

Article

The Wave Amplification Mechanism of Resonant Caisson

Jiawei Hao ¹, Dietao Ding ¹, Jiawen Li ^{1,2,3,*} and Ji Huang ^{1,2,3,4,*}

- ¹ School of Naval Architecture and Maritime, Guangdong Ocean University, Zhanjiang 524088, China; vion@stu.gdou.edu.cn (J.H.); 202111442208@stu.gdou.edu.cn (D.D.)
- ² Key Laboratory of Philosophy and Social Science in Hainan Province of Hainan Free Trade Port International Hipping Development and Property Digitization, Hainan Vocational University of Science and Technology, Haikou 570100, China
- ³ Guangdong Provincial Key Laboratory of Intelligent Equipment for South China Sea Marine Ranching, Guangdong Ocean University, Zhanjiang 524088, China
- ⁴ Doctoral Degree Program in Ocean Engineering Technology, National Taiwan Ocean University, Keelung 20224, Taiwan
- * Correspondence: jiawen-li@gdou.edu.cn (J.L.); huangji@gdou.edu.cn (J.H.)

Abstract: Previous studies have introduced a resonant caisson designed to enhance wave energy extraction in regions with low wave energy density; however, its operational mechanism remains poorly understood. This paper seeks to elucidate the operational mechanism of the resonant caisson by leveraging Star-CCM+ for Computational Fluid Dynamics (CFD) simulations, focusing on the influence of guides and their dimensions on the water levels, flow velocities, and vortex dynamics. The findings demonstrate the remarkable wave-amplification capabilities of the resonant caisson, with the maximum amplification factor reaching 2.31 at the calculated frequency in the absence of guides. Incorporating guides and expanding their radii substantially elevate the flow rates, accelerate the water currents, and alter the vortex patterns, thereby further enhancing the amplification factor. This study will provide a reference for optimizing the design of resonant caissons and wave energy converters based on resonant caissons, thus promoting the effective use of wave energy resources.

Keywords: resonant caisson; guides; water level; flow velocity; vortex



Citation: Hao, J.; Ding, D.; Li, J.; Huang, J. The Wave Amplification Mechanism of Resonant Caisson. *J. Mar. Sci. Eng.* **2024**, *12*, 1038. <https://doi.org/10.3390/jmse12071038>

Academic Editors: Elizaldo Domingues Dos Santos and Liércio André Isoldi

Received: 27 May 2024
Revised: 17 June 2024
Accepted: 19 June 2024
Published: 21 June 2024



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1. Introduction

The vast expanse of the ocean serves as a rich reservoir of energy, with wave energy standing out for its high energy density, significant storage capacity, and minimal ecological footprint [1–3]. Therefore, it presents considerable potential for development [4–6]. Nonetheless, the distribution of wave energy density varies greatly across different temporal and spatial dimensions. In regions characterized by low wave energy density, such as specific low latitudes even during the summer monsoon, energy levels are notably diminished compared to the winters in higher latitudes [7]. As a result, past wave energy projects have placed significant emphasis on site selection to optimize wave energy density [8–10]. Consequently, enhancing wave energy density has become critical to meet the demands of wave energy development. In tackling this challenge, some researchers have introduced the concept of a resonant caisson [11], which aims to amplify incident wave heights and address the challenges posed by low wave energy density.

The origins of the resonant caisson can be traced back to the phenomenon of harbor basin resonance. Harbor basin resonance refers to the intense water oscillation within a harbor, triggered when incoming wave frequencies closely align with the harbor's resonance frequency [12,13]. This vigorous oscillation can cause moored vessels to sway at a low frequency, disrupt cargo operations, reduce efficiency, and potentially lead to ship damage. Avoiding harbor basin resonance is crucial [14–16]. Previous studies have explored various aspects of harbor basin resonance, including the mechanics of the phenomenon [17,18], the effects of different wave types on resonance [19–21], numerical quantification of wave

height amplification in harbors [22,23], and strategies to mitigate resonance effects effectively [24,25]. While much attention has been given to the negative impacts of harbor basin resonance, the resonant caisson aims to harness these adverse effects. Through innovative structural design, the resonant caisson actively induces resonance within its structure, leading to wave amplification and increased wave energy density. It is important to note that, while the resonant caisson draws inspiration from harbor basin resonance, it operates in an open water environment, distinct from the semi-open water conditions of harbor basins with defined boundary characteristics. In the context of circular harbor basins, resonance in semi-open water may be subject to reflection and interference from neighboring structures or boundaries, resulting in a certain degree of constraint on the frequency, amplitude, or energy propagation of the resonance effect. In contrast, within the resonant caisson positioned in fully open water, the expression of resonance effects is less restricted, potentially yielding a more prominent and persistent resonance phenomenon. Similarly, if we focus on the harbor resonance of a semi-enclosed island, we will obtain results similar to those of a resonant caisson [26]. The layout of such a harbor is actually analogous to the structure of a resonant caisson. The presence of the island exacerbates the resonance within the harbor, mirroring the role played by a resonant caisson.

Currently, there exists a paucity of research on resonant caissons. Lin et al. [27] employed the OpenFOAM open-source code to investigate wave amplification within a caisson under varying wave incidence angles and wave numbers, analyzing the waveform characteristics within the caisson and validating the practical utility of the resonant caisson. Huang et al. [28] proposed a generalized finite difference method based on potential flow theory, conducting a series of studies on the impact of caisson opening angles and wave incident angles on resonance in the frequency domain, accurately evaluating the resonant peak wave frequency. While previous studies have examined factors influencing caisson wave amplification, there is still a gap in understanding the fundamental mechanisms through which the resonant caisson operates.

The primary purpose of a resonant caisson is essentially the WEC–resonant caisson system. The main function of the resonant caisson is to induce resonance within its structure, thereby increasing the energy density of waves and improving the power generation efficiency of the system. Our ultimate goal is to design an efficient and reliable WEC–resonant caisson system. In order to achieve a structurally sound design for this system and maximize its working efficiency, it is crucial to elucidate the wave-amplification mechanism of the resonant caisson.

To deepen our understanding of the resonant caisson for enhanced efficiency and reliability, this study investigates wave amplification within the caisson using Star-CCM+. Our objective is to precisely quantify the caisson's wave amplification capabilities and elucidate the mechanism behind wave amplification through the resonance phenomena. The focus is on the functionality of the guides, exploring the impact of guide presence or absence and guide radius on the resonance phenomenon. The subsequent sections are structured as follows: Section 2 outlines the resonant caisson parameters, governing equations, mesh division, and boundary conditions; Section 3 conducts convergence analysis and rigorously validates the results. In Section 4, the amplification factor is defined, and the wave amplification capacities of three caisson types are quantified. Section 5 elaborates on the wave-amplification mechanism of the caisson and the operational mode of the guide through water-level contour maps, velocity cloud maps, and vorticity diagrams. Finally, the article concludes with a comprehensive summary.

2. Numerical Model

2.1. Physical Model

The primary function of the resonant caisson is to induce resonance within its structure to enhance wave energy density, thereby improving power-generation efficiency. Additionally, integrating the wave energy converter (WEC) within the caisson can enhance the overall device's resilience to wind and waves. In fact, the WEC is a device designed to

capture and convert wave energy into electricity through a specific structure. According to statistics from the European Marine Energy Centre (EMEC), there are currently dozens of proposed WEC designs. Considering the geometric characteristics of the resonant caisson, the point absorber type of WEC is deemed most suitable within the WEC–resonant caisson system. Further discussion of specific details will be reserved for future research. Figure 1 depicts two variations of the resonant caisson: The unguided caisson depicted in Figure 1a features an inner diameter of 9.14 m, an outer diameter of 9.71 m, an opening angle of 60 degrees, and a draft of 12.19 m. On the other hand, Figure 1b showcases the guided caisson with a guide radius of a_g , while maintaining the same parameters as the unguided caisson. For clarity, the unguided caisson is denoted as caisson A, the guided caisson with $a_g = 0.5a$ is labeled as caisson B, and the guided caisson with $a_g = a$ is identified as caisson C.

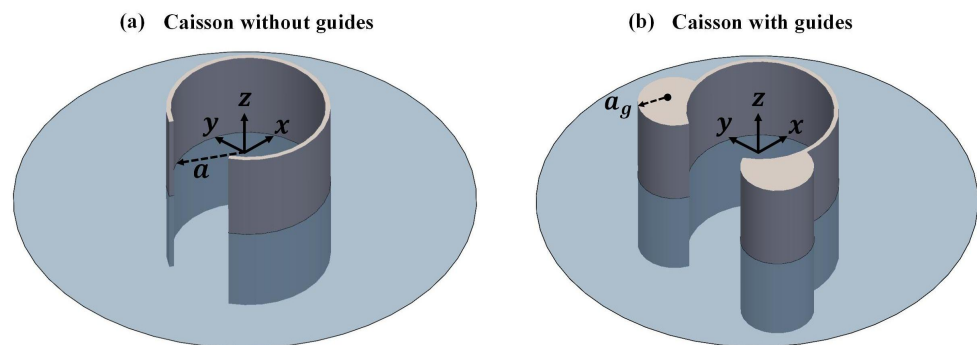


Figure 1. Schematic structure of resonant caissons.

2.2. Mathematical Model

2.2.1. Governing Equation

The objects of study in this paper are all incompressible viscous fluids whose basic governing equations are the continuity equation, the momentum conservation equation, and the energy conservation equation. The vector forms of the continuity equation and Navier–Stokes equation are as follows:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

$$\partial \rho \mathbf{u} / \partial t + \nabla \cdot (\rho \mathbf{u} \mathbf{u}^T) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{u}) + \rho \mathbf{g} \quad (2)$$

where $\mathbf{u}$ is the velocity vector, t is time, ∇ is the gradient notation with $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right)$, ρ is the density of the fluid, μ is the dynamic viscous coefficient of the fluid, P is the total pressure, and $\mathbf{g}$ is the local gravitational acceleration.

2.2.2. Turbulence Model

A dual-range turbulence model (*Realizable $k - \varepsilon$*) has been employed in this study, incorporating facets associated with rotation and curvature along with a revised dissipation rate equation in contrast to conventional turbulence models ($k - \varepsilon$). This model effectively captures the dynamics of spinning homogeneous shear flows, planar mixing flows, planar jets, circular jets, fully developed flows in tubes, and backstep flows. The transport equations governing the turbulent kinetic energy and turbulent dissipation rate play a crucial role in calculating turbulent vortex viscosity. These transport equations are outlined as follows:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \bar{\mathbf{v}}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho(\varepsilon - \varepsilon_0) + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla \cdot (\rho\varepsilon\mathbf{\bar{v}}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_z} \right) \nabla \varepsilon \right] + \frac{1}{T_e} C_{z1} P_z - C_{zz} f_2 \rho \left(\frac{\varepsilon}{T_e} - \frac{\varepsilon_0}{T_0} \right) + S_z \quad (4)$$

It should be noted that the *Realizable* $k - \varepsilon$ turbulence model has certain limitations, primarily manifested in the following aspects: (1) the *Realizable* $k - \varepsilon$ turbulence model uses wall functions to handle wall effects, which may introduce errors; (2) it requires high-quality grids; (3) numerical oscillations may occur under highly unsteady flow conditions. In this study, the *Realizable* $k - \varepsilon$ turbulence model is chosen for simulating boundary layer flow and flow with moderate turbulence intensity, as it performs well and is more aligned with the practical issues addressed in this research. Furthermore, this model effectively balances computational cost and accuracy. Hence, the selection of this model is appropriate (as will be validated in the subsequent discussion).

2.2.3. VOF Interface Tracking Model

The monitoring of liquid levels is conducted through the classical Volume of Fluid (VOF) methodology [29], renowned for its proficiency in addressing both steady-state and transient scenarios involving interfaces between air and fluid. This approach is underpinned by the utilization of a volume fraction transport equation to delineate the interface accurately.

$$\frac{\partial}{\partial t} \int_V \alpha_i dV + \oint_A \alpha_i \mathbf{v} d\mathbf{a} = \int_V \left(S_{\alpha_i} - \frac{\alpha_i}{\rho_i} \frac{D\rho_i}{Dt} \right) dV - \int_V \frac{1}{\rho_i} \nabla \cdot (\alpha_i \rho_i \mathbf{v}_{dj}) dV \quad (5)$$

Where a is the surface area vector, v is the mixing (mass-averaged) velocity, $V_{d,i}$ is the diffusion velocity, S_{α} is the custom source term for phase i , and $D\rho/Dt$ is the material or Lagrangian derivative of phase density ρ_i .

2.3. Boundary Conditions and Mesh Division

The pivotal aspect of this study lies in the numerical wave-generation technique implemented using Star-CCM+. As depicted in Figure 2, the wave inlet and the upper and lateral boundaries of the computational domain are defined by velocity inlet boundary conditions. The wave outlet is characterized by pressure outlet boundary conditions, while the bottom boundary and the walls of the resonant caisson are governed by no-slip wall boundary conditions. Furthermore, to mitigate the impact of wave reflections from the pool boundary on wave generation, a damped dissipation zone is established downstream of the computational domain to enhance the accuracy of wave transmission. The momentum source function was derived by Choi and Yoon [30] and Li et al. [31].

To optimize mesh quality, a three-layer mesh transition is established to refine both the representation of the free liquid surface and the flow field in proximity to the resonant caisson. The free liquid surface mesh was discretized using anisotropic techniques, utilizing a 20-layer mesh in the wave height direction and an 80-layer mesh in the wavelength direction. In contrast, the caisson mesh was subjected to isotropic discretization. The dimensions of the computational domain and the specific mesh refinement technique are detailed in Table 1.

Table 1. Computational domain size and mesh encryption method. (The symbol “ λ ” denotes the wavelength of the wave; the parameter “ h ” signifies the water depth; the symbol “ H ” represents the wave height; the symbol “ a ” corresponds to the caisson radius.)

Encryption area	Length	Breadth	Height	Wave absorbing
computational domain	5λ	1.5λ	$2h$	2λ
Encryption area	Height	Encrypted area	Radius	Height
free surface	$1.5H$	caissons	$1.5a$	$1.5h$
free level transition 1	$2.5H$	transition 1	$2.0a$	$1.2h$
free level transition 2	$4.0H$	transition 2	$3.0a$	$1.0h$

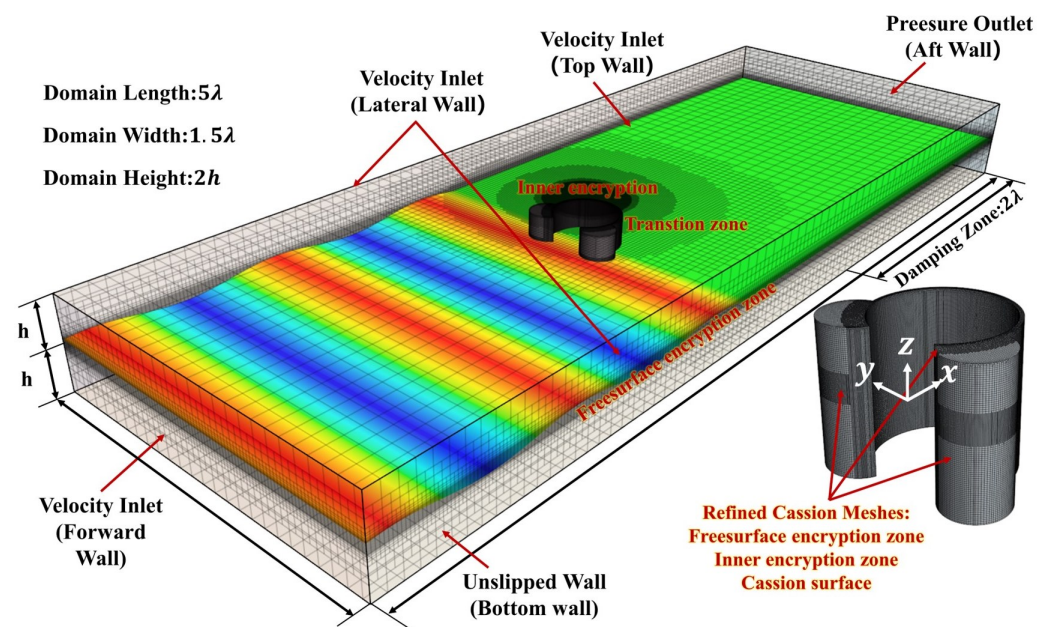


Figure 2. Boundary conditions and meshing (using a caisson with guides as an example).

3. Convergence Analysis and Model Validation

3.1. Convergence Analysis

To address the potential impact of grid size and time step variations on the Computational Fluid Dynamics (CFD) results, convergence assessment relies on the wave height measured at the central point within caisson B. This assessment entails employing a consistent time step across different grid resolutions, with time step convergence analysis contingent upon achieving an optimal grid configuration. The simulation incorporates a Stokes fifth-order wave characterized by specific period and wave height parameters. Numerical computations were conducted on a computing platform featuring a 12th Gen Intel (R) Core (TM) i7-12799 2.1 GHz CPU and 32 G of RAM. Further details concerning the total grid count and time steps for each computational case are outlined in Table 2.

Table 2. Case settings for different total grids and time steps.

No.	Time Steps $\Delta t/s$	Total Grids N/million	No.	Total Grids N/million	Time Steps $\Delta t/s$
Grid 1	0.0050	1.50	Time Step 1	1.50	0.0025
Grid 2		2.00	Time Step 2		0.0050
Grid 3		3.00	Time Step 3		0.0075

Figure 3 depicts the wave heights observed at monitoring points under three different grid configurations and varying time step settings. The simulation results of the three grid

configurations exhibit only minor differences, as do the results for the three time steps. Regarding the grid sizes, the relative error between Grid 1 and Grid 3 is 3.82%, taking Grid 3 as the reference, while the relative error between Grid 2 and Grid 3 is merely 2.18%. As for the time step durations, in relation to Time step 1, the relative error between Time step 3 and Time step 1 is 1.11%, and the relative error between Time step 2 and Time step 1 is only 0.58%. Both the grid and time step errors fall within acceptable ranges. To achieve a balance between computational accuracy and efficiency, specific values for the total grid count and time steps, represented as $N = 1.50$ million and $\Delta t = 0.0050$ s, respectively, have been established for this study.

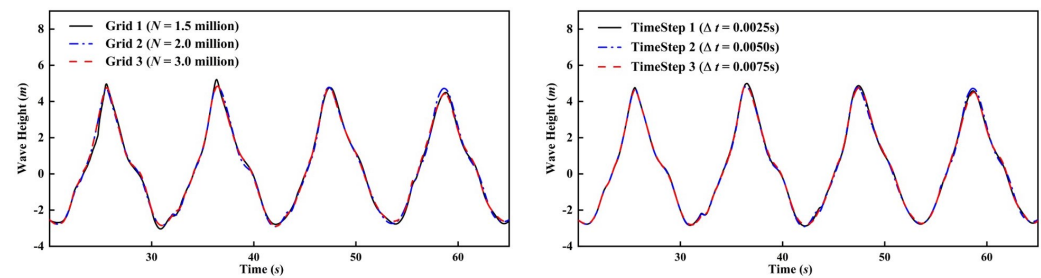


Figure 3. Verification of grid independence alongside validation of time step independence.

3.2. Model Validation

To validate the reliability of the computational model proposed in this study, we replicated an investigation conducted on a circular harbor basin as outlined by Lee [22]. The schematic representation of the basin is presented in Figure 4, illustrating key parameters such as the water depth $h = 1.0\text{ft}$ (0.3048 m), harbor basin radius (considered as the characteristic length) $a = 0.75\text{ft}$ (0.2286 m), and the opening of the harbor basin $\theta_c = 60^\circ$. The computational scope encompasses the first-order resonance mode ($ka = 0 \sim 1$), and we computed the wave heights at point P located at the circle's center for $ka = 0.37$, $ka = 0.45$, $ka = 0.51$, $ka = 0.57$, $ka = 0.62$, and $ka = 0.67$ (where k represents the wave number). The computational numerical results are visualized in Figure 5. These findings reveal a significant agreement between the numerical predictions and the experimental data, thus validating the capability of our numerical model to accurately simulate phenomena related to harbor basin resonance.

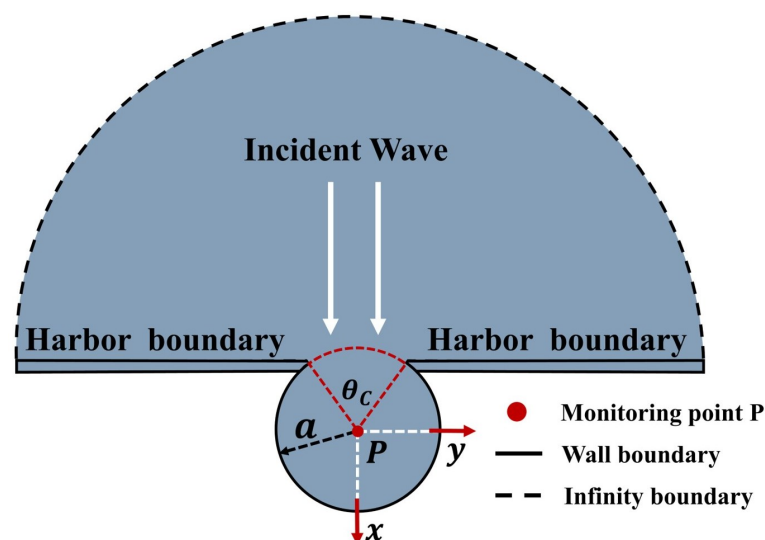


Figure 4. Schematic diagram of a circular harbor basin.

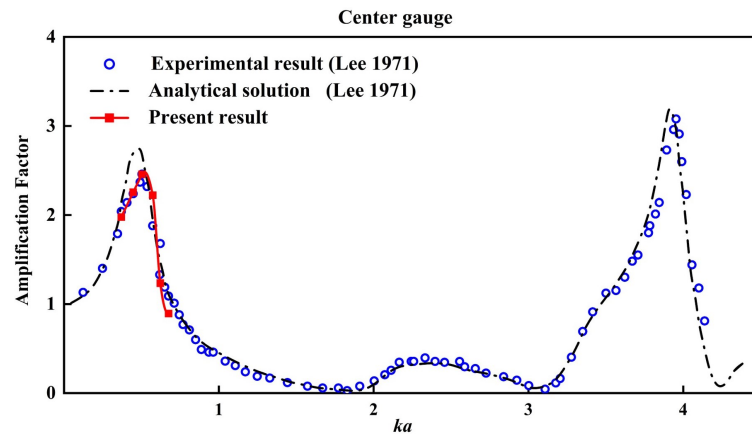


Figure 5. Comparison of the amplification factor at the center gauge with Lee's results [22].

4. Wave Amplification in Resonant Caissons

In this section, we introduce the concept of the amplification factor to quantify the wave-amplification capacity of the resonant caisson. The introduction of resonant caissons prompts the emergence of vortices and backflows internally, fostering a notably complex flow pattern. With a prolonged computation time and iteration count, maintaining a stable wave height within the caisson poses a challenge. Attempting to depict the fluctuating wave height within the caisson throughout the entire simulation duration with a solitary value becomes impractical. Consequently, we employed the quadratic averaging method to ascertain the amplification factor. Figure 6 illustrates the positioning of five internal wave height-monitoring points within the caisson, with particular emphasis on the central point P_E . The distances of the other four monitoring points P_A , P_B , P_C , and P_D from the caisson's center point P_E are $\Delta d = 5a/6$. After filtering out the initial unstable wave heights during the preliminary computational phases, we meticulously recorded the wave heights at the five designated monitoring points across four successive cycles of the calendar time, denoted as $\bar{S}_A$, $\bar{S}_B$, $\bar{S}_C$, $\bar{S}_D$, and $\bar{S}_E$. The initial averages of these five wave heights were individually calculated and subsequently subjected to quadratic averaging, thereby yielding a composite average wave height denoted as $\bar{S}$. Subsequently, the amplification factor R is determined as $R = \bar{S}/H$ (where H represents the incident wave height).

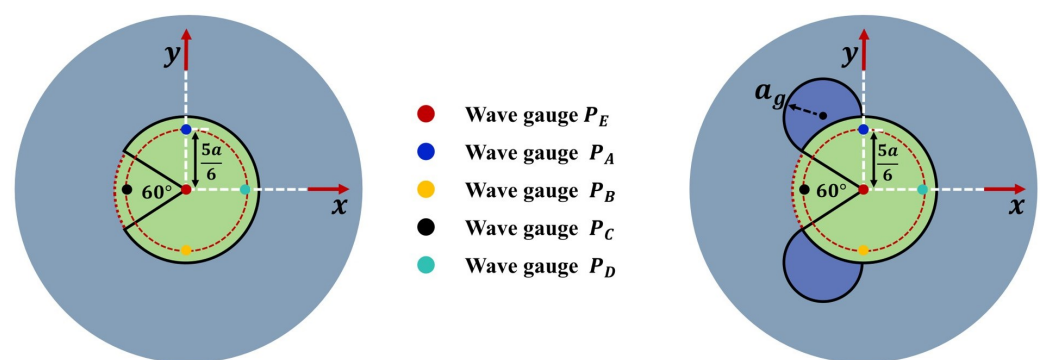


Figure 6. Location of wave height-monitoring points in resonant caissons.

Huang et al. [28] conducted an extensive investigation into the diverse resonant modes of resonant caissons, elucidating that these structures manifest broader capture bandwidths and higher resonance peaks in the first-order resonant modes. Therefore, this study exclusively delves into the examination of several wave cycles within the first-order resonant modes. The wave-amplification characteristics of the three caissons are evaluated by defining the wave height H . It is important to note that this study does not consider the impact of wave height on wave amplification. Therefore, in order to maintain consistency with previous research, $H = 2.43$ m (consistent with the wave heights

utilized in the calculations delineated in Section 5). However, it is acknowledged that wave height is a crucial variable, and its influence on the resonant caisson will be the focus of future research discussions. Figure 7 illustrates the amplification factors of the three caissons across varying wave periods. Within the first-order resonance mode ($ka = 0 \sim 1$), the resonance peak is observed at $ka \approx 0.5$, resulting in amplification coefficients for the three caissons of $R_A = 2.31$, $R_B = 3.10$, and $R_C = 3.37$, respectively. The findings indicate that the caisson enhances the wave height within the enclosure, the caisson with the guide demonstrating notably superior amplification capabilities compared to the unguided counterpart. Furthermore, as the radius of the guide increases, the wave amplification potential of the resonant caisson is further enhanced.

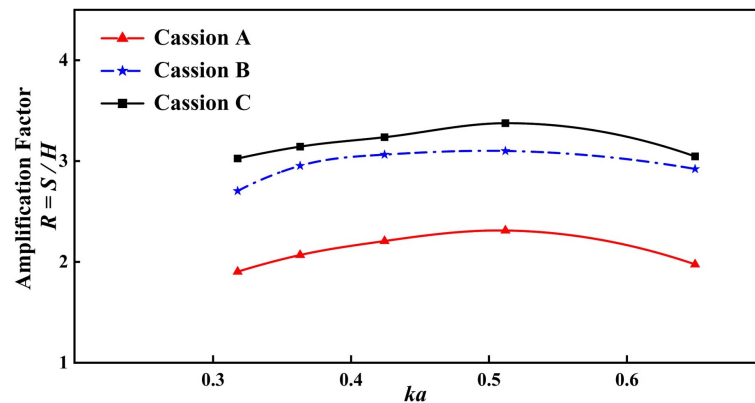


Figure 7. Comparison of wave amplification factors for three caissons.

5. Discussion of Results

In this section, an in-depth analysis of the flow field phenomena will be conducted, examining the interaction between waves and three variations of resonant caissons through changes in the water level, flow velocity, and vortex development. Furthermore, a comprehensive elucidation of the wave amplification mechanism within the caissons will be provided. Notably, emphasis will be placed on assessing the impact of the guide and its radius on resonance, accompanied by a detailed description of the mode and mechanism of the guide. The subsequent flow field phenomena of the three caissons are derived from observations encompassing an entire wave cycle under $T = 11$ s.

5.1. Changes in Water Level

Figures 8–10 depict the water level variations for the three resonant caissons over a single cycle at $T = 11$ s.

The water level inside the caisson exhibited periodic fluctuations as the wave propagated. Each of the three caissons displayed a resonance peak at $t = 3T/6$ and a resonance trough at $t = 6T/6$, with both the peak and trough positioned at the caissons' center. The resonance peaks for caissons A, B, and C were $H_{Amax} = 3.15$ m, $H_{Bmax} = 4.88$ m, and $H_{Cmax} = 5.08$ m, respectively, while the resonance troughs were $H_{Amin} = -2.74$ m, $H_{Bmin} = -3.02$ m, and $H_{Cmin} = -3.52$ m. Introducing guides facilitated a more controlled flow of water into or out of the caisson. Moreover, as the radius of the guide increased, the diversionary effect intensified, leading to increasingly pronounced changes in the caissons' water level.

At $t = 1T/6$, water began to enter the caisson, triggering the formation of vortices at the openings of all three caissons. This vortex motion directed water from either side towards the center, resulting in a localized elevation of water levels at the outlet's midpoint. As the inflow phase commenced, it was evident that the water levels on the sides further from the opening were notably lower than those nearer to the opening, indicating a tilting tendency from front to back.

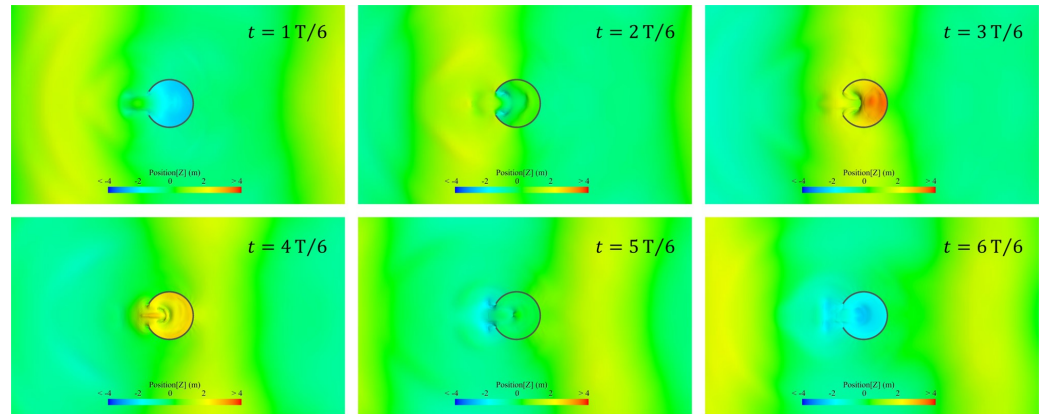


Figure 8. The course of water level changes in caisson A during a cycle.

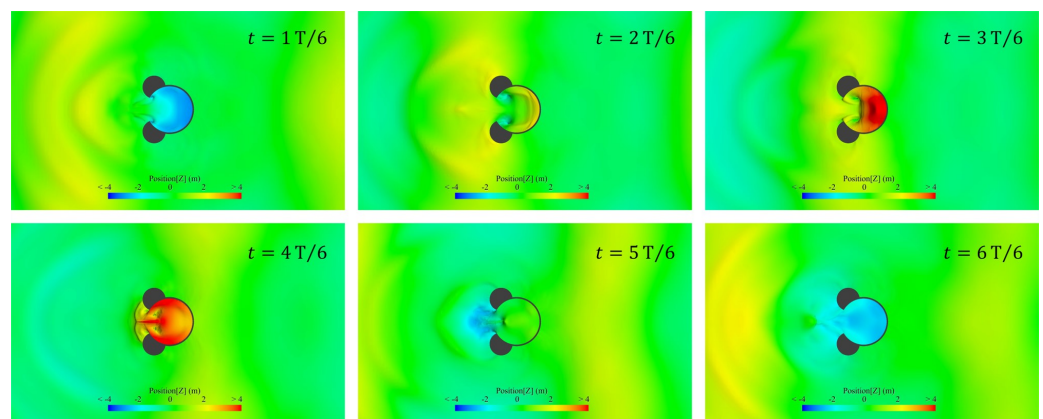


Figure 9. Process of water level change in caisson B during a cycle.

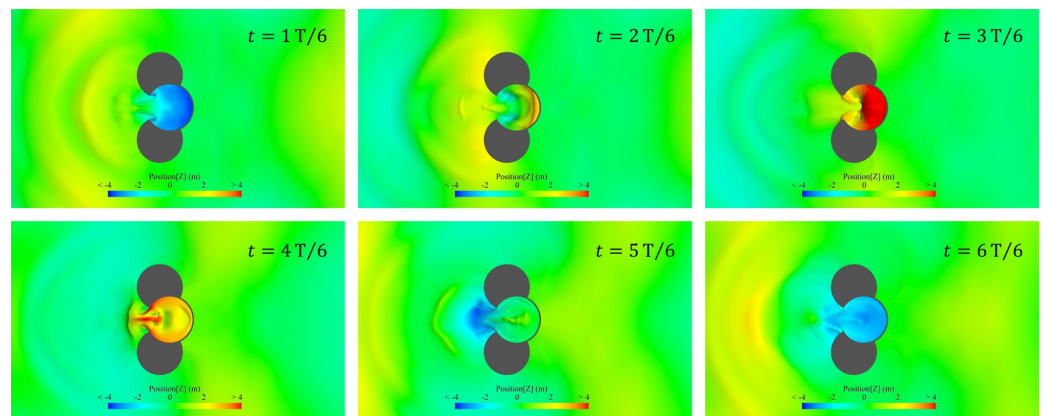


Figure 10. The course of water level changes in caisson C during a cycle.

By $t = 2T/6$, the wave crest had arrived at the caisson. The examination of the free liquid levels within the three caissons revealed that the initial water mass entering the caisson had reached the rear wall before reflecting, causing a sudden change in the liquid level and steepening it. Comparatively, caissons B and C appeared to experience greater water inflow than caisson A, resulting in steeper liquid levels.

Upon reaching $t = 3T/6$, the caisson had fully engaged with the wave crests. Reflections within the caisson had peaked for all three types, culminating in a resonance peak following the superposition of incident waves and radially reflected water at the caisson's center. Notably, the resonance peak location observed in this study aligned with Huang et al.'s [28] findings concerning first-order resonance. The analysis of the free liquid levels on the symmetric sides of the caissons revealed a hierarchical water level arrangement

from high to low, caisson A, caisson B, and caisson C externally, whereas internally, the pattern reversed. The guides' positive impact on enhancing wave energy absorption and resonance peaks became increasingly evident with the expansion of the guides' radii.

As $t = 4T/6$ approached, the wave crest had completely passed, prompting the gradual outflow of water from the caisson. At the perimeter, the reflected waters met, resulting in water levels akin to the lifting zone. However, the height of this lifting zone surpassed $t = 1T/6$. Detailed observation of caisson C's liquid level highlighted an asymmetric flow within the lifting zone at the opening, attributed to vortex instability [32]. Notably, at this juncture, caisson B exhibited a significantly higher water level at its center than caisson C, underscoring the guides' efficacy in directing rapid outflows and hastening water level adjustments.

As $t = 5T/6$ arrived, water continued to pour out of the caisson, gradually lowering the internal water levels towards stabilization. Notably, the central water levels within the caissons slightly exceeded those in the surrounding areas due to hindrances posed by the caisson opening at the lifting zone, resulting in reflux and elevated central water levels. Additionally, externally, caisson C, followed by caisson B and caisson A, exhibited lower lying areas, indicating strong currents transporting water away and contributing to lowered peripheral water levels—a phenomenon elaborated in Section 5.2.

By $t = 6T/6$, the caisson resided at the trough's center, completely emptied of water. At this juncture, all three caissons featured their lowest water levels across the cycle, with the center water levels ranking from low to high: caisson C, caisson B, and caisson A. The inclusion of guides and the subsequent increase in their radii facilitated enhanced water outflow, resulting in lower resonance valleys, signifying the completion of a full cycle.

The consideration of WEC-resonant caisson systems is crucial in the context of uneven water level distribution inside the caisson. When the water level undergoes drastic changes, the internal shear force distribution within the caisson's floater becomes significantly uneven, putting considerable strain on the floater's strength. It is essential to undertake a rational shear resistance design to address this challenge. Additionally, asymmetrical flow inside the caisson may generate substantial torque, which is transmitted through the floater to the power-transmission structure and the power-generation system. Therefore, it is necessary to incorporate a torsion-resistant device for the floater to minimize torque transmission.

5.2. Flow Rate Variations

Figures 11–13 illustrate the fluctuation of flow velocity of the three resonant caissons positioned at the free liquid surface during a complete cycle of $T = 11$ s.

As the wave propagates forward, the water body accelerates into the opening, creating a complex flow field within the caisson. Simultaneous reflection and incidence phenomena interact with each other. The presence of guides alters the flow field within the caisson, facilitating easier inflow and outflow of water, thereby aiding in creating resonance. Furthermore, an increase in the guide radius amplifies this beneficial effect.

At $t = 1T/6$, to adhere to the conservation of mass, the water body experiences acceleration at the caisson opening. Influenced by the lifting zone at the opening, the water body is constrained to enter from both sides, resulting in a reduction in the width of the inlet and a further increase in flow velocity. A comparison of the flow velocities at the opening during this phase indicates that the flow velocities, from highest to lowest, are observed in caisson C, caisson B, and caisson A. This observation highlights the positive impact of the guide and its radius on enhancing flow velocity. Subsequently, as the water enters the caisson and disperses in all directions, energy dissipates gradually, leading to a significant reduction in velocity.

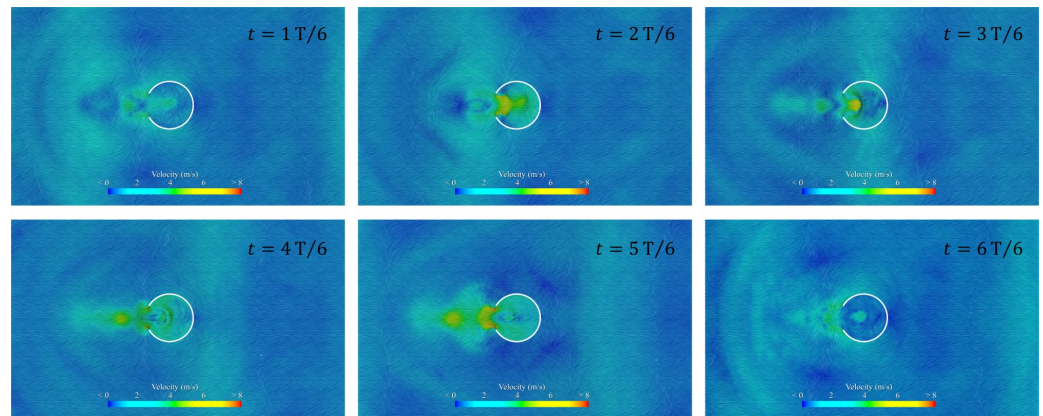


Figure 11. Change in flow velocity of caisson A during a cycle.

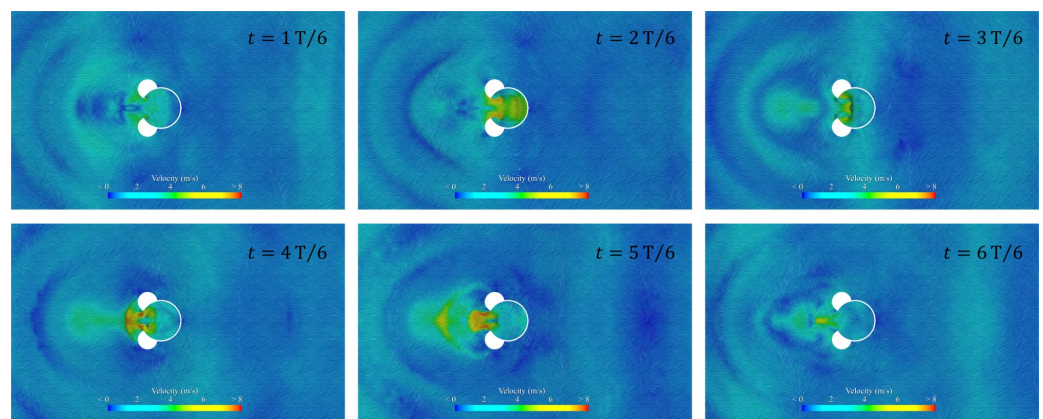


Figure 12. Changes in flow velocity of caisson B during a cycle.

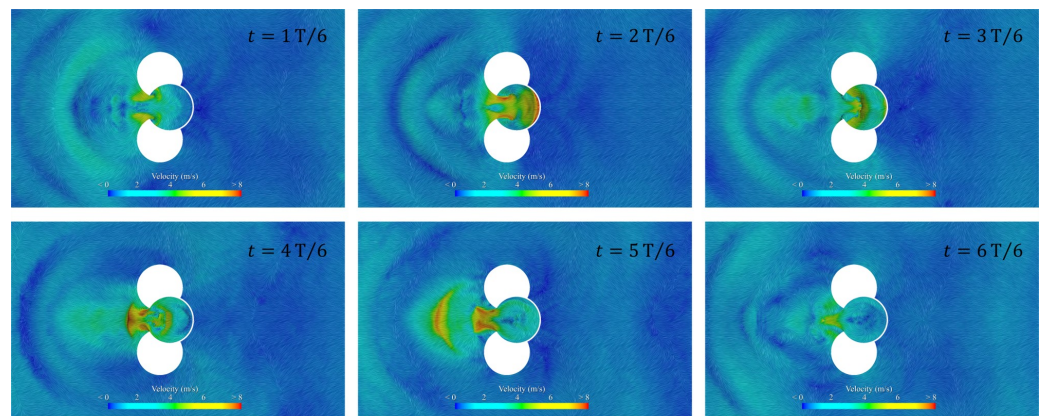


Figure 13. Changes in flow velocity of caisson C during a cycle.

At $t = 2T/6$, as the wave crests, high-energy water begins to flow into the caisson. In comparison to the previous moment, the flow velocity at the opening significantly increases, allowing water to penetrate deeper into the caisson, resulting in a corresponding rise in flow velocity at the rear of the caisson. Notably, in caisson C, as the water body reaches the rear wall and prepares for reflection, a concentration of energy occurs, leading to a sudden acceleration in the outwardly reflecting flow along the inner wall of the caisson. Conversely, in both caissons A and B, the velocity of the incident flow is insufficient to clearly observe this phenomenon.

At $t = 3T/6$, simultaneous incidence and reflection occur at the opening. With the disappearance of the lifting zone from the first two moments, the unimpeded flow allows the water body to enter the caisson directly. A closer inspection of the interior of the

three caissons reveals accelerated water inflow near the center of the caisson due to the vortex effect. Similarly, the outflow of water along the inner wall of the caisson experiences acceleration in this region. Furthermore, the liquid level inside the three caissons near the inner wall gradually stabilizes, with a slight accumulation of energy near the wall of caisson C, indicating a greater water inflow in caisson C.

At $t = 4T/6$, the flow field within the caisson becomes more intricate. Reflected water flows outward along the inner wall, and the radially reflected water is redirected and accelerated by the vortices at the backside of the lifting zone, following a circular path before merging with the water flowing along the inner wall near the opening. As mentioned in the preceding section, the narrowing of the outlet due to the lifting zone effect accelerates water outflow from both sides, resulting in the radial spreading of the water. During this process, water from both sides converges at the front edge of the caisson, briefly increasing the flow rate.

At $t = 5T/6$, the flow inside the caisson becomes streamlined, and water continues to flow out from both sides of the opening. As detailed in Section 5.1, a region of high-velocity flow forms outside the opening, transporting water outward to create a depression, with the flow velocities of the three caissons, in descending order, being caisson C, caisson B, and caisson A. Beyond the depression, the outflowing water briefly accelerates after convergence.

At $t = 6T/6$, a small portion of the water body within the caisson opening continues to flow outward at a relatively slow speed. Inside the caisson, the inflow and outflow of water occupy the same space, representing unregulated flow, thus completing a cycle.

Considering the WEC–resonant caisson system, it is evident that the water velocity within the caisson equipped with guides is significantly higher and more variable compared to the caisson without guides. Consequently, the motion speed of the floater also varies accordingly. In the WEC–resonant caisson system with guides, there arises a need for a more efficient PTO damping device that can automatically adjust based on the changing flow rates, ensuring continuous and stable power generation. Moreover, excessively high flow velocities may affect the flow state behind the floater, creating a low-pressure zone. Combined with the impact of water flow, this phenomenon tends to drive the floater inward, posing a severe challenge to the connection between the floater and the transmission rod. Therefore, it is imperative to consider how to effectively enhance the strength and stiffness of the connection in the design process.

5.3. Development of the Vortex

Figures 14–16 illustrate the variations in vortices among the three resonant caissons over one cycle.

The distinct motion of water within the three caissons is attributed to the vortex, which plays a crucial role in the inherent mechanism of caisson fabrication resonance. Meanwhile, the guide and the guide radius influence the generation and development of the vortex. Moreover, the vortices at different locations and scales accelerate or redirect the water within the tanks, resulting in diverse flow phenomena.

At $t = 1T/6$, for caisson A, the non-smooth opening leads to the immediate formation of two symmetrical vortex columns adjacent to the wall, guiding water from both sides towards the center and, consequently, lifting the water level at the opening's center. This also accelerates the inflow of water from both sides. In the case of caissons B and C, the vortex columns are positioned more inward, primarily raising the water level at the opening's center and accelerating the inflow into the caisson. Additionally, two vortices with opposite rotations are generated at the center of the lifting area, further accelerating the inflow from the sides, similar to the role played by the vortices in caisson A.

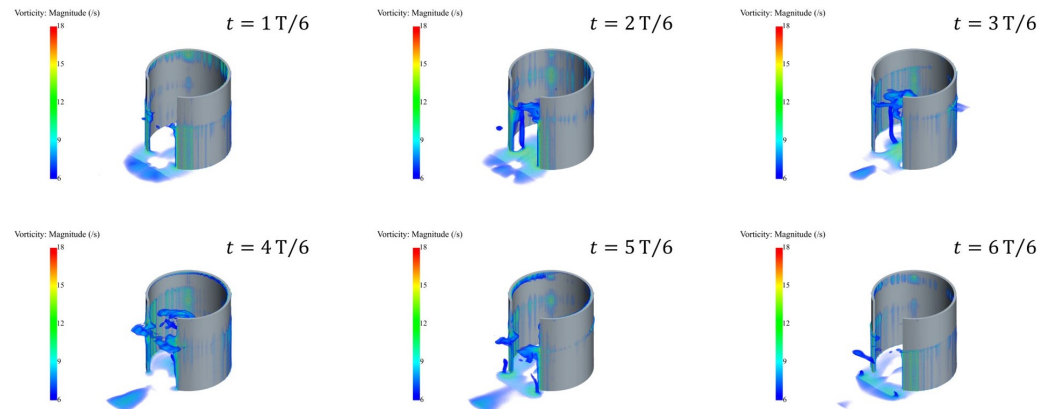


Figure 14. Changes in vortex of caisson A during a cycle.

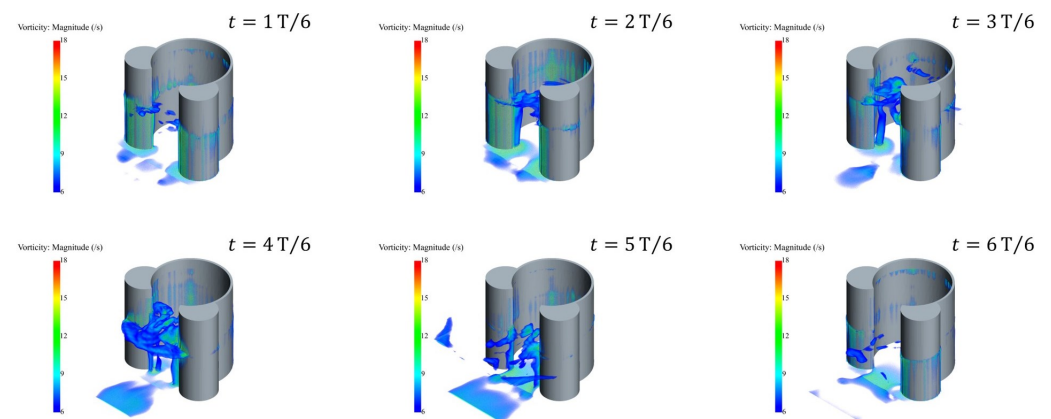


Figure 15. Changes in vortex of caisson B during a cycle.

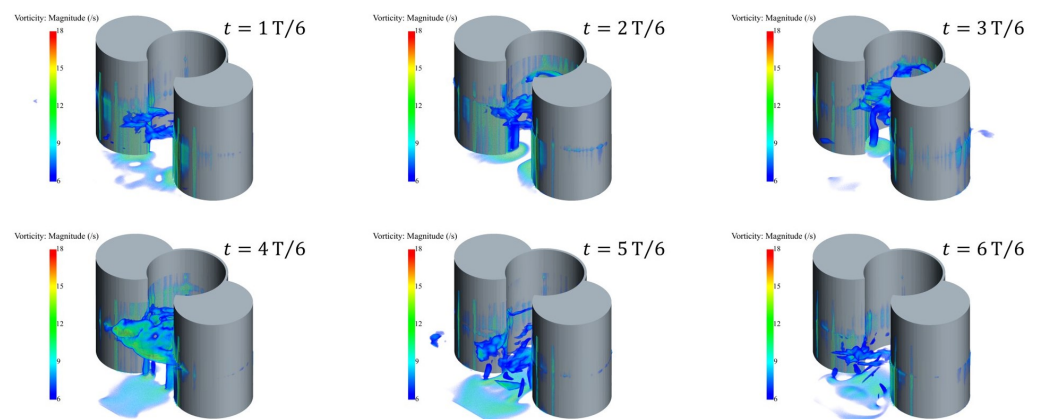


Figure 16. Changes in vortex of caisson C during a cycle.

At $t = 2T/6$, as the water enters the caisson, the previously generated vortex columns in all three caissons are pushed inward by the water flow, on the verge of detaching from the wall. The water inside the caisson is guided by the vortices to accelerate and disperse in all directions. Vortex columns in caissons B and C carry higher energy, resulting in a stronger accelerating effect. Furthermore, the lifting zone at the opening of caissons B and C is much lower, leading to the dissipation of internal vortices and a more regular flow at this stage.

At $t = 3T/6$, the higher energy water further advances the vortex columns inward, particularly in caisson A, where they approach the center, while those in caissons B and C move less. As detailed in Section 5.2, these vortices accelerate both the inflow and outflow.

Moreover, the flow field inside the caissons becomes increasingly complex, with large and small vortices forming on the water surface.

At $t = 4T/6$, the vortex columns inside all three caissons disperse due to swiftly exiting water and then re-forming on both sides of the openings. Notably, the vortex columns at the water surface have a larger scale than those below the surface, accelerating the outflow of water. The direction of rotation of the vortex at the center of the water surface in caisson A changes, guiding the internal water mass outward, albeit with weaker intensity. In contrast, caissons B and C experience a redirection of the vortices, replenishing them with sufficient energy, resulting in increased strength and scale. In caisson C, the vortex carries more energy, leading to highly unstable flow and the asymmetry described in Section 5.1 at the liquid surface.

At $t = 5T/6$, the vortex on the water surface inside caisson A dissipates due to a lack of energy replenishment, resulting in a smooth and regular internal flow. In caissons B and C, the vortices weaken, but continue to guide the internal water, accelerating outward flow. The vortex columns at the openings of all three caissons reduce in size, directing the water column outward and creating the low-lying area mentioned in Section 5.1. Comparing the scale of vortices for the three caissons at this point, caisson C exhibits the largest, followed by caisson B and caisson A, explaining the different water levels in the depression area.

When $t = 6T/6$, the water has essentially flowed out of the caissons, causing the dissipation of the vortices due to insufficient energy. Outside caisson C, the vortices on both sides of the opening will dissipate after a certain time, while for caissons A and B, the external vortices become negligible, completing the cycle.

6. Conclusions and Outlook

In this study, we utilized Star-CCM+ to simulate the interaction between waves and resonant caissons. Initially, we validated the numerical model for convergence and stability. Subsequently, we delved into the resonance phenomena within the three types of caissons by analyzing variations in water level, flow velocity, and vortices in the flow field. Furthermore, we elucidated the wave amplification mechanism of the resonant caisson and expounded on the impacts of the guide and guide radius on resonance. The key findings of our investigation can be summarized as follows:

- 1 The resonant caisson effectively induces resonance, reaching its peak resonance at a specific point.
- 2 The guide efficiently channels more water flow into the caisson outlet, consequently augmenting wave energy density and capturing a greater amount of energy.
- 3 Within a certain range, with an increase in the radius of the guide, the guiding effect is further enhanced, leading to an improvement in peak resonance.
- 4 Incorporating the guide alters the flow field both inside and outside the caisson, resulting in a substantial increase in inlet and outlet velocities. Additionally, enlarging the guide radius has a more pronounced positive impact on water velocity.
- 5 The guide and its radius influence the development and location of vortices, thereby facilitating the generation of resonance.

This research offers insights for the design and advancement of offshore equipment. Future studies could explore integrating wave energy capture and power-conversion modules into the resonant caisson, potentially transforming it into a wave energy generator. Such endeavors aim to foster the efficient harnessing and utilization of wave energy resources.

Author Contributions: Conceptualization, J.L.; Methodology, J.H. (Jiawei Hao) and J.H. (Ji Huang); Software, J.H. (Jiawei Hao) and D.D.; Validation, D.D.; Formal analysis, D.D.; Resources, J.H. (Ji Huang); Data curation, J.H. (Jiawei Hao); Writing—review & editing, J.L. and J.H. (Ji Huang); Funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ocean Young Talent Innovation Programme of Zhanjiang City (Grant No. 2022E05002), the Young Innovative Talents Grants Programme of Guangdong

Province (Grant No. 2022KQNCX024), The China Institute of Navigation Young Elite Scientist Sponsorship Program by CIN (Grant No. YESSCIN2023008), and the College Student Innovation Team of Guangdong Ocean University (Grant No. CXTD201812).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest. This submitted manuscript is approved by all authors for publication. We would like to declare that the work described is original research that has not been published previously, and is not under consideration for publication elsewhere, in whole or in part. The authors listed have approved the manuscript that is enclosed.

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