

Net Deformation and Cage Volumes in Towed Gravity Fish Cages

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Abstract

The deformations of the nets and cage volumes of gravity cages are investigated through experimental and numerical methods. The gravity cage model is towed in calm water as well as in regular waves. Pressure sensors are used to measure the depths at different points on the cage net. These depths are successfully measured in calm water and long waves. A numerical model is developed using ANSYS/APDL to compute the cage deformation. The results from the numerical model align well with the experimental results. Furthermore, cage volumes are calculated using a numerical method. Notably, the cage volume decreases as flow velocity increases. Increasing the bottom weight can help counteract the reduction in cage volume. Furthermore, the cage volume reduces more substantially in short waves, while that in long waves approaches the values observed in uniform flow. Finally, the limitations of the experiment are discussed, and suggestions for further enhancements are provided.

Keywords Gravity cage; Cage volume; Towing experiment; Net deformation; Effect of wavelength

1 Introduction

Gravity cages are widely used in the aquaculture industry due to their simple operation, large cage volume, and low construction costs. However, the cage volume can decrease rapidly when subjected to currents due to the large deformation of the flexible nets. This reduction in volume adversely affects the health and growth of the enclosed fish. Hence, accurately assessing the cage volume is crucial for determining fish production.

Numerous studies have been conducted to evaluate the performance of gravity cages. Berstad and Tronstad (2005) investigated the performance of a fish farm using numerical methods, considering the effects of currents with and

without the presence of waves. Their study focused on the impact of regular and irregular waves on mooring forces. Kristiansen and Faltinsen (2009) conducted experimental and numerical analyses on the motion of a gravity cage model, achieving notable agreement between the two methods.

DeCew et al. (2010) investigated the dynamics of a submergence cage through experiments and used the data to validate their numerical model. Their findings indicated that high net solidity could lead to increased mooring forces and deep immersion depths. In another study, Xu et al. (2013) developed a numerical model to assess various mooring designs for cage arrays. In their experiments, Zhao et al. (2013) discovered that column cages outperformed square cages, exhibiting lower mooring forces and motion amplitudes. Xu et al. (2014) explored the application of a rigid frontal frame connected to the mooring lines to maintain cage volume, and they validated the effectiveness of this method through a numerical model.

Bi et al. (2014) investigated wake flow and net deformations using finite element method (FEM) and computational fluid dynamics (CFD). They found that increasing the number of net layers could reduce current velocity. Kristiansen and Faltinsen (2015) evaluated the performance of cages with varying dimensions through experimental and numerical methods. They concluded that the variations in the numerical results were relatively insensitive to the variables used in their calculations.

He et al. (2018) placed over 800 fish in a gravity cage model to examine their impact on mooring forces and compared the deformation of the cage. They found that when

Article Highlights

- The deformation of the gravity cage is successfully measured in both calm water and regular wave conditions and the results are used to validate a numerical method.
- Increasing the bottom weight of the cage can both mitigate the cage deformation and volume reduction.
- The cage volume decreases with increasing flow velocity, with a more pronounced reduction observed in short wave conditions compared to long wave.

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the flow is considerably strong, the fish school gathered at the rear of the cage, increasing net deformation due to greater contact with the nets. Hou et al. (2018; 2022) used their FEM results for subsequent fatigue analysis to evaluate the lifespan of the mooring ropes. Faltinsen and Shen (2018) reviewed current methods for simulating fish cages and discussed the important factors that must be considered in these simulations.

Zhao et al. (2019) used numerical methods to analyze the stress on the collar. They found that increasing the number of bridle ropes helped reduce stress concentration. In the experiment by Klebert and Su (2020), they measured the flow velocities inside and behind a commercial cage. Their findings revealed that the flow decreased, and turbulence occurred closely behind the floating part of the cage. Bui et al. (2020) modeled the nets using porous zones and calculated the flow around different cage arrays. Liu et al. (2021a) compared the calculated cage volumes from their numerical model with published experimental results, achieving good agreement. Dong et al. (2021) assessed model uncertainty in calculations related to the behavior of aquaculture structures, drawing on experimental and computational studies from the literature.

Cheng et al. (2021) analyzed the performance of a cage after a mooring rope fractured in a cage array comprising four cages. They found that the fracture only had a temporary effect on the cage volume. Liu et al. (2021b) validated their numerical model using theoretical approaches. Subsequently, Liu et al. (2022) applied the same numerical method to create a model for a fish farm featuring six gravity cages, analyzing mooring forces and identifying the location of the maximum mooring force. Jin et al. (2021) used potential flow theory to calculate the motion of a solid cage system and compared their results with experimental findings.

Using the numerical framework developed by Martin et al. (2021), large deformations and fluid interactions were considered in their calculations of cage behavior using CFD and the lumped mass method. In the experiment conducted by Park et al. (2021), they measured the mooring forces for different bridle rope designs and found that increasing the number of bridle ropes and connecting them in the middle of the frame ropes helped reduce the mooring forces.

Zhao et al. (2021) observed low-velocity regions behind the frames of a cage through their CFD calculations. They also found that the presence of the net expanded these areas. Mjåtveit et al. (2022) used numerical methods to assess the performance of cages with varying dimensions. Their investigation revealed that square cages provide a larger volume per net area and require less mooring force per unit of culturing volume. Ma et al. (2022a) investigated the dynamics of hinged cage arrays under waves, noting that the stiffness of the hinged connections substantially influences cage motions.

Wang et al. (2022) compared the numerical results for a

vessel-shaped cage, with and without considering diffraction and radiation waves. Their comparison emphasized the importance of accounting for diffraction and radiation waves in numerical calculations. In their subsequent research, Wang et al. (2023) applied this approach to calculate the performance of cages in irregular waves.

In their experiments, Liu and Guedes Soares (2022a; 2022b) constructed a small-scale model to study the wake flow behind gravity cages. They observed that the nets experienced considerable deformation in short waves. Ma et al. (2022b) studied the response of a vessel-shaped aquaculture platform in their experiments and found that the square frame was preferred over the triangular frame for the floating part of the platform. Gharechae and Ketabdari (2022) developed a semi-analytical approach to study the behavior of collars in an array, considering the hydroelastic interaction. They found that the load on the upstream collars in the array is even larger than that on a single collar.

Shaik et al. (2023) examined the impact of cage arrangement on the performance of net cages using experimental and numerical methods, providing recommendations for an overall optimization scheme. Liu et al. (2023) conducted experiments to assess the motion and mooring forces of gravity cages with varying dimensions under regular waves. They observed distinct behavioral differences in cages subjected to short and long waves. Liu and Guedes Soares (2024a) used these results to validate their numerical calculations and computed the mooring forces for gravity cages located in potential areas around Portugal. Using potential flow theory, Xu et al. (2024a; 2024b) established a model to predict wave heights for floating structures, while Lei et al. (2024) constructed a numerical model of a floating system combining a wind turbine and a solid fish cage. They compared the mooring forces and motion, emphasizing the importance of the second-order wave forces in the calculations.

Based on the existing studies mentioned above, the experiments mainly measure the forces or motions of the cages, while the cage's deformation is usually based on observation or numerical calculations. Due to the flexible nature of the nets, measuring their deformation underwater is very challenging. Conversely, it is essential for validating the numerical calculations.

This paper introduces a method of using pressure sensors to determine the depth of the nets at different positions within the cage during towing tests. Considering the limited number of measurement points, the volume of the net cage cannot be directly calculated from the measurement results. The experimental results are used to validate a numerical model, which is then utilized to calculate the cage volumes. Additionally, the impact of waves on the deformation and cage volume is examined through experiments and numerical calculations. Sections 2 and 3 present the physical and numerical models, respectively. Section 4

compares the calculated and measured cage depths in calm water and analyzes the trends observed in waves, while Section 5 presents the calculated cage volumes. Section 6 discusses the findings and uncertainties from the experiments, and Section 7 provides a concluding summary.

2 Physical model of the gravity cage

The models are towed in calm water and regular waves within a towing tank. The towing tank has a length of 170 m and a width of 7 m, maintaining a consistent water depth of 3.65 m. Towing velocities vary across different conditions: in calm water, velocities range from 0.2 to 0.5 m/s. In towing tests conducted under regular wave conditions, the velocities are set at 0.2 and 0.5 m/s. Aiming to comprehensively assess cage performance, waves of varying heights and periods are generated within the tank to simulate different environmental conditions. The wave heights for Waves 1 to 4 are close to 0.045 m, while the heights for Waves 5 to 8 are close to 0.075 m. The wavelengths range from 2 to 8 m, increasing by 2 m with each successive wave. The wave parameters are listed in Table 1. Measurements are taken over at least 40 periods for each operating condition to reduce measurement errors.

Table 1 Parameters of the waves in the towing tests

Wave number	Wave height (mm)	Wave length (m)	Wave period (s)	Froude scaled wave periods (s)
1	45	2	1.13	3.57
2	45	4	1.60	5.06
3	45	6	1.96	6.20
4	45	8	2.26	7.15
5	75	2	1.13	3.57
6	75	4	1.60	5.06
7	75	6	1.96	6.20
8	75	8	2.26	7.15

The gravity cage model is constructed using high-density polyethylene (HDPE) pipes, nylon nets, and rebar. The pipes and rebar are formed into ring structures, serving as the floating collar and bottom ring. The cage has a diameter of 2 m. Two distinct models are assembled, each featuring a different-weight bottom ring. Model 1 incorporates a bottom ring with a diameter of 16 mm, while Model 2 features a bottom ring with a diameter of 12 mm. The nylon nets are securely fastened to the floating collar and bottom ring using belts. The overall height of cage models is maintained at 2 m. Figure 1 shows the configuration of the model submerged in water. The dimensions of the cage and Froude scaling are presented in Table 2, while the mechanical properties of the components are listed in Table 3.

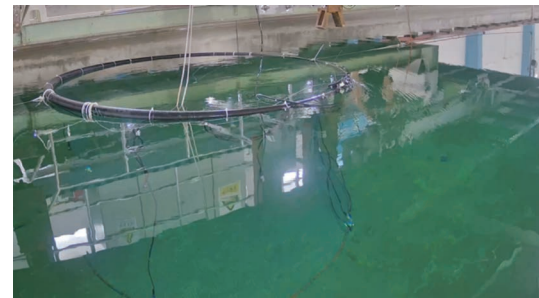


Figure 1 Physical model in the water flume

Table 2 Dimensions of the gravity cage model

Parameter	Small-scale model	Full-scale cage	Froude scale
Diameter of the collar	2 m	20 m	0.1
Cage depth	2 m	20 m	0.1
Diameter of the collar cross-section	63 mm	0.63 m	0.1
Thickness of the collar	5.3 mm	53 mm	0.1
Length of the nets	1.95 m	19.5 m	0.1
Diameter of the cross-section of the bottom ring	12 mm/16 mm	120 mm/160 mm	0.1

Table 3 Mechanical properties of the physical model

Component	Material	Density (kg/m ³)	Young's modulus
Collar	HDPE	860	1.1 GPa
Net	Nylon	1150	350 MPa
Bottom ring	Rebar	7800	200 GPa

Pressure sensors are attached to the cage to measure its height during the towing tests. The MPM258 sensor from the Microsensor is used, with a range of 30 kPa. The sensor locations are shown in Figure 2. The first sensor is located in the middle of the left side of the cage. The second sensor is positioned at the center of the back of the cage. The third sensor is located at the bottom of the cage, rotated 135° counterclockwise from the front. The sensors are connected to a water-resistant microcontroller mounted on the collar, which transmits the data to the computer on the carriage.

In some previous studies (Lader et al., 2008; Gansel et al., 2018), the points measured on the nets are assumed to move solely within planes parallel to the flow direction. Horizontal displacements of the nets were subsequently determined using the measured depths and net lengths, considering the negligible elongation of the nets. However, in the current experiment, observations indicate that the measured points on the nets do not exclusively move within planes parallel to the flow direction. The previous method is not applicable to this study. Therefore, the measured

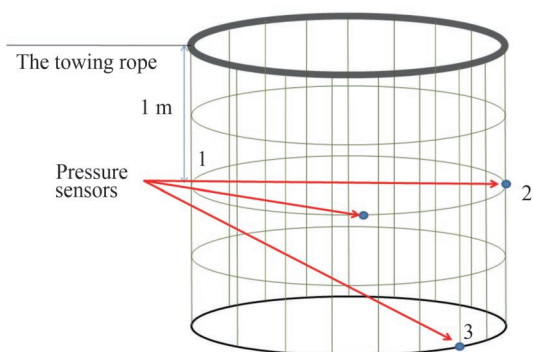


Figure 2 Locations of the pressure sensors on the cage model

depths of the nets became the only data available for validating the numerical model. A comparison between the measured results and numerical calculations is presented in Section 4.

3 Numerical model of the gravity cage

A finite element model is used to compute cage deformation and volume. A transient analysis is performed in Ansys/APDL to simulate the cage's response to currents and waves. The structures, such as the bottom ring and floating collar, are modeled using beam elements with the same dimensions to account for bending moments. Flexible nets are represented using link elements, which are uniaxial tension–compression elements with three degrees of freedom at each node: translations in the nodal x -, y -, and z -directions. Several continuous link elements are used between two knots to model the behavior of the flexible nets, which do not have bending stiffness.

The structural dynamic equilibrium equation can be expressed as follows:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{G} + \mathbf{f}_b + \mathbf{f}_H \quad (1)$$

where $\mathbf{M}$ is the mass matrix, $\ddot{\mathbf{x}}$ is the acceleration vector, $\mathbf{C}$ is the damping matrix, $\dot{\mathbf{x}}$ is the velocity vector, $\mathbf{K}$ is the stiffness matrix, $\mathbf{x}$ is the displacement matrix, $\mathbf{G}$ is the gravity, $\mathbf{f}_b$ is the buoyancy, and $\mathbf{f}_H$ is the hydrodynamic load on the structure.

As a crucial parameter for calculating the hydrodynamic load, the solidity of the knotted nets can be expressed as:

$$S \approx \frac{\pi r^2 + 2d(L - 2r)}{L^2} \quad (2)$$

where S is the solidity, r is the radius of the knotted part, d is the width of the net twine, and L is the length of the net mesh. The net mesh length used in this study is 21 mm, the twine width is 0.9 mm, and the radius of the knotted part is 1.3 mm.

If the link elements have the same dimensions as the twines of the nets, then the numerical model will contain an excessive number of elements, resulting in long calculation times. Aiming to reduce the total number of elements and computational time, the net structure is simplified based on its solidity. The schematic representation of the numerical model is presented in Figure 3. While maintaining the cross-sectional areas of the vertical, horizontal, and bottom elements identical to the original structure, the projected area of the nets is reduced. Consequently, the revised net structure maintains the same axial stiffness and weight characteristics compared to the original design, with the material properties remaining unchanged. Aiming to compensate for the reduction in the projected area and ensure that the hydrodynamic load remains consistent, coefficients are adjusted in accordance with the ratio in Table 4.

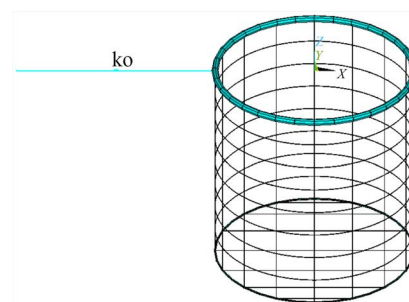


Figure 3 Numerical model using Ansys/APDL

Table 4 Parameters of link elements to model the nets

Name	Number of the lines	Radius of the lines (mm)	Ratio of the projected area reduction
Horizontal lines	6	1.78	4.08
Vertical lines	16	1.93	4.43
Bottom lines	14	1.37	3.15

The Morison equation (Faltinsen, 1990) is used to calculate the current and wave load and can be expressed as:

$$f = C_M \rho \frac{\pi D^2}{4} \ddot{u} - (C_M - 1) \rho \frac{\pi D^2}{4} \ddot{x} + \frac{1}{2} C_D \rho D |u - \dot{x}| (u - \dot{x}) \quad (3)$$

where f is the hydrodynamic force per length, C_M is the mass coefficient, C_D is the drag coefficient, ρ is the density of seawater, D is the diameter of the slender structure, u and $\dot{u}$ are the velocity and acceleration of the water particle, respectively, and $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the structure element, respectively. Detailed information regarding the simplifications in the numerical model can be found in earlier works (Liu and Guedes Soares, 2023; 2024b).

4 Comparison between the measured and calculated cage depth

The validation of the numerical model includes comparisons of the towing forces and vertical displacements of the nets. In a previous study (Liu and Guedes Soares, 2024c), the drag forces in the numerical calculations were validated by comparing them with measured towing forces from the experiments. The average difference between the numerical and experimental results in calm water was 7.1%. The towing experiments in calm water simulate the behavior of the cage in uniform flows; thus, the results from these experiments are compared in Section 4.1. However, towing experiments conducted in waves do not fully capture the interaction between waves and currents. Therefore, in Section 4.2, only the trends of the results in waves, rather than the exact values, are compared.

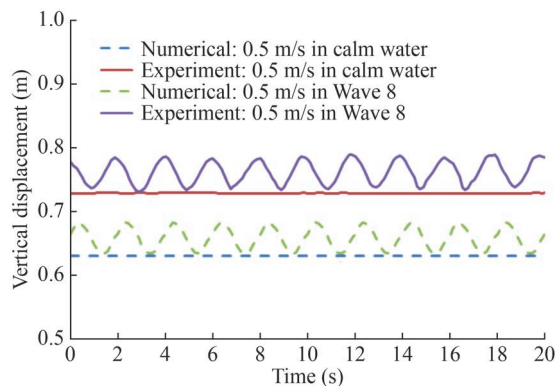


Figure 4 Numerical and measured results in the time domain at 0.5 m/s

4.1 Results of the vertical displacements in calm water

Figures 5 and 6 show the measured and calculated vertical displacements for Models 1 and 2, respectively. The results show that the vertical displacement increases with higher towing and current velocities. Model 2, which has a lighter bottom ring, has larger vertical displacements than Model 1. The measured vertical displacement at Point 3 for Model 2, with a towing velocity of 0.5 m/s, is 1.13 m, indicating a 0.4 m increase compared to Model 1. This finding indicates that the weight of the bottom ring notably influences cage deformations.

Moreover, observations from both figures reveal that differences between measured and calculated results become more noticeable at high velocities. At a towing velocity of 0.2 m/s, the differences remain below 12 mm. However, as the velocity increases to 0.5 m/s, the largest difference reaches 0.177 m for Model 2. However, the average difference between the calculated and measured results is 11%, confirming the reliability of the numerical model.

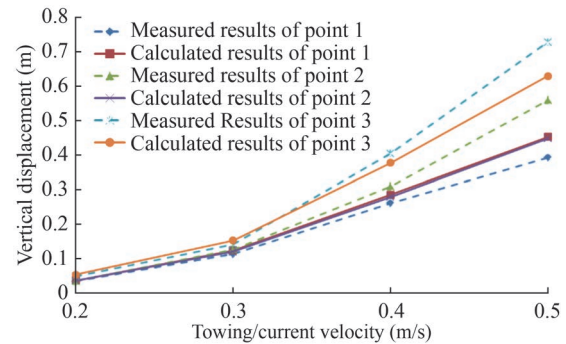


Figure 5 Vertical displacements of Model 1 in calm water

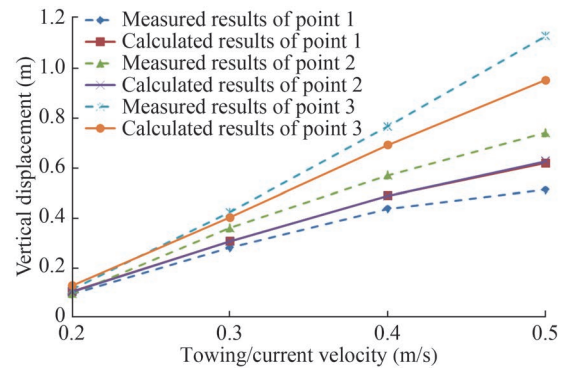


Figure 6 Vertical displacements of Model 2 in calm water

In addition, for Points 1 and 2, the calculated vertical displacements are remarkably close because they are located in the same horizontal layer of the cage. As shown in Figures 5 and 6, the plots for the two points almost coincide. However, as the velocity increases, the measured results of Point 1 become smaller than the calculated value, while the measured results for the other two points, located at the back part of the cage, become larger than the calculated values. This discrepancy can be attributed to the inclination of the bottom ring, as discussed in Section 6.

4.2 Results of the vertical displacements in regular waves

This section presents the amplitudes and mean values of the vertical displacements. The displacements subjected to all the waves were measured. Choosing the use of the smallest possible equipment to minimise its impact on the results, the chosen microcontroller has limited capacity, resulting in a low sampling frequency of only 7 to 8 Hz, resulting in the number of measured points for the short waves for each period being insufficient. Thus, only the results for the longest waves are compared in this section. The amplitudes and the mean values of the measured and calculated vertical displacements are shown in Figures 7 and 8.

Unlike the analysis in calm water, where the towing speed can be directly equated to the current velocity in the numerical model, the conditions in the towing tests under regular waves differ from those in the numerical model. Therefore,

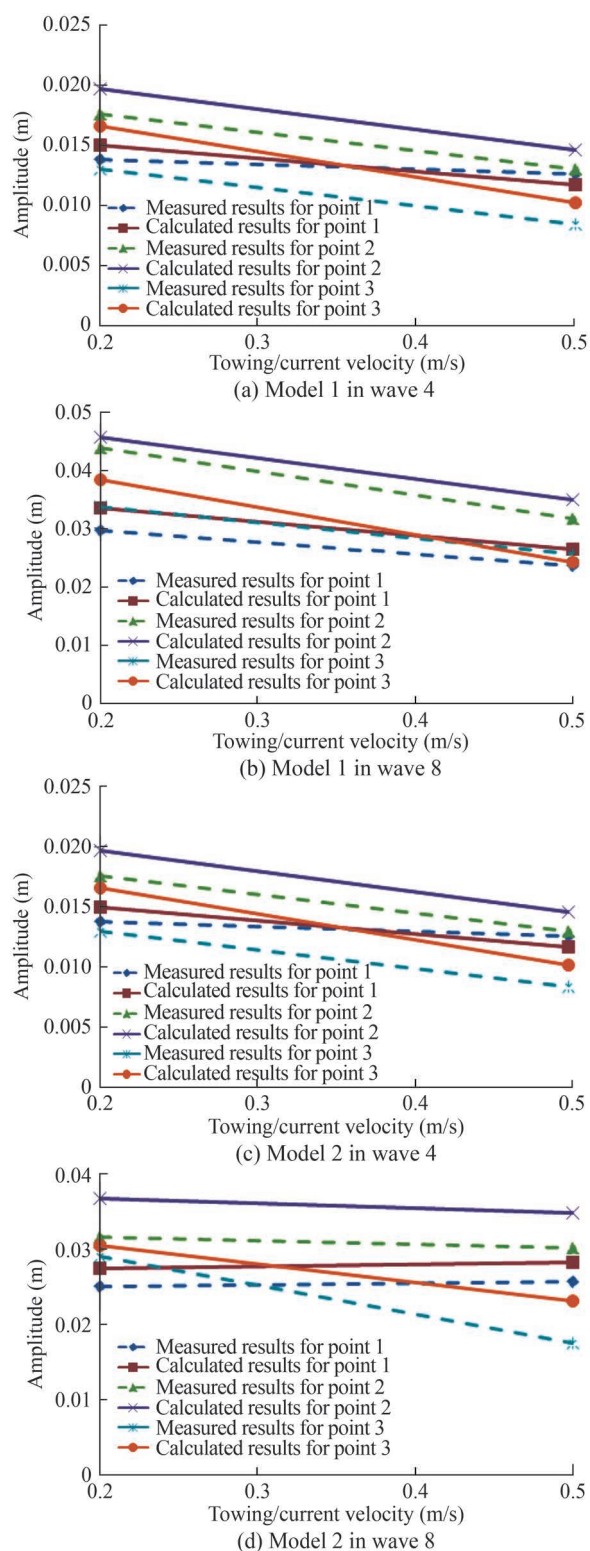


Figure 7 Amplitudes of the vertical displacements

the wave periods in the numerical calculations are adjusted based on the towing velocities as follows:

$$\omega_N = \omega_T + \frac{\omega_T^2 v}{g} \quad (4)$$

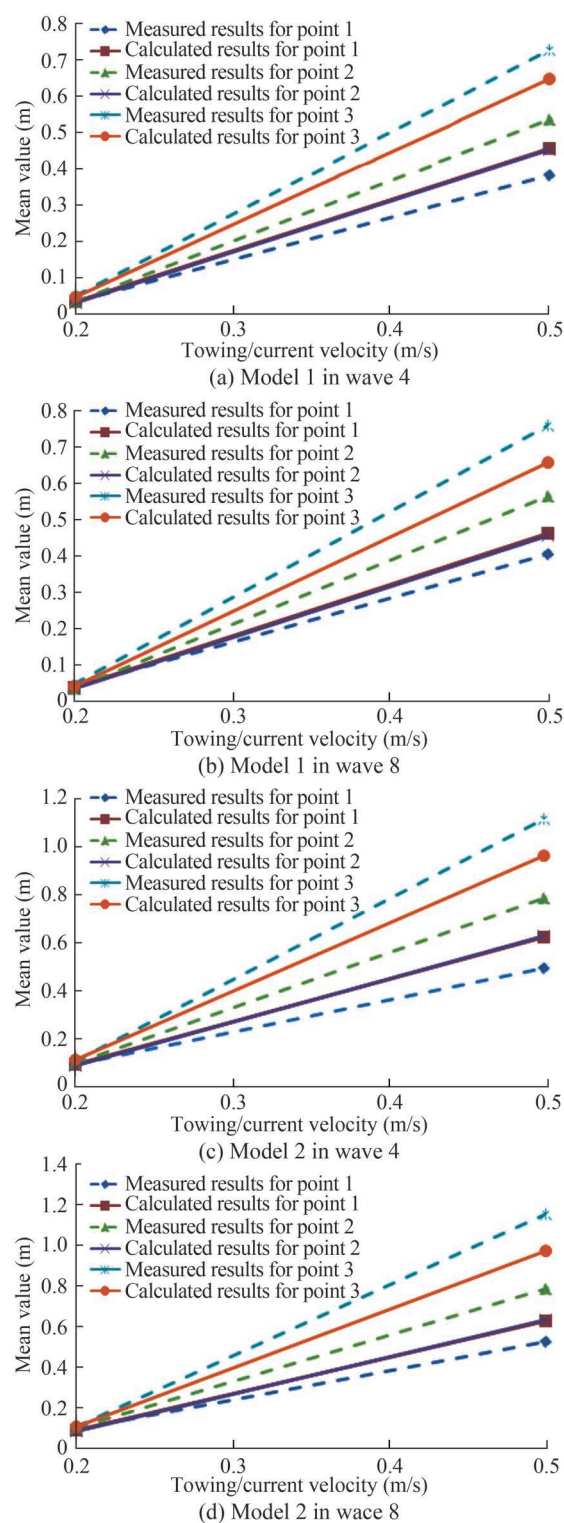


Figure 8 Mean values of the vertical displacements

where ω_N is the calculated encounter frequency, which is applied in the numerical model, ω_T is the frequency in the towing tests, and v is the towing velocities in the towing tests. As shown in Figure 4, the frequencies of the results are consistent, and the trends of the mean values and amplitudes are consistent. The similarity in trends between the numerical

models and the experimental results further supports the validity of the numerical calculations. First, Figure 7 shows that the amplitudes decrease as the current velocity increases. Additionally, the amplitude values are relatively small compared to the mean values, indicating that currents have a greater effect on cage deformation than waves. Furthermore, similar to the situation in calm water, nets at greater depths tend to rise more under the same conditions. The consistency of these trends, along with the conclusions from Section 4.1, validates the reliability of the numerical model.

However, the wave-current interaction is not simulated in the towing tests. The hydrodynamic loads acting on the cage in the experimental and numerical models remain inconsistent due to differences in environmental conditions. Consequently, the differences between the experimental and numerical calculations increase. On average, the differences in amplitudes and mean values are 11.9% and 12.5%, respectively. The maximum amplitude difference reached 28.3%, with the differences increasing as the towing velocities rise.

5 Calculated results of the cage volume

The cage volumes are determined based on the numerical results obtained from the above models. Node coordinates are recorded and used as input data in CAD software, creating a solid representation of the cage. The software then calculates the cage volume based on this geometric model. Comparing the cage volumes, the normalised cage volume is defined as the ratio between the volumes of the deformed cage to the volume of the undeformed cage, which can be expressed as:

$$V_n = \frac{V_c}{V} \text{ or } \frac{V_w}{V} \quad (5)$$

where V_n is the normalised volume, V_c is the cage volume in the uniform flow, V is the cage volume in calm water, and V_w is the minimum cage volume in a period from five points taken evenly within one period. Aiming to explore the influence of waves, the effect factor, α , is defined as the proportion between the cage volumes in calm water and in the regular waves under the same current velocity, which is expressed as follows:

$$\alpha = \frac{V_c}{V_w} \quad (6)$$

5.1 Cage volumes subjected to currents

As shown in Figure 9, the cage volume decreases as the current velocity increases. The normalised cage volumes of Models 1 and 2 are 0.94 and 0.89 at 0.2 m/s, respectively, while those for Models 1 and 2 reduce to 0.62 and 0.46, respectively, at 0.5 m/s. The bottom weight of Model 1 is 1.78 times that of Model 2. The cage volume of Model 1

is 5% larger than that of Model 2 at 0.2 m/s, which then increases to 33.8% at 0.5 m/s. A heavy bottom ring is beneficial in mitigating the reduction in cage volume, particularly under high current velocities.

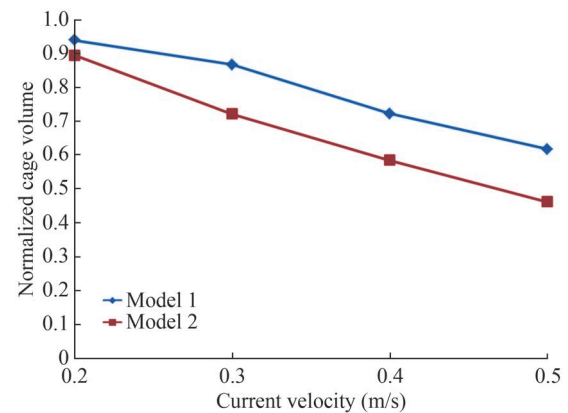


Figure 9 Normalized cage volume of the two cage models subjected to uniform flow

5.2 Cage volumes subjected to currents and waves

Figures 10 and 11 show the effect factor, α , for Models 1 and 2, respectively, in different current velocities and waves. Waves have a notably smaller effect on cage volumes than the current. The smallest effect factor is 95.2%, obtained by Model 2 subjected to 0.5 m/s current velocity and waves with 75 mm height and 2 m length. Based on the plots, as the wavelength increases, the impact of the waves on cage volumes becomes gradually negligible. Previous numerical investigations and experimental observations (Liu et al., 2023; Liu and Guedes Soares, 2023) revealed that this phenomenon is mainly due to changes in cage shapes induced by short waves. Conversely, the cage behaves similarly to a solid body in motion when exposed to long waves.

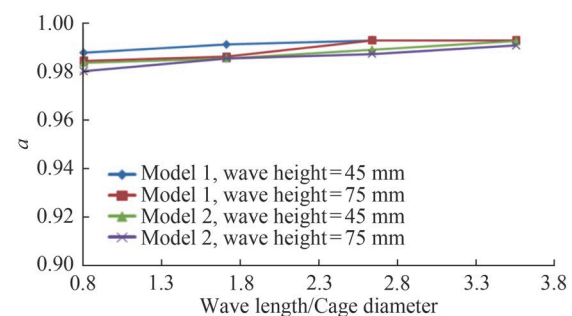


Figure 10 Effect factors of the two models subjected to regular waves at 0.2 m/s

In addition, from Figures 10 and 11, cage volumes demonstrate considerable reductions under high waves, especially when subjected to short waves. For instance, the effect factor is 96.6% for Model 2 at a velocity of 0.5 m/s and waves of 2 m length and 45 mm height. The effect factor decreases to 95.2% when the wave height increases to 75 mm. Furthermore, a heavy bottom ring can help reduce

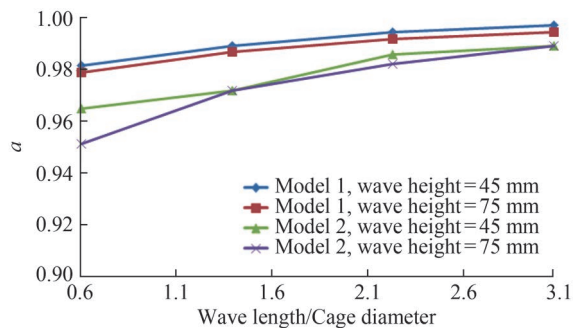


Figure 11 Effect factors of the two models subjected to regular waves at 0.5 m/s

the impact of waves on the cage volume. Under the same conditions, the volume of Model 1 is consistently larger than that of Model 2.

6 Discussion

This section addresses the limitations of the towing tests and the difficulties encountered during the experiment, which could provide insights for future experimental studies.

6.1 Uneven distribution of the nets

A relatively large model is established for this experiment to obtain a small ratio between the wavelength and the cage diameter. However, this model increases the difficulty during the manufacturing process. Considering the elasticity of the net, achieving uniform hanging on the collar and the bottom ring proved challenging. However, as depicted in Figure 3, the numerical model demonstrates evenly distributed nets, with the diameters of the net circles precisely matching that of the cage. By contrast, the physical model does not exhibit this precision due to the shrinkage of the nets. Consequently, this discrepancy leads to differences in the projected area between the models.

In addition, the uneven distribution of the nets leads to uneven stretching. Some parts are tightly stretched, while some parts are loose. Figure 12 compares the cage deformations at 0.5 m/s. Although the wide-angle camera under the water distorts the dimension of the photographed cage, the bottom ring still declined. However, this phenomenon is not visible in the numerical model. This finding also helps explain the discrepancies found in Section 4.1, where the measured results for Point 1, located at the front part of the cage, are smaller than the calculated results, while the measured results for Points 2 and 3, located at the back part of the cage, are larger than the calculated results.

6.2 Limitation of the measuring system

As mentioned, the sampling frequency of the measuring

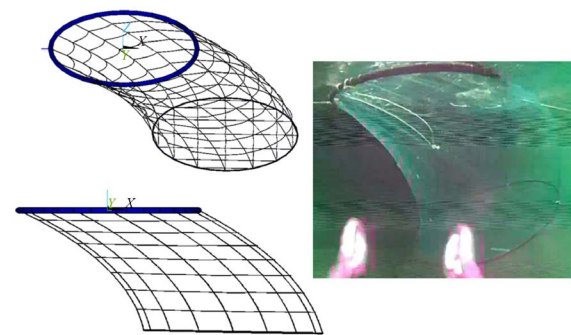


Figure 12 Comparison between the cage shapes of the numerical and physical models

system is relatively low, which is another limitation of the experiment. During the design phase of the experiment, the depths of more points are supposed to be measured, enabling direct calculation of the cage volumes from these measurements. The results can then be used to validate the numerical calculations of the cage volumes. Commercial waterproof sensors were not selected to reduce the weight and influence of the measuring system. Instead, lightweight, bare sensors were used, and a waterproof cover for the entire system was constructed. However, due to a lack of experience, the capabilities of the microcontroller were not considered, and the waterproofing was insufficient for long-term measurement. During the tests, some sensors failed due to water intrusion, and the sampling frequency was not sufficiently high to capture displacements caused by short waves. Thus, the verification of the numerical model relies solely on the measured results from three points, while for waves, only the measured results from long waves were used. Unfortunately, the calculated results for short waves cannot be validated at this time. Thus, future tests should focus on measuring the results for short waves.

Furthermore, in this experiment, only the depths are compared, and the displacements in other directions are not considered. Unfortunately, building a suitable system that can move with the carriage is challenging and would have minimal effect on the fluid field. A system that can measure net deformations should be developed for future experimental studies on cage volume.

6.3 Influence of the measuring system on the results

Although the weight and size of the sensors are kept as light and small as possible, they still affect the net deformation. However, comparing the cage depths with and without the sensors is impossible. Fortunately, a previous study (Liu and Guedes Soares, 2024c) measured the drag forces. The drag forces for Model 1, with and without the sensors, were measured, and the differences were all less than 0.8%. This finding indicates that the effect of the sensors on the measured results is minimal.

7 Conclusions

This study investigates the deformations and volumes of the cage in currents and waves using experiments and numerical methods. The vertical displacements at different points on the cage, which are measured and calculated, are compared. The cage volumes are calculated using the same FEM method. The following conclusions can be drawn:

1) The numerical calculations agree well with the experimental findings. In calm water, the average difference between the measured and calculated results is 11%. Additionally, the trend observed in the towing tests aligns closely with the numerical results.

2) Waves, especially long waves, have notably smaller effects on the cage volumes compared to currents. The cage volumes are reduced to 62% and 46% for models with different bottom weights at 0.5 m/s. By contrast, the smallest effect factor of regular waves results in a volume reduction of only 95.2%.

3) Comparing the cage's results with bottom rings of different weights reveals that increasing the weight of the bottom ring is an effective method for preserving the cage volume.

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