, corresponding with the reflection coefficient. For short-period waves, the energy conversion efficiency decreases as the chamber width increases, remaining below 0.5. In contrast, for long-period waves, the energy conversion efficiency increases with wider chamber widths. The peak frequency of absorption efficiency shifts to lower frequencies with increasing chamber width, indicating that a larger chamber width results in a lower resonance frequency of the water column.

The curves for wave energy conversion efficiency at $a = 0.25$ and $a = 0.30$ are relatively close, but the reflection coefficient curves show significant differences. This suggests that increasing the chamber width beyond a certain point can exacerbate the oscillation of the water column inside, leading to greater viscous dissipation. Kim, Nam et al. [32] also found through experimental studies that reducing the oscillation of the fluid inside the chamber benefits energy conversion performance. Considering the balance between wave energy conversion efficiency and construction costs, a chamber width of $a = 5h/9$ is chosen.

Combining Figure 12c,d, for the same device, the maximum pressure difference on both sides of the front wall shows a similar variation pattern to the energy dissipation coefficient. The energy dissipation coefficient peaks around a period of 1.4 s. However, for different devices, when $a > 0.5$, although the vortex intensity at the base of the front wall is smaller than that for $a = 0.2$, the surface oscillation of the water column in the chamber is more intense, resulting in a relatively higher energy dissipation coefficient. From Figure 12e, it is evident that the average amplitude of the water column in the chamber increases as the frequency of the incident wave decreases, gradually approaching the resonance frequency of the water column's amplitude, which is not equal to the resonance frequency of its velocity. Analyzing Figure 12a,f together reveals that the relative increase at the front wall decreases as wave energy conversion efficiency increases. This indicates that the absorption and conversion of wave energy help mitigate the impact of waves on offshore structures.

4.2.3. The Impact of Slope

The incident wave height H_i is set to 0.05 m, the draft of the front wall d is 0.1 m, the front wall thickness b is 0.01 m, the chamber width a is 0.25 m, and the depth of the rear wall is equal to the water depth. Considering four slope cases $i = 1, 2, 3, 4, 5$, the slope variations are illustrated by the dashed lines in the Figure 13. This describes the impact of different slopes on the hydrodynamic characteristics of the sloped OWC device.

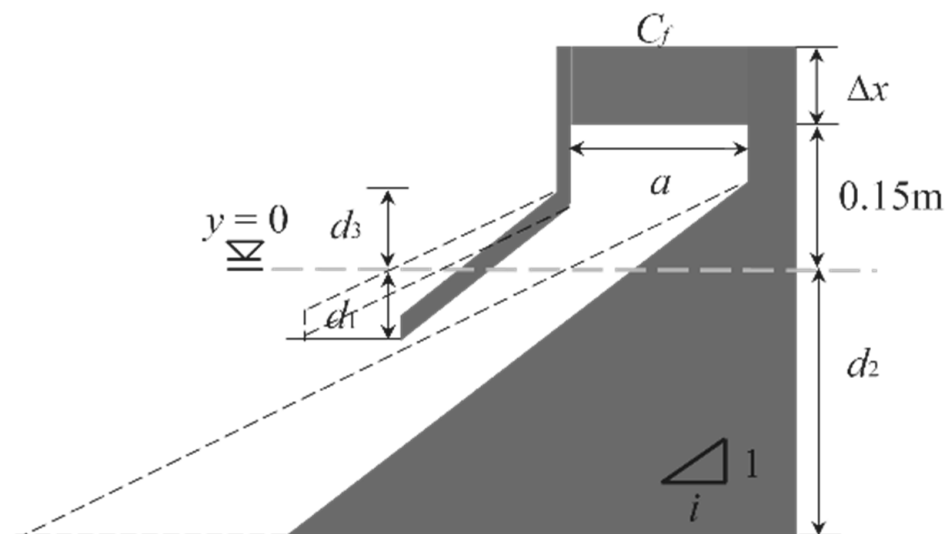


Figure 13. Schematic diagram of slope variation for sloped OWC device.

From Figure 14a, it can be observed that, in the high-frequency range, wave energy conversion efficiency increases with the slope, while in the low-frequency range, it decreases as the slope increases. When $i = 2$, the peak conversion efficiency is the highest, and the effective frequency range is also the widest. In the cases of $i = 4$ and $i = 5$ the wave energy conversion efficiency curves are very close, indicating that beyond a certain slope range, the impact on wave energy conversion efficiency diminishes. The interaction between the incident wave and the sloped OWC device is also a process of energy conversion, where part of the incident wave energy is converted into aerodynamic energy, some is reflected, and some is dissipated. The reasons for energy dissipation include vortices, oscillations of the water column surface, wave breaking, and viscous dissipation. From Figure 14b, for steep slopes $i < 3$, the reflection coefficient initially decreases and then increases with increasing incident wave frequency. For gentler slopes $i = 3$, the reflection coefficient is less affected by the incident wave frequency, the steeper the slope, the smaller the reflection coefficient. Looking at Figure 14c, the wave energy conversion efficiencies for $i = 4$ and $i = 5$ are nearly identical, but the energy dissipation coefficient is larger for $i = 5$, resulting in a lower reflection coefficient. For $i = 2$, when the non-dimensional frequency of the incident wave is in the range of $[0.71, 0.92]$, stronger vortices are generated at the bottom of the front wall, leading to greater energy dissipation, which corroborates with the maximum pressure difference on both sides of the front wall bottom (as shown in Figure 14e). When $i \geq 3$ and the incident wave frequency is higher, the energy dissipation coefficient is larger, mainly due to higher wave run-up and wave breaking at the top. At lower incident wave frequencies, energy dissipation is primarily due to the intense oscillation of the water column surface and vortices at the bottom of the front wall.

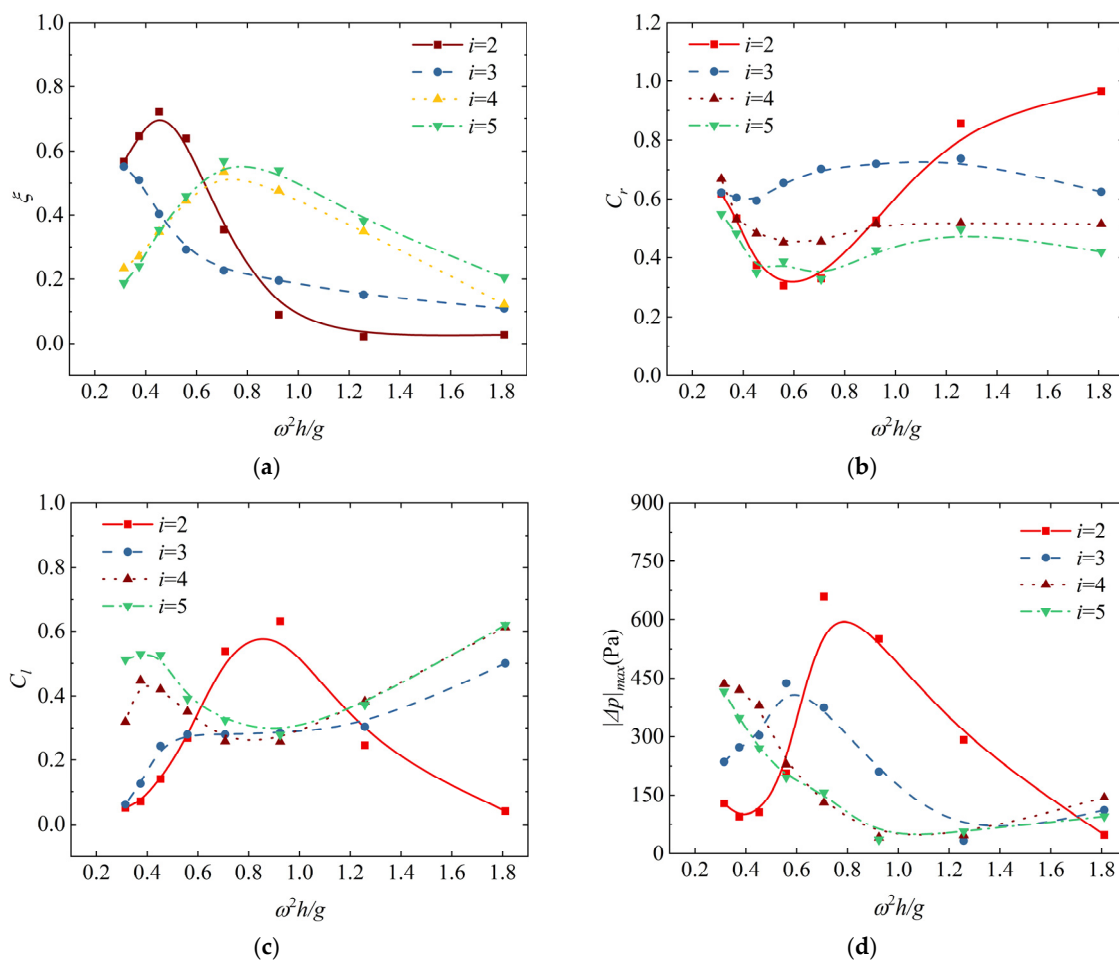


Figure 14. Cont.

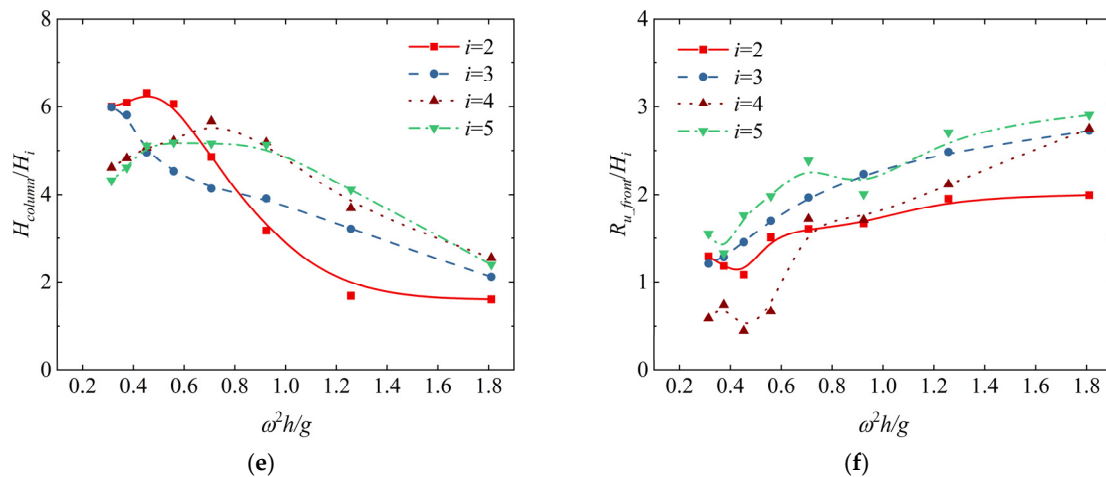


Figure 14. The impact of slope on the hydrodynamic characteristics of the sloped OWC device. (a) Wave energy absorption efficiency, (b) reflection coefficient, (c) energy dissipation coefficient, (d) maximum pressure difference on both sides of the front wall, (e) relative amplitude of the water column in the air chamber, and (f) relative wave run-up at the front wall.

The pattern of the relative amplitude of the water column in the chamber closely aligns with the wave energy conversion efficiency. The relative amplitude of the water column reflects the flow rate of air entering and exiting the chamber; under the same oscillation period, a larger amplitude corresponds with a higher airflow velocity, resulting in greater pneumatic energy. Figure 14f illustrates the impact of slope on the relative run-up of the front wall. The run-up of the front wall increases with the frequency of the incident wave. Except for the case of $i = 4$, a greater slope results in a larger relative run-up of the front wall. Within the studied frequency range, the slope of $i = 2$ exhibits a relatively small run-up, effectively reducing overtopping phenomena. Considering wave energy conversion efficiency and engineering safety, $i = 2$ is identified as the optimal slope.

5. Conclusions

Our study initially conducted physical experiments in a wave tank to investigate the hydrodynamic characteristics of the sloped oscillating water column (OWC) device under varying incident wave heights and tide conditions. Subsequently, a porous medium numerical model was established. By comparing the numerical results with experimental data, it was found that the porous medium model accurately simulates the wave climbing process on the front and rear walls, wave energy conversion efficiency, and wave reflection. Building on this, the effects of geometric features such as front wall draft depth, chamber width, and slope on the hydrodynamic performance of the sloped OWC device were further explored. The following conclusions were drawn from these investigations:

For land-based sloped oscillating water column (OWC) devices, at low tide, the reduced draft of the front wall significantly enhances wave energy capture. However, the proximity of the front wall's base to the wave surface raises the free surface, increasing the likelihood of water piling up. When the dimensionless wave frequency $\omega^2 h/g \geq 0.45$, the rear wall's run-up is noticeably higher than in high tide conditions. Therefore, it is crucial to design an appropriate chamber height to prevent the water column from impacting critical mechanical structures.

The overall impact of wave height on the wave energy conversion efficiency of sloped oscillating water column (OWC) devices is minimal. In the low-frequency range, higher wave heights are less favorable for energy extraction, while the opposite is true in the high-frequency range. For low-frequency waves, wave height has a minor effect on reflection; however, for high-frequency waves, increased wave height correlates with reduced reflection. Strong nonlinear waves can lead to significant wave breaking, resulting in greater energy loss. Additionally, the relative change in the free surface at the rear wall

is insensitive to wave height. It is important to note that larger wave heights inherently possess more energy, leading to greater energy extraction and increased wave run-up.

A smaller front wall draft depth results in a wider efficient frequency bandwidth, with the velocity resonance frequency shifting toward the low-frequency range. Moreover, the velocity resonance frequency and displacement resonance frequency of the water column within the chamber are distinct; a larger water column amplitude does not necessarily indicate higher wave energy conversion efficiency. It is possible that the displacement resonance frequency of the water column is below the frequency range under investigation.

Increasing the width of the chamber leads to a decrease in the water column's velocity resonance frequency. However, after a certain point, further widening the chamber exacerbates the oscillation of the water column and increases viscous dissipation, which is detrimental to wave energy conversion. Keeping the water surface as flat as possible, a larger chamber width results in a greater water column mass, which enhances wave energy extraction.

The slope significantly impacts the performance of the sloped OWC wave energy conversion device. As the slope increases, the bandwidth of the efficient frequency range decreases, and the peak wave energy extraction efficiency also drops. In fact, prior to contacting the front wall, the incident wave undergoes shallow water deformation, resulting in different frequency changes for waves encountering walls of varying slopes. Additionally, changes in the geometric dimensions of the structure alter the resonance mechanisms, making it challenging to generalize the variations in hydrodynamic parameters. Focusing on wave energy conversion efficiency and front wall run-up, the device with a slope of $i = 2$ demonstrates optimal performance.

This study presents an OWC device integrated into a breakwater, utilizing a 2D numerical model. While this approach cannot fully capture the complex interactions between waves and the OWC device in real conditions, the results indicate that the model's accuracy can still provide valuable guidance for engineering design and application.

Author Contributions: Data curation, W.L.; funding acquisition, Z.D.; investigation, T.T. and M.L.; supervision, P.C.; validation, Z.D. and W.L.; writing—original draft, Z.D.; writing—review and editing, T.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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