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Hydrodynamic Analysis of Combined Offshore Wind Turbine and Net Cage Under Finite-Depth Waves

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Abstract: Offshore wind turbines are subjected to long-term wave loads, which shorten their service life. Marine aquaculture cages are common structures in the ocean engineering field. Therefore, investigating the hydrodynamic characteristics of combined wind turbine and cage facilities under wave loads is crucial. This study employs a porous medium model to analyze the hydrodynamic behavior of a fixed wind turbine base integrated with cages under finite-depth wave conditions. First, the transmission coefficients of waves passing through cages at different positions were examined under varying cage solidity conditions. The results indicate that the cages minimally affect wave height in regions close to the cage group. Subsequently, the wave forces acting on the fixed wind turbine base behind the cages were analyzed under different solidity and wave height conditions. The variation curves of the drag coefficient and inertia coefficient were obtained for solidity values ranging from 0.3 to 0.6 and Keulegan–Carpenter (KC) numbers between 1 and 4.

Keywords: offshore wind turbine; net cage; porous medium model; net solidity; wave force



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1. Introduction

Wave action on offshore pile-supported wind turbines is a common ocean environmental dynamic load. Reducing wave loads on offshore wind turbines has been a research focus for scholars worldwide. China's offshore aquaculture net cage industry currently features low intensification and scattered small-scale operations. With the increasing application of deep-water aquaculture net cages and offshore wind turbines, and the national emphasis on integrating marine economic development with ecological protection, offshore wind power projects urgently need to seek complementary advantages and integration with marine ranching and deep-sea aquaculture. More researchers are focusing on studying combined structures of offshore wind turbines and aquaculture net cages. This integration can improve production efficiency by leveraging wind turbines for reliable mooring support and net cages for wave damping and dissipation. Combined wind turbine and net cage systems enhance management and comprehensive benefits [1].

China's deep-sea aquaculture has developed over nearly 40 years, establishing a diversified technological system. In terms of equipment development, domestically developed systems such as the bottom-sitting 'Changjing No. 1' (130 m in circumference), the semi-submersible 'Dehai No. 1' (designed to withstand typhoons), and the fully submersible 'Deep Blue No. 1' (for aquaculture in the Yellow Sea cold water mass) have achieved breakthroughs, with single-cage aquaculture water volume exceeding 70,000 cubic meters

and an operating depth of up to 60 m. High-density polyethylene (HDPE) gravity cages account for over 95% of the market [2,3]. Copper alloy netting has become a recent research focus due to its superior anti-biofouling properties compared to traditional polymers, as biofouling can increase resistance by 30–50% [4,5]. In contrast, countries in Europe, the United States, and Japan have entered the industrialization stage. Norway's 'Ocean Farm 1' (250,000 cubic meters of water volume) and the 'Jostein Albert' aquaculture vessel (400,000 cubic meters of water volume) employ truss structures and external turret mooring systems, capable of withstanding Category 12 typhoons, and integrate AI algorithms for fully automated feeding [6–9]. The European Union has established standards covering structural design and environmental assessment, while the global cage database established by the Norwegian University of Science and Technology provides important references for the industry [10,11]. In the fields of hydrodynamics and intelligent management, domestic scholars have proposed a quasi-static analysis model, significantly improving the efficiency of fatigue life prediction through the virtual displacement principle and fluid mechanics screen model. It has been found that water flow velocity significantly affects fatigue life [12–15]. Experimental studies show that biofouling increases the drag coefficient of cages by 3.3–7.7 times and the inertial coefficient by 5.0–10.8 times, with significant differences in flow field blocking effects depending on the type of fouling [16–20]. Numerical simulations have revealed the vortex shedding patterns of cruciform cylinders in oscillatory flow, indicating that node effects significantly enhance the overall drag and inertial coefficients [2]. In recent years, artificial intelligence has also been applied to the engineering field of marine aquaculture. In terms of intelligent management, China's training data volume for domestic AI decision-making models is only one-fifth that of Norway, with its fault warning accuracy being 15–20% lower [21]. However, machine learning technology has been applied to predict structural stress in cages, with errors below 5% [22,23]. Norway's AquaOptima digital twin system enables full lifecycle management of cages, promoting the development of full-industry chain simulation technology [7]. Recent research has focused on the following three main directions: structural innovation (such as bionic cages and composite material cages), the integration of clean energy (floating photovoltaic panels reducing energy consumption by over 30%), and intelligent upgrades (digital twin technology enabling full lifecycle management) [24–27]. Norwegian scholars have also found that increasing the porosity of spherical cages reduces wave excitation forces but enhances damping coefficients, providing theoretical support for stability optimization under extreme sea conditions [28,29]. Overall, technological innovation and policy coordination are driving deep-sea aquaculture to become a strategic direction for ensuring food security and expanding marine space.

Offshore aquaculture cages are mainly distributed in coastal areas with water depths typically ranging from 5 to 30 m. Due to the large-scale construction of monopile wind turbines in nearshore waters, the available marine space has tended to become saturated. Therefore, it is imperative to explore reasonable layout schemes for the structural facilities of wind turbines and cages in waters with a depth of 5 to 30 m. Currently, there is relatively little international research on combined structures of offshore monopile wind turbines and aquaculture cages, and reference materials applicable to engineering practice are extremely limited. Thus, this paper further investigates the effects of wave action on the wave forces and surrounding wave fields of combined wind turbine and net cage facilities in finite water depths. Key factors include net cage solidity, wave period, and wave steepness. The OpenFOAM v12 and porous media approach were used to simulate the flow field around aquaculture cages and wind turbine structures under wave action. An optimal mesh generation strategy for the netting model was obtained through grid independence analysis, and the accuracy of the model was verified by comparing it with the results of physical

model experiments. This study focused on investigating the wave field characteristics around circular cage clusters under different wave conditions and their effects on the loads on wind turbine foundations. The results provide a foundation for future research on combined wind turbine and net cage facilities.

2. Methods

This study employs the open-source CFD software OpenFOAM, based on the finite volume method, for the hydrodynamic analysis of combined aquaculture net cage and offshore wind turbine facilities. OpenFOAM is a C++-based CFD package with multiple solvers for various fluid mechanics problems, or custom solvers/tools can be developed. It includes pre- and post-processing interfaces, ensuring consistent data transfer across different computing environments.

2.1. Porous Medium Model

A porous medium model was used to simulate the influence of net cages on surrounding wave fields and analyze the effects on nearby wind turbine foundations. The porous medium model for marine aquaculture cages involves several key assumptions to simplify fluid–structure interaction analysis, as follows:

(1) Continuum representation: The discrete net structure is treated as a homogeneous, continuous medium rather than resolving individual filaments or meshes. This ignores microscale details (e.g., exact shape of net nodes, individual thread deformations) and focuses on averaged macroscopic properties like net solidity.

(2) Negligible solid skeleton deformation: The model assumes that the net's structural deformation (stretching and bending) under fluid forces is negligible. It treats the cage as a rigid or quasi-rigid framework, even though real nets may exhibit flexibility. This simplifies the mechanical equilibrium by ignoring dynamic structural responses.

(3) Uniform porosity and permeability: The net's porosity (fraction of void space) and permeability (fluid flow resistance) are assumed to be uniform across the cage volume. Variations due in node intersections or mesh density changes are overlooked, assuming isotropy or orthogonal anisotropy (e.g., different flow resistances along axial/radial directions).

(4) Volume-averaged flow: Fluid flow through the net is described using Darcy-like or Forchheimer-type equations, which average velocity and pressure over the representative elementary volume (REV). The effect of individual threads (e.g., drag on filaments) is lumped into bulk resistance coefficients, ignoring local flow disturbances around nodes or mesh edges.

(5) Hydrodynamic force simplification: Forces exerted by water on the net are modeled via empirical drag/lift coefficients based on the net solidity, rather than resolving viscous interactions at the filament scale. Node geometry (e.g., thickness, shape) is assumed to have no impact on overall drag, focusing solely on the macroscopic porosity effect.

These assumptions balance computational tractability with engineering accuracy, making the model suitable for large-scale simulations of cage hydrodynamics (e.g., wave/current loads) while sacrificing microscale structural fidelity. Previous studies on netting and net cage flow fields have successfully used this approach [30]. This paper simplifies circular net cages into cylindrical porous media (Figure 1).

The fluid governing equation for its application is as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \rho g_i + \frac{\partial}{\partial x_j} (\mu + \mu_t) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + S_i \quad (2)$$

where μ is the dynamic viscosity of the fluid, μ_t is the eddy viscosity, k represents the turbulent kinetic energy, p is the pressure, u_i is the velocity component, g_i is the gravitational acceleration, i and j represent the coordinate components, t is the time, ρ is the density of the fluid, and S_i is the source term of the momentum equation.

In the fluid region, outside the porous medium, $S_i = 0$, and inside the porous medium, S_i , is given as follows:

$$S_i = -\frac{1}{2}\rho C_{ij} \left| \vec{u} \right| \vec{u} \quad (3)$$

$$C_{ij} = \begin{pmatrix} C_n & 0 & 0 \\ 0 & C_t & 0 \\ 0 & 0 & C_t \end{pmatrix} \quad (4)$$

where $\vec{u}$ is the velocity vector of water particles, C_n is the normal resistance coefficient, C_t is the tangential resistance coefficient, and C_{ij} represents the porous medium coefficient matrix.

The flow resistance acting on the porous medium region is as follows:

$$F = S_i \lambda A \quad (5)$$

where λ is the thickness of the porous medium region, A is the area of the porous medium region, and the direction of the force (F) is opposite to the direction of the water flow.

By substituting Equation (3) into Equation (5), the expression of drag force ($\vec{F}_d$) and lift force ($\vec{F}_l$) on the net can be obtained:

$$\vec{F}_d = \frac{1}{2}\rho \lambda A C_n \left| \vec{u} \right| \vec{u} \quad (6)$$

$$\vec{F}_l = \frac{1}{2}\rho \lambda A C_t \left| \vec{u} \right| \vec{u} \quad (7)$$

The porous medium coefficient (C_n and C_t) in Equations (6) and (7) can be obtained through physical model experiments. In addition, lift and drag force can also be obtained by Morison's equation:

$$\vec{F}_d = \frac{1}{2}\rho A C_d \left| \vec{u} \right| \vec{u} \quad (8)$$

$$\vec{F}_l = \frac{1}{2}\rho A C_l \left| \vec{u} \right| \vec{u} \quad (9)$$

where the drag coefficient (C_d) and lift coefficient (C_l) can be obtained by the empirical formula.

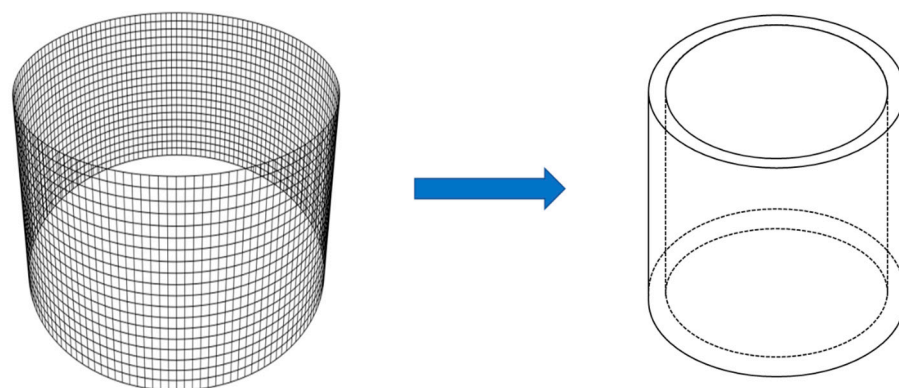


Figure 1. Schematic diagram of transforming a circular cage into a porous medium model.

2.2. Morison's Equation

The wind turbine model and wave conditions satisfy the small-diameter criterion ($D/L \leq 0.15$, L refers to wavelength). Thus, Morison's equation is used to calculate wave forces on the foundation. For small-diameter piles, wave forces include inertial force F_i and drag force F_d :

$$F_i = f_i \Delta Z = C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} \Delta Z \quad (10)$$

$$f_i = C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} \quad (11)$$

$$F_d = f_d \Delta Z = C_d \frac{\rho}{2} D u |u| \Delta Z \quad (12)$$

$$f_d = C_d \frac{\rho}{2} D u |u| \quad (13)$$

$$f_H = f_i + f_d = C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} + C_d \frac{\rho}{2} D u |u| \quad (14)$$

The total wave force per unit height on the pile is $f_H = f_i + f_d$, where D is the pile diameter and u is the horizontal velocity of water particles. Using the coordinate system shown in Figure 2, the wave force on a pile segment of height dz can be given as follows:

$$dF_H = f_H dz = C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} dz + C_d \frac{\rho}{2} D u |u| dz \quad (15)$$

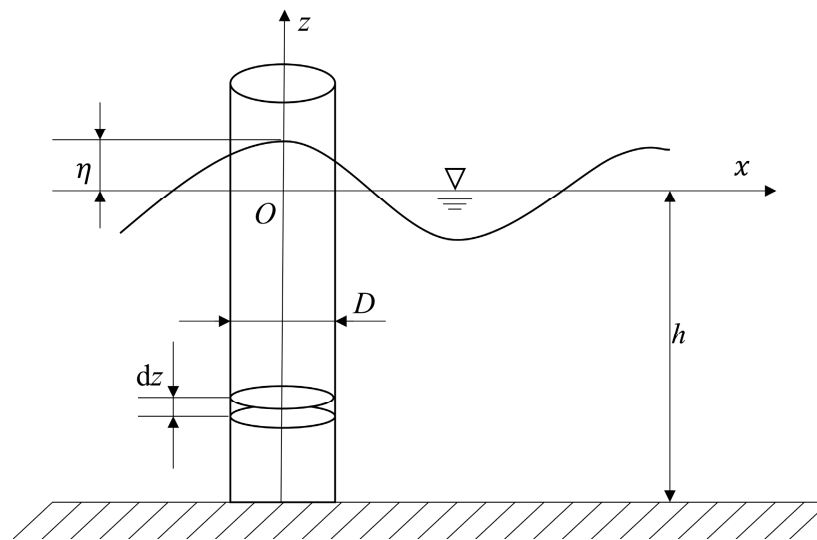


Figure 2. Schematic diagram of coordinate system for the calculation of wave force.

The total force on the entire pile is obtained by integrating Equation (15) from the seabed to the free surface:

$$F_H = \int_{-h}^{\eta} C_d \frac{\rho}{2} D u |u| dz + \int_{-h}^{\eta} C_m \rho \frac{\pi D^2}{4} \frac{\partial u}{\partial t} dz \quad (16)$$

Stokes second-order wave theory is used, with horizontal velocity u and free surface elevation η given by:

$$u = A\omega \left[\frac{\cosh k(z+h)}{\sinh kh} \cos \theta + \frac{3}{4} Ak \frac{\cosh 2k(z+h)}{\sinh^4 kh} \cos 2\theta \right] \quad (17)$$

$$\eta = A \left[-\frac{Ak}{2 \sinh 2kh} + \cos \theta \right] \quad (18)$$

where $\theta = kx - \omega t$ and $k = 2\pi/L$.

2.3. Flow Field Calculation Model

LES directly resolves large-scale turbulent structures and models small-scale turbulence, offering higher accuracy and reliability than Reynolds-Averaged Navier–Stokes (RANS) methods while being more computationally efficient than the direct numerical simulation (DNS). Thus, LES is adopted and time-step is constrained (Courant number < 0.5) to ensure accurate vortex transport.

A 1:50 scale numerical flume was built (Figure 3) as follows: length 13 m, width 0.45 m, height 0.6 m, water depth 0.4 m. Based on the results of our previous experimental studies, the influence of the Reynolds number on the hydrodynamic characteristics of the cage structure is negligible under wave action [10]. Thus, the Froude scaling law is adopted to achieve dynamic similarity. The fluid parameters are selected as follows: the density of water is 1000 kg/m^3 , the dynamic viscosity of fluid is $1.0 \times 10^{-6} \text{ m}^2/\text{s}$, and the gravity acceleration is 9.8 m/s^2 . A wave-making zone (2 L) and wave-damping zone (2 L) were included. The scale ratio of 1:50 for the numerical model aims to balance the efficiency of numerical calculations. Moreover, dimensionless processing was adopted in the results analysis to ensure that the numerical simulation results have a certain degree of generalizability.

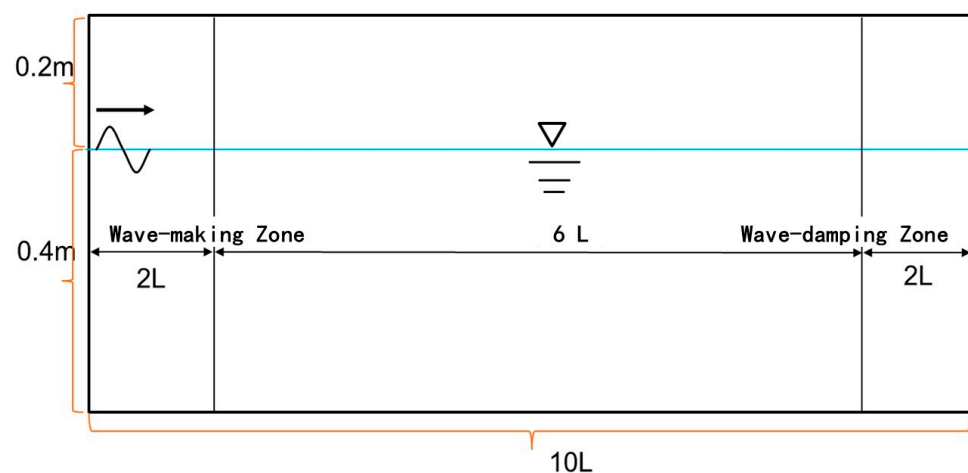


Figure 3. Size diagram of the numerical flume.

The diameter of the cage is 0.254 m, the height of the cage is 0.3 m, and the net cages are fixed to seafloor. The diameter of the wind turbine base is 0.1 m. The center distance of the cage is 0.4 m, and the four cages are evenly distributed. The wind turbine base is 0.4 m away from the cage. The grid division around the cage and the wind turbine is shown in Figure 4. The maximum grid is 0.03 m, the mesh is encrypted in the area around the net coat and the fan, and the minimum grid is 0.001 m. The wave propagation direction grid of the whole tank is evenly distributed. The vertical grid is evenly distributed within the splash zone. Away from the splash zone, it gradually becomes sparser, with an expansion rate of 1.2, as shown in Figure 5.

Generally, the accuracy of the numerical results improves with higher grid quality and quantity. However, this is accompanied by increased computational time. Therefore, we aim to select reasonable grid numbers through grid convergence verification. For clarity in the subsequent sections, two variables, N_x and N_y , are defined as follows (see Figure 5):

- N_x : Number of grids per wavelength in the wave propagation direction (along the wavelength);

- N_y : Number of grids per wave height in the y-direction (wave height direction) within the splash zone.

The wave parameters are set as follows: wave height = 0.04 m, period = 1 s. A relaxation zone (length = 1.5–2 times the wavelength) is placed between 0 m and 3 m in the flume to maintain the ideal wave profile. A damping zone (length = 3 m) is installed at the flume's rear to absorb waves. Six N_x cases ($N_x = 30, 40, 60, 80, 100$, and 120) and four N_y cases ($N_y = 5, 10, 20$, and 30) are tested.

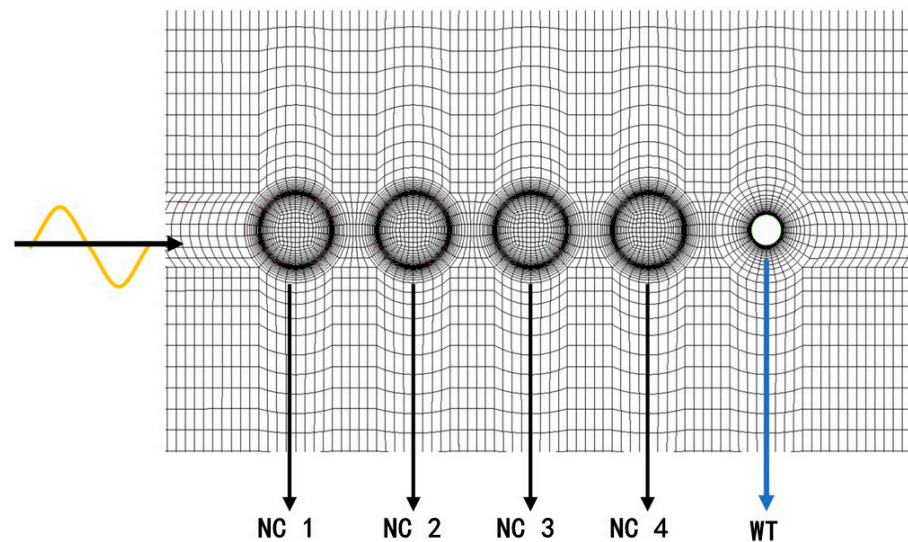


Figure 4. Grid division around the net cages (NC) and wind turbine (WT).

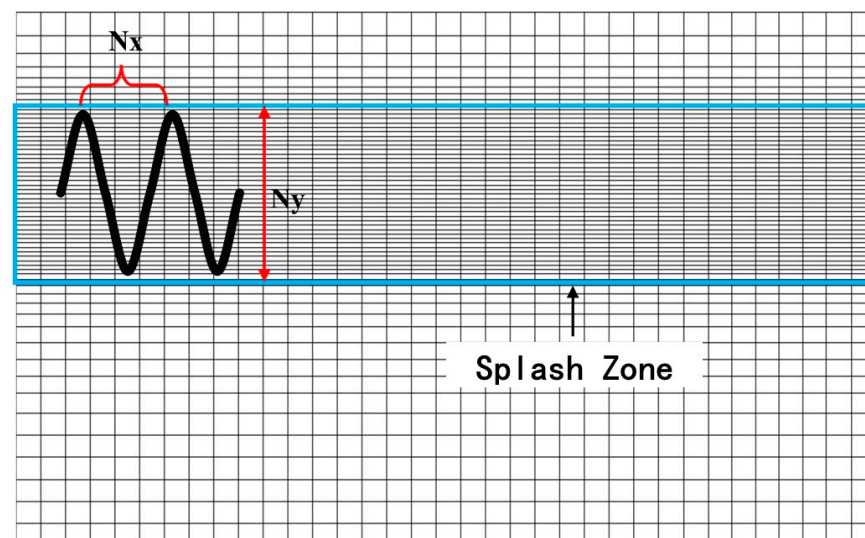


Figure 5. Grid division diagram of the water tank.

A comparison of the wave height and their amplitude spectrums simulated with different grids in the vertical direction (splash zone) is shown in Figure 6. To control variables, N_x is uniformly set to 40. N_y is assigned values of 5, 10, 15, and 20, respectively. As illustrated in the figure, the accuracy improves with an increase in grid resolution. However, higher grid density typically results in longer computational time and elevated computational costs. Balancing computational efficiency and accuracy, $N_y = 10$ is ultimately selected.

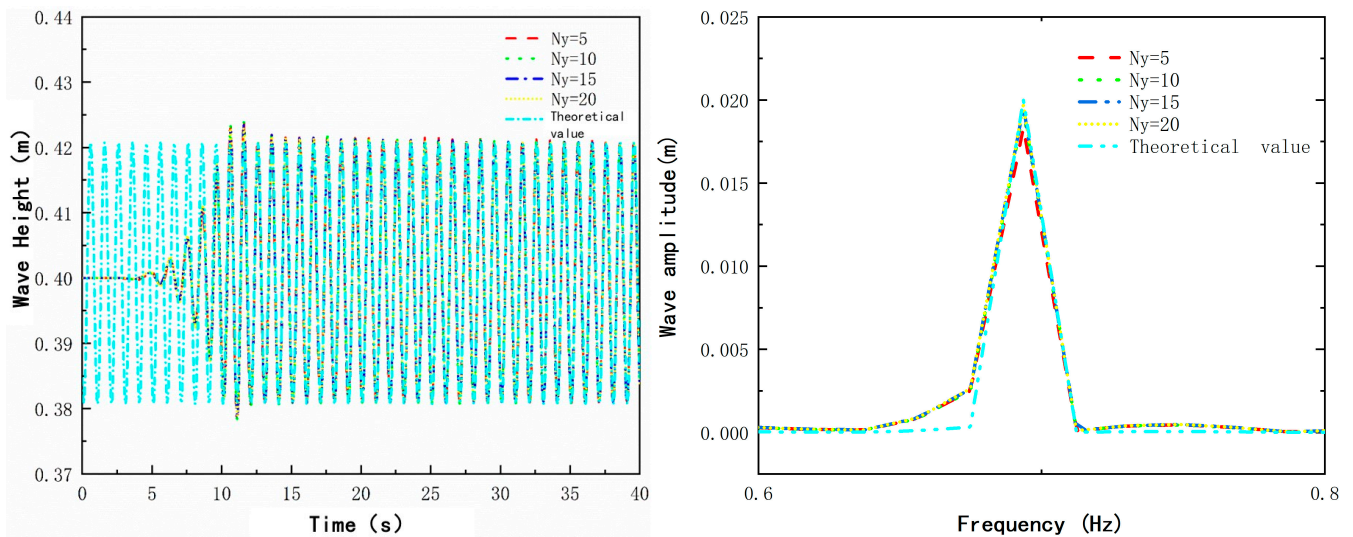


Figure 6. Comparison of grid selection in vertical direction (splash zone).

Under the conditions of $N_y = 10$ and $t = 20$ s, the simulation results for different grid numbers in the wave propagation direction are shown in Figure 7. The results indicate that when the grid number in the wave propagation direction exceeds 80, the wave height simulation results achieve convergence. Therefore, when balancing computational cost and wave attenuation, $N_x = 80$ is selected as the optimal grid number in the wave propagation direction.

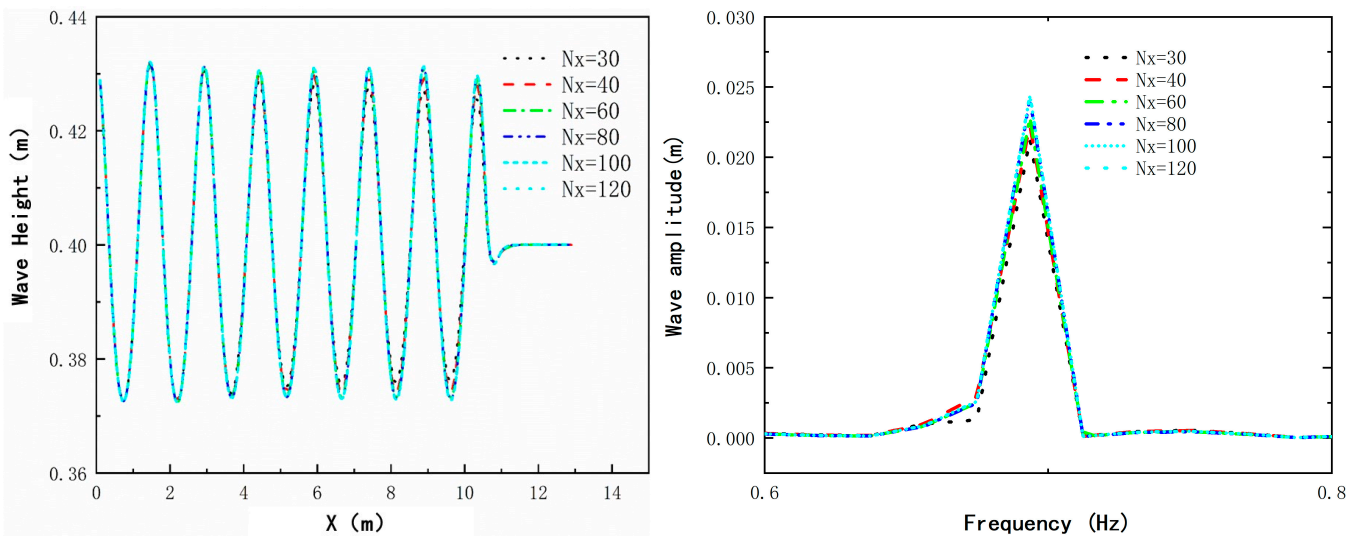


Figure 7. Wave surface curve at 20 s for different grid numbers in wave propagation direction.

2.4. Numerical Model Validation

The relevant parameters of the net cage model in this research are consistent with those in Bi et al.'s paper [31]. The numerical model validation in this study is completed by performing numerical calculations on the wave fields around cages for different wave periods at $H = 4$ cm and different wave heights at $T = 1.0$ s and comparing the results with the physical model experimental values from Chun-Wei Bi et al. The results are shown in Figure 8. Measurement points were set up 1.3 m downstream from the center of the first cage. Under different wave conditions, the simulated wave transmission coefficient (C_T) downstream of a single cage shows minimal differences from the corresponding experimental values, with the maximum relative error not exceeding 2%. As the number

of cages increases, the transmission coefficient exhibits a decreasing trend, and the error between the numerical simulations and experimental results gradually decreases to less than 1%. Therefore, it can be concluded that the numerical model used in this paper has high accuracy.

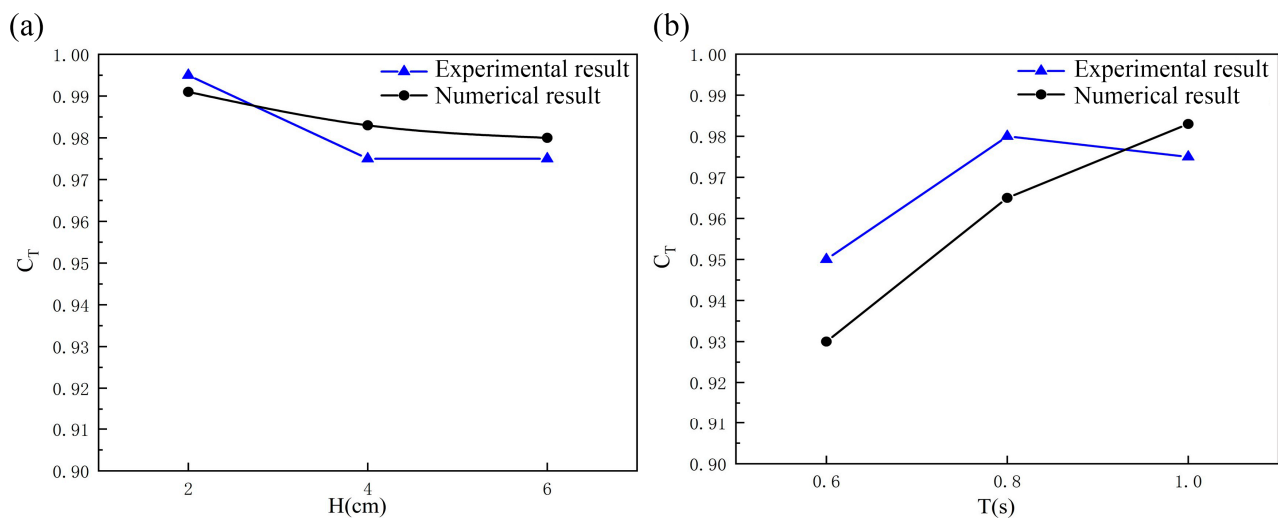


Figure 8. The numerical simulation results of wave transmission coefficient C_T downstream of the cage model are compared with the experimental results: (a) different wave heights at $T = 1.0$ s, (b) different wave periods at $H = 4$ cm.

3. Results and Discussion

To investigate the hydrodynamic characteristics around the wind turbine foundation under finite water depth conditions with varying solidity conditions and wave heights, the following two sets of working conditions are established:

- Condition 1: identical wave parameters but different solidity conditions (see Table 1);
- Condition 2: identical solidity conditions and wave period but varying wave heights (see Table 2).

Table 1. Condition 1: identical wave parameters but different solidity conditions.

Sn	Wave Height (m)	Wave Length (m)	Wave Steepness (H/L)	Period (s)	h/L
0.30	0.05	2.5	0.02	1.4479	0.16
0.35					
0.40					
0.45					
0.50					
0.55					
0.60					

Table 2. Condition 2: identical solidity conditions and wave period but varying wave heights.

Sn	Wave Height (m)	Wave Length (m)	Wave Steepness (H/L)	Period (s)	h/L
0.3	0.05	0.25	0.020	1.4479	0.16
	0.06		0.024		
	0.07		0.028		
	0.08		0.032		
	0.09		0.036		
	0.10		0.040		
	0.12		0.048		

Both conditions share a constant water depth of 0.4 m.

3.1. Influence of Net Solidity on Waves

To investigate the impact of net solidity on wave dynamics, numerical simulations were conducted in a wave flume containing only cages (without the turbine). Here, ΔX denotes the distance between the measurement point and the first cage in the wave propagation direction, while d represents the center-to-center spacing between adjacent cages. To evaluate the wave attenuation effect of the cages, the transmission coefficient C_T ($C_T = H_T/H_I$, where H_T is the transmitted wave height and H_I is the incident wave height) after waves pass through four cages was measured and plotted against solidity conditions, as shown in Figure 9. It has been found that the transmission coefficient C_T increases significantly with higher solidity S_n in the cage array. After passing through the cage array, higher solidity S_n leads to a more rapid decrease in C_T .

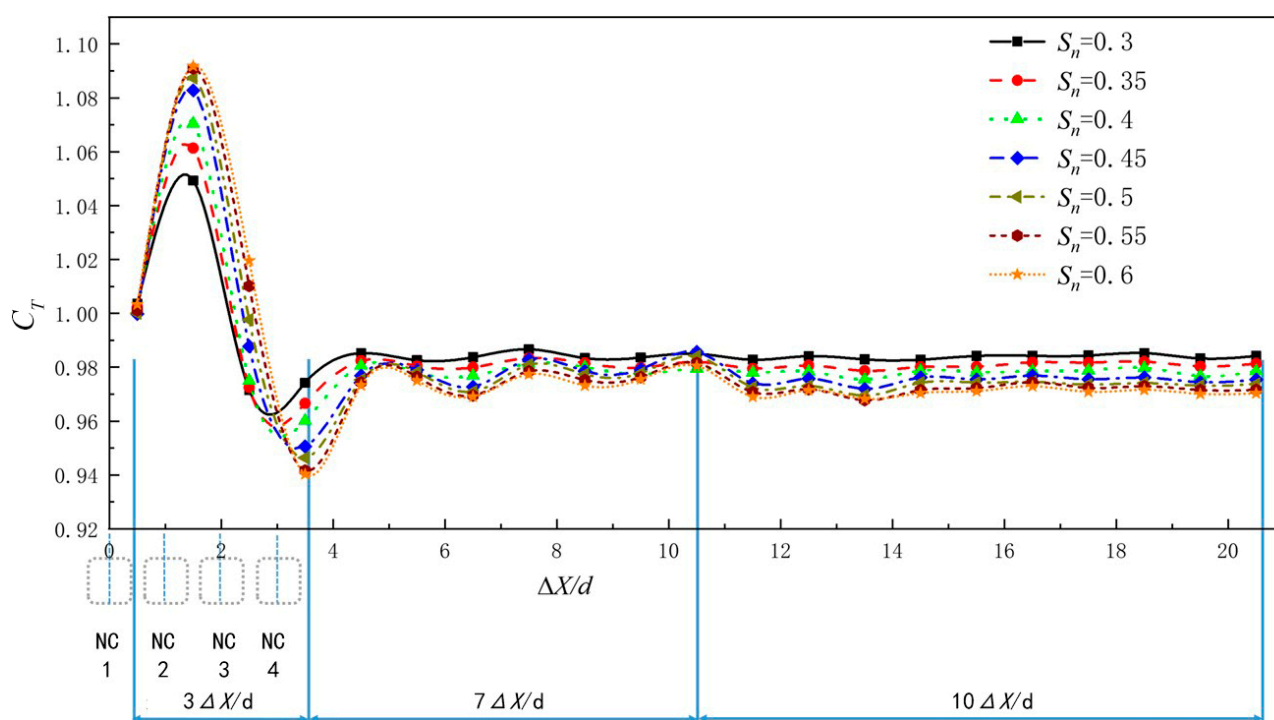


Figure 9. Transmission coefficient curves at different positions when different compactness is selected.

When waves encounter cylindrical structures in the ocean, significant changes occur on the free surface around the cylinder. A portion of the waves is obstructed by the cylinder, leading to rapid upward flow along its surface. The maximum vertical distance between the peak water level and the still water surface during this process is defined as the wave run-up R . For offshore platforms, excessive wave run-up can cause green water on the deck (overtopping) and generate intense slamming loads on the platform's base, potentially resulting in structural damage. Therefore, comprehensive analysis of wave run-up is critical in engineering design.

Conversely, setting the platform deck too high also poses challenges. Excessive deck elevation increases construction costs and compromises the platform's overall stability. Thus, investigating wave run-up around wind turbine foundations holds significant practical value. As shown in Figure 10, a secondary wave peak is observed on the windward side of the turbine foundation. However, the installation of cages reduces both the maximum wave amplitude and the secondary peak intensity. Additionally, the wave surface stabilizes after 20 s, suggesting that subsequent numerical calculations should focus on this steady-state phase for improved accuracy.

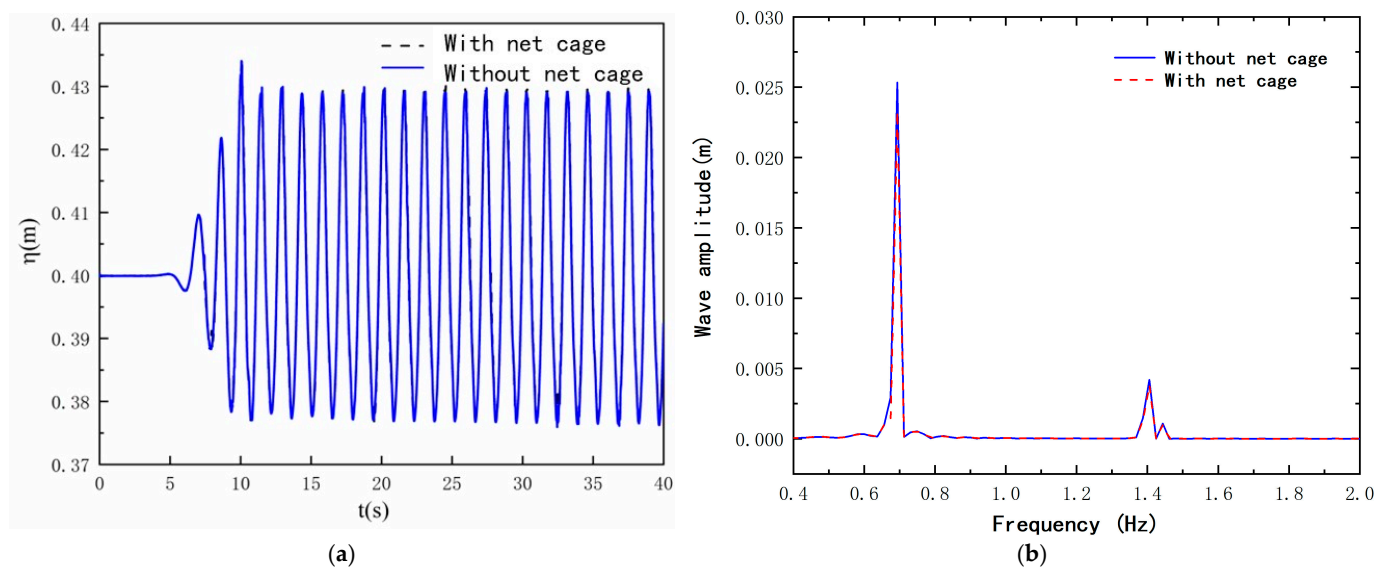


Figure 10. (a) Wave duration curve and (b) its amplitude spectrums at the cylindrical wave-facing surface.

Figure 11 illustrates the wave run-up (R) around the wind turbine foundation under varying solidity conditions. The wave run-up is calculated using the steady-state wave surface data after 20 s. It has been found that, at $\alpha = 180^\circ$ (upwave direction) for $S_n = 0.3$ to 0.5, the wave run-up at the upwave side of the foundation is the highest among all measurement points. At the same solidity conditions, the second-highest run-up occurs at $\alpha = 0^\circ$ (downwave direction, equivalent to $\alpha = 360^\circ$). For $S_n > 0.55$, the previous trend no longer holds. The wave run-up at the upwave direction ($\alpha = 180^\circ$) ceases to be at maximum and instead increases with higher S_n . On the other hand, the lowest wave run-up is observed within $\alpha = [45^\circ, 90^\circ]$ and $\alpha = [270^\circ, 315^\circ]$. These regions are recommended for placing critical equipment and support structures on the foundation to minimize wave impact on the platform.

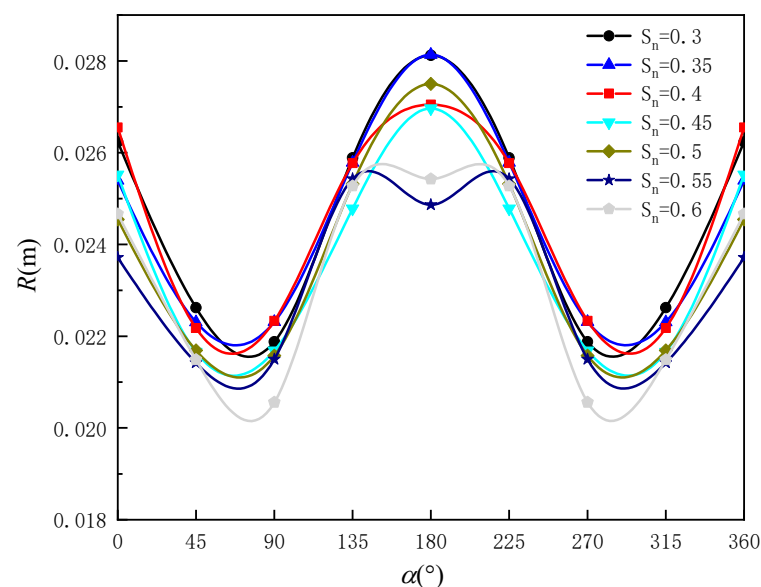


Figure 11. Wave run-up around the wind turbine foundation for different solidity conditions.

Figure 12 shows the variation curve of the average wave run-up $\bar{R}$ at all eight measurement points around the wind turbine foundation with cage solidity conditions in this

numerical simulation. The results demonstrate that, as S_n increases, $\bar{R}$ across the eight points gradually decreases. This indicates that higher solidity benefits the fixed wind turbine foundation near the cages. Over time, biofouling (marine organism attachment) on aquaculture cages inevitably increases their effective solidity. While this phenomenon is typically detrimental to standalone cages, in the combined turbine–cage system, it paradoxically enhances the hydrodynamic performance of the turbine foundation. These findings are in a good position to validate the combination of aquaculture cages and OWTs.

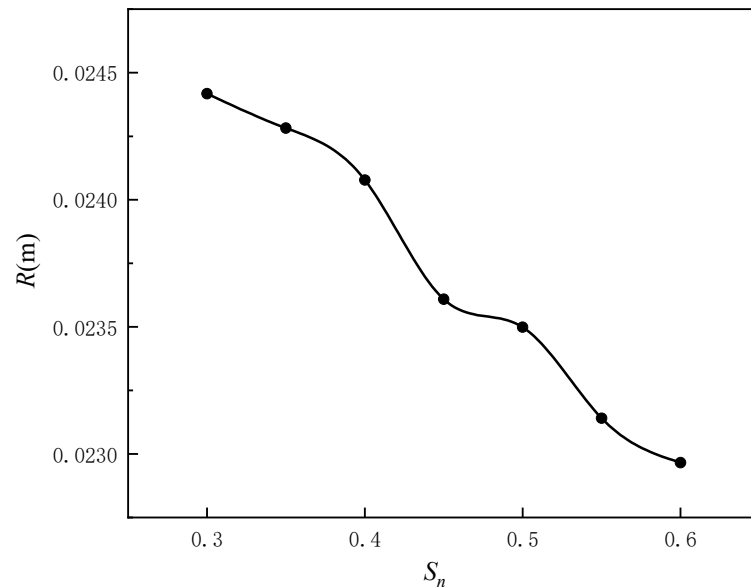


Figure 12. Curve of the average wave run-up around the wind turbine foundation.

3.2. Influence of Net Solidity on Hydrodynamic Forces of the Turbine Foundation

The wave-induced forces on the turbine foundation primarily consist of first-order wave forces (wave force at the fundamental frequency, F_1) and second-order wave forces (wave force at twice the fundamental frequency, F_2). This section analyzes the impact of net solidity S_n on these forces. Figure 13 illustrates the variation of first-order wave forces with S_n . The results show that, as S_n increases, the first-order forces on the turbine foundation located behind the cage array gradually decrease.

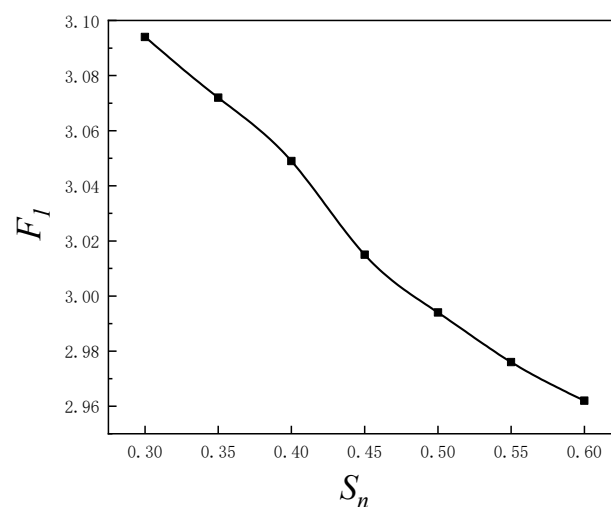


Figure 13. Variation of first-order wave forces on the turbine foundation with S_n .

Figure 14 presents the second-order wave forces as a function of S_n . For S_n between 0.3 and 0.6, the second-order forces diminish with increasing solidity. Figure 15 displays the ratio of second-order to first-order forces versus S_n , which aligns with the trend observed in Figure 14. These findings indicate that higher S_n reduces the nonlinearity of horizontal wave loads on the turbine foundation in the combined turbine–cage system.

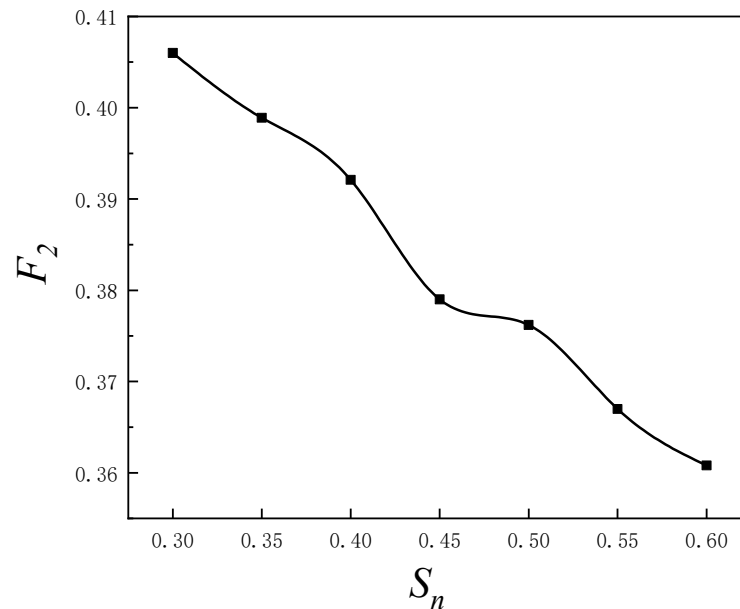


Figure 14. Variation of second-order wave forces on the turbine foundation with S_n .

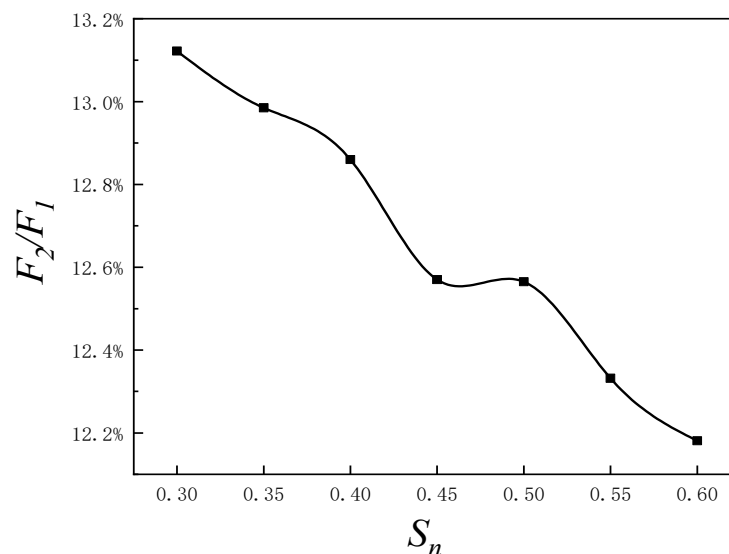


Figure 15. The ratio of second-order to first-order forces versus S_n .

Figure 16a shows the variation of the maximum horizontal wave force (peak positive force) with S_n . When S_n increases from 0.3 to 0.55, the maximum force decreases gradually, reaching its minimum at $S_n = 0.55$. However, for $S_n > 0.55$, the force unexpectedly increases. The reduction in maximum force between $S_n = 0.3$ and $S_n = 0.55$ is marginal, at only 2.5%. On the other hand, Figure 16b depicts the minimum horizontal wave force (peak negative force) versus S_n . The absolute value of the minimum force decreases with higher S_n , similar to the trend for the maximum force. The overall variation in peak forces (both maximum and minimum) is limited, with a total reduction of 6.4% across the tested S_n range.

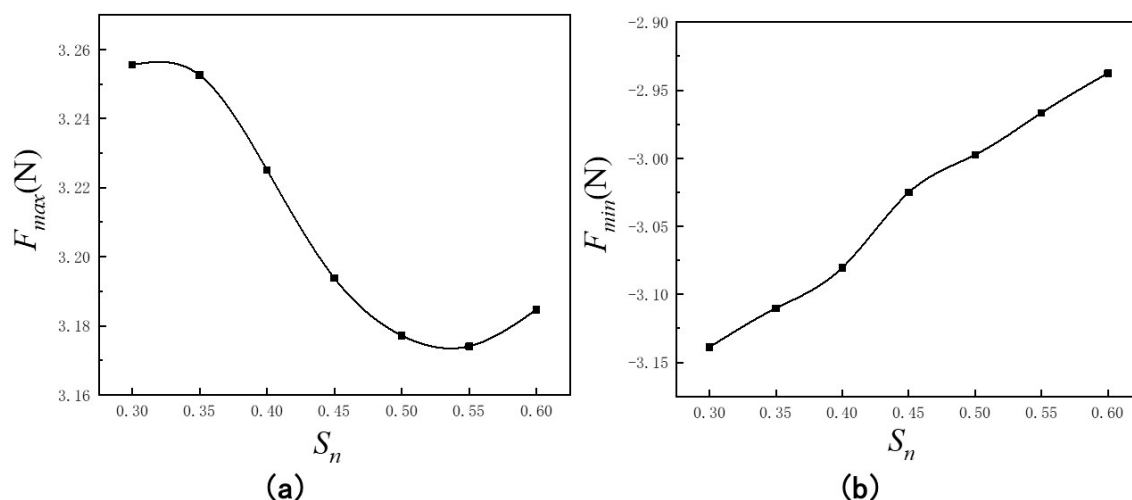


Figure 16. Variation of (a) maximum horizontal wave force and (b) minimum horizontal wave force with S_n .

The above results prove that the limited sensitivity of wave forces to S_n may stem from the permeable nature of cages and their relatively large dimensions compared to the turbine foundation. Only a small fraction of wave energy is dissipated after passing through the cages, resulting in minor changes to the peak horizontal forces acting on the foundation. It can be seen that increasing S_n effectively reduces nonlinear wave load components but has a limited impact on peak horizontal forces. The combined turbine–cage system demonstrates robustness against variations in net solidity, supporting its practical feasibility.

In this study, the Keulegan–Carpenter (KC) number for the wind turbine foundation is defined as $KC = \frac{U_{max}T}{d}$, where U_{max} represents the maximum horizontal velocity below the wave surface, T is the wave period, and d is the diameter of the foundation. Figure 17 shows the variation of the drag coefficient C_d and inertia coefficient C_m for the turbine foundation with S_n . As indicated in Figure 9, the transmission coefficient C_T at this position is minimal (0.95), implying wave height (H) attenuation does not exceed 5%. Given the minor attenuation, the theoretical wave forces were calculated using the unattenuated wave height, and the measured forces were combined with least squares fitting to determine C_d and C_m . The results in Figure 16 reveal that C_d increases with higher S_n , while C_m decreases.

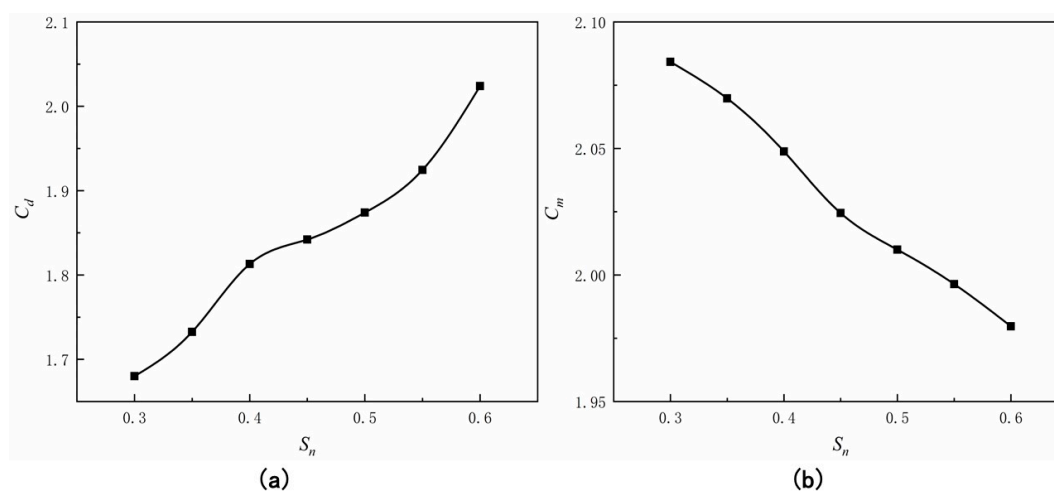


Figure 17. Variation of (a) the drag coefficient C_d and (b) the inertia coefficient C_m for the turbine foundation with S_n .

3.3. Influence of KC on Hydrodynamic Forces of the Turbine Foundation

Figure 18 illustrates the variation of C_d and C_m with the KC number for the turbine foundation at $Sn = 0.5$ and $T = 1.4479$ s under varying wave heights (see Table 2). The overall trend shows an initial increase in C_d , followed by a plateau, and then a gradual decrease. For $KC < 1.7$, C_d rises with increasing KC. At $KC = 1.7$ – 2.7 , C_d stabilizes near its maximum value. For $KC > 2.7$, C_d declines sharply. However, the inertia coefficient C_m exhibits a distinct three-phase behavior. For $KC < 2.5$, C_m decreases rapidly with rising KC. At $KC = 2.5$ – 3.2 , C_m remains relatively stable. For $KC > 3.2$, C_m resumes a gradual decline. The observed phenomena can be attributed to the following mechanisms: At low KC numbers, the flow field is dominated by inertial forces, and the velocity variation occurs over a longer time scale. Thus, the drag coefficient (C_d) increases with rising flow velocity, while the inertia coefficient (C_m) decreases rapidly due to reduced dominance of acceleration effects. With KC further increasing, turbulence intensifies around the turbine foundation, leading to stronger energy dissipation. It causes a decline in C_d (as turbulent mixing reduces steady drag forces) and a further reduction in C_m (as inertial effects are overshadowed by turbulent kinetic energy). The transition from inertial dominance to turbulence-driven energy loss governs the inverse relationship between KC number and force coefficients. This behavior aligns with classical fluid–structure interaction principles for bluff bodies in oscillatory flows.

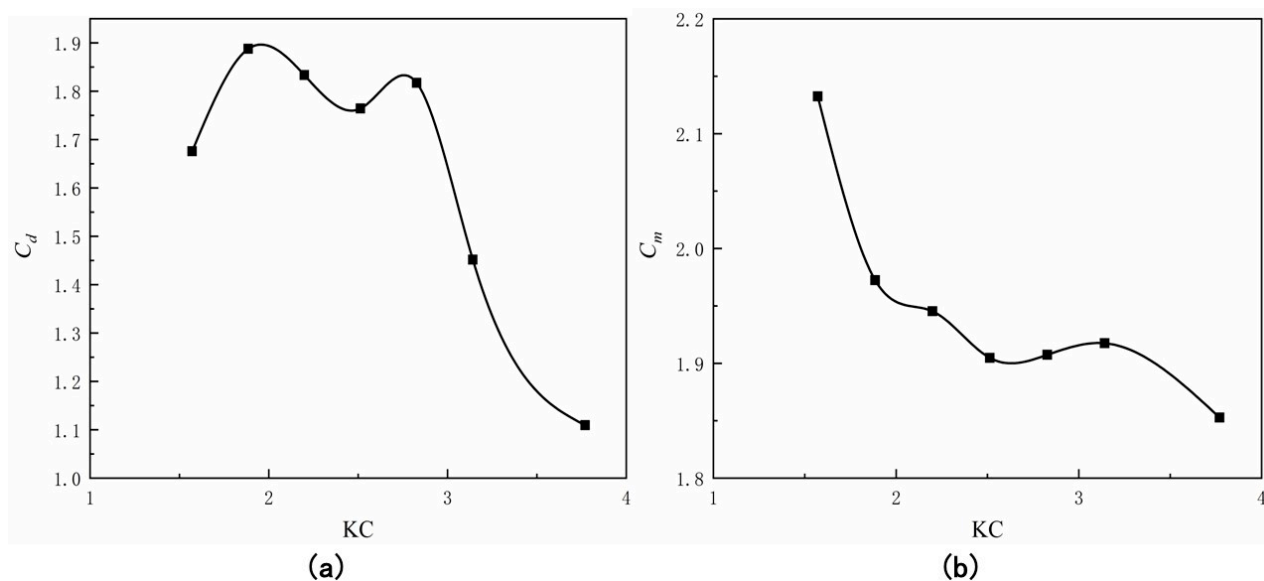


Figure 18. Variation of (a) C_d and (b) C_m with KC number for the turbine foundation at $Sn = 0.5$.

4. Conclusions

The hydrodynamic characteristics of a fixed offshore wind turbine foundation integrated with aquaculture cages under finite-depth wave action were investigated using a porous media model in numerical simulation software. The numerical model in this study was validated by grid convergence analysis and physical experimental comparisons, thereby ensuring the computational efficiency and accuracy of the grid-based simulations. This study focused on the influence of cage solidity conditions on wave run-up around the turbine and horizontal wave forces. The key conclusions are as follows:

(1) Within the cage array, the transmission coefficient C_T occasionally exceeds 1, likely due to wave reflection and local standing wave effects. Near the cage group ($\Delta X/d < 3$), C_T decreases rapidly with distance, indicating strong wave attenuation. Higher net solidity

(Sn) significantly reduces wave energy in the vicinity of the cages, demonstrating that increased Sn effectively dampens the surrounding wave field.

(2) At $Sn = 0.55$, the maximum wave run-up R no longer occurs in the upwave direction ($\alpha = 180^\circ$) for the monopile, suggesting a critical solidity threshold. At $Sn = 0.6$, the maximum wave run-up R at $\alpha = 180^\circ$ for the monopile decreases by 9.6% compared to the case at $Sn = 0.6$. In addition, the wave run-up at $\alpha = 180^\circ$ becomes comparable to adjacent measurement points ($\alpha = 45\text{--}90^\circ, 270\text{--}315^\circ$), flattening the spatial distribution of R . Increasing Sn reduces the average wave run-up around the turbine foundation, enhancing structural safety.

(3) Higher Sn weakens the nonlinearity of horizontal wave forces, reducing both first-order (fundamental frequency) and second-order (double frequency) forces. Negative horizontal forces (minimum values) decrease monotonically with Sn . The maximum positive horizontal force decreases initially with Sn , reaches a minimum at $Sn = 0.55$, and then increases for $Sn > 0.55$. This nonlinear reversal may arise from turbulent flow separation or vortex shedding occurring in the monopile.

(4) The drag coefficient C_d for the turbine foundation increases with Sn , while C_m decreases, reflecting enhanced drag dominance and reduced inertial effects at higher solidity. C_d initially rises with KC , stabilizes at $KC = 1.7\text{--}2.7$, and declines sharply at $KC > 2.7$. C_m decreases rapidly at $KC < 2.5$, plateaus at $KC = 2.5\text{--}3.2$, and resumes decreasing at $KC > 3.2$. This trend aligns with the transition from inertia-dominated to turbulence-dominated flow regimes.

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