NUMERICAL ANALYSIS ON THE REFLECTION COEFFICIENT OF A CURTAIN BREAKWATER USING OPENFOAM

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Abstract: This paper presents a two-dimensional numerical investigation on the reflection coefficient of a curtain breakwater including a seaside drooping plate and a leeside caisson. A numerical wave flume is developed based on the continuity equation and the Navier-Stokes equation where the VOF method is used to track and locate the free surface. Relaxation zone method is used to implement the generation and absorption of waves. The numerical results of the reflection coefficient for the curtain breakwater are in good agreement with experimental data in literature. The variations of the reflection coefficient versus factors of the wavelength, the wave chamber width, the immersed depth of the drooping plate and the angle at the bottom of the drooping plate are examined. It is found that for reaching lower reflection, the values of the wave chamber width should be around one tenth of the wavelength. The incident wave energy is dissipated by the vortex flows around the drooping plate effectively. The present numerical wave flume based on OpenFOAM can well estimate the hydrodynamic performance of the curtain breakwater for practical application.

***Key Words**: Reflection coefficient; Curtain breakwater; Numerical wave flume; OpenFOAM*

1 Introduction

Research on the hydrodynamic performance of vertical plate-type breakwaters has been of great interest since the last century. Very important developments have been achieved thanks to the efforts of different researchers. Ursell and Dean (1947) studied the reflection coefficient of a vertical plate breakwater in deep water. Mei (1966) studied the effect of a vertical plate on the progressing waves. Evans (1970) analytically investigated the diffraction of water waves by a submerged vertical plate. Ikeda et al. (1985) studied the eddy's type and the energy dissipation near a vertical plate. Nakamura et al. (1999) experimentally studied the hydrodynamic performance of a curtain breakwater (a drooping plate in front of a vertical wall) and analyzed the effects of the chamber width and the immersed depth of the drooping plate on the reflection coefficient of the breakwater. Ono et al. (2003) analyzed the flow field around a vertical plate. Nakamura and Nakahashi (2005) experimentally investigated the effectiveness of a water exchanging curtain breakwater and analyzed its ability of wave power extractions by wave induced vortex flows.

As mentioned above, most of the existing research on the vertical plate-type breakwater is based on theoretical research or experimental tests. A numerical analysis may give more understanding in the hydrodynamic performance of the breakwater. In this paper, a numerical wave flume based on OpenFOAM is used to study the reflection coefficient of a curtain breakwater as shown in Figure 1. The curtain breakwater consists of a seaside drooping plate and a leeside vertical wall (caisson) providing a simple method to reduce the reflected waves. The drooping plate hanging in front of the vertical wall forms a wave chamber. With this structure, the reciprocating motion of wave resonance increases the phenomenon of eddy at the bottom of the plate. Vortex flow can be utilized to dissipate the incident wave energy effectively. Compared with the conventional vertical wall breakwater, the reflection coefficient of the curtain breakwater is significantly decreased.

In the following Section 2, the numerical method based on OpenFOAM for analyzing the present wave-structure interaction problem is introduced. In Section 3, the numerical results of the reflection coefficient for the curtain breakwater are presented and discussed. Finally, the main conclusions of this study are drawn.

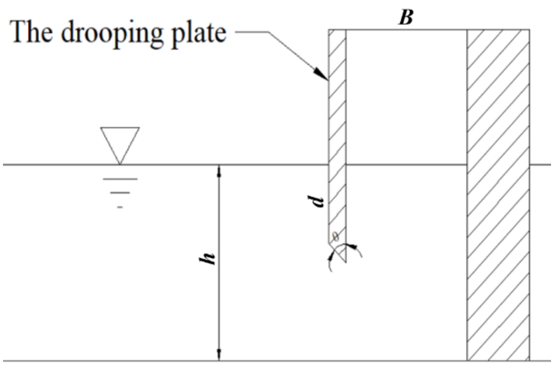


Figure 1: Sketch of a curtain breakwater

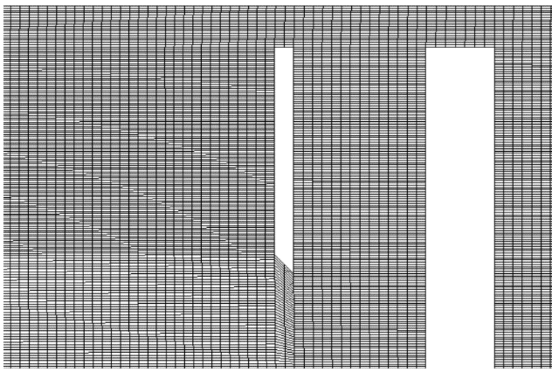


Figure 2: The mesh near the curtain breakwater in numerical method

2 Numerical methods

2.1 Governing equations

In this study, both air and water are incompressible viscous fluid. The continuity equation and N-S equation for incompressible viscous fluid are expressed as below:
Continuity equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

N-S equation：

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})+g \tag{3}$$

where ρ represents density, t represents time, p represents pressure, μ represents dynamic viscosity, u and v represent respectively velocity components in x- and y-directions, g is the gravitational acceleration.
The above equations are solved based on interFoam solver. The second-order Stokes wave theory is adopted, and the relaxation zone method proposed by Jacobsen et al. (2012) is used to implement the generation and absorption of waves. The basic principle of the relaxation zone method can be expressed as

$$u=\alpha_R u_{\text{model}}+(1-\alpha_R)\,u_{\text{target}} \tag{4}$$

$$\alpha_R=1-\frac{\exp\left(X_R^{3.5}\right)-1}{\exp\left(1\right)-1} \qquad X_R\in[0,1] \tag{5}$$

where u_{model} is the velocity calculated by N-S equation and u_{target} is the target velocity that we expected.
Volume of fluid (VOF) is a numerical method for tracking and locating free surface which is the interface of air and water in the numerical wave flume. This method is used by OpenFOAM to specify the fraction of each fluid (air and water) in each cell. The phase fraction equation is given by

$$\frac{\partial \alpha}{\partial t}+\nabla\,\alpha\boldsymbol{U}=0 \tag{6}$$

where α represents the phase fraction and $\boldsymbol{U}$ refers to velocity. α is always between 0 and 1. α = 0 means the cell is fully filled by air and α =1 means the cell is only filled by water. The density of each cell can be calculated by

$$\rho=\alpha\rho_{\text{w}}+(1-\alpha)\;\rho_{\alpha} \tag{7}$$

where ρ_{w} is the water density and ρ_{α} is the air density. Note that this density is the density of the mixture of air and water inside each cell.

2.2 Numerical wave flume

The two-dimensional numerical wave flume was 12 m long, 0.42 m wide and 0.8 m high. The drooping plate was placed in a position, 2 m to the end of the water flume. In order to obtain the incident and reflected wave heights using Goda’s method, the free surface elevations were recorded in the position about 4.4m, 4.6m and 4.8m away from the drooping plate. As shown in Figure 1, the width of the wave chamber B were 21 cm, 23 cm, 25 cm, 27 cm and 29 cm, respectively. The immersed depth d of the drooping plate with a thickness of 4.2 cm were also 21 cm, 23 cm, 25 cm, 27 cm and 29 cm, respectively. The angles θ at the bottom of the drooping plate were 30°, 45°, 60°, 90° and -45°, respectively. The water depth h was 42 cm and the incident wave height H was 6 cm. The wave period was changed from 0.9 s to 1.8 s. The width of the leeside vertical wall was 15 cm. All the above parameters were adopted by referring to the experimental tests of Nakamura et al. (1999). The mesh near the curtain breakwater in the numerical wave flume is plotted in Figure 2.

3 Results and discussion

3.1 Verification of numerical results

In this section, the numerical results of the reflection coefficient C_r and the free surface elevation H_c inside the wave chamber are compared with the experimental data of Nakamura et al. (1999). It is noted that no less than 10 waves were taken into account to obtain the reflection coefficient and the free surface elevation. Figures 3 – 5 show comparisons between the numerical results and experimental data for the reflection coefficient C_r, where L is the incident wavelength. It can be seen from these figures that the numerical results and experimental data are in good agreement. In addition, the reflection coefficient attains a minimum value with the increasing wavelength. Figure 6 shows a comparison between the numerical results and the experimental data for the free surface elevation H_{c} inside the wave chamber divided by the incident wave height H. Again, the two results are in good agreement. But, the free surface elevation inside the chamber decreases with the decreasing incident wavelength. It is proved that the present numerical wave flume can well estimate the hydrodynamic performance of the curtain breakwater.

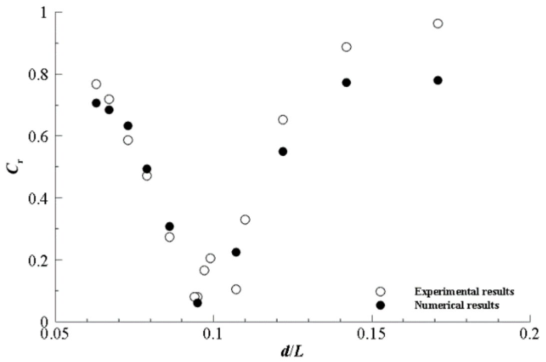


Figure 3 Variation of C_r versus d/L (B=21 cm, d=21 cm, θ=45°)

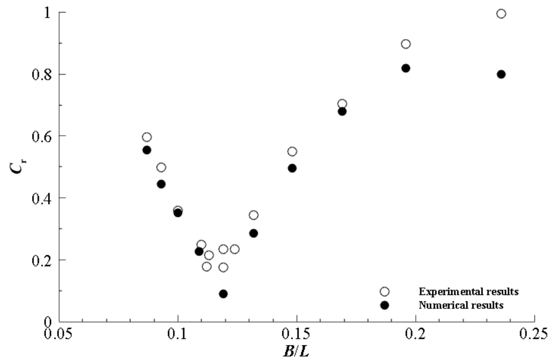


Figure 4 Variation of C_r versus B/L (B=29 cm, d=21 cm, θ=45°)

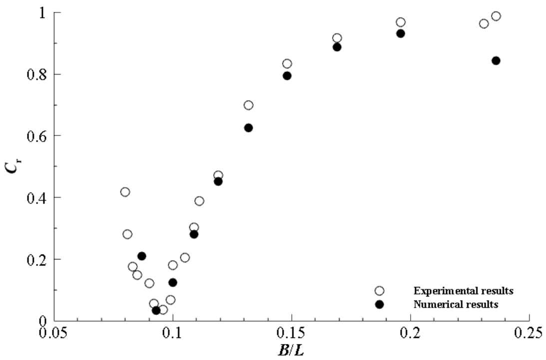


Figure 5 Variation of C_r versus B/L(B=29 cm,d=29 cm,θ=45°)

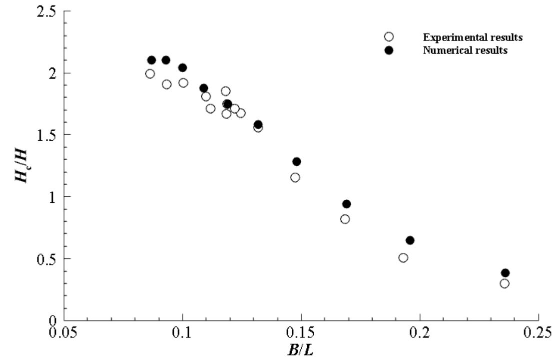


Figure 6 Variation of H_c/H versus B/L(B=29 cm,d=21 cm, θ=45°)

3.2 Further discussions

Numerical results are given in figures 7 and 8 to show the effects of the wave chamber width B and the immersed depth d of the drooping plate on the reflection coefficient C_r, respectively. It can be seen from these figures that for long period waves, the curtain breakwater with a larger wave chamber width B or a larger immersed depth d of the drooping plate can dissipate more incident wave energy and thus has a lower reflection coefficient. But this is just the opposite for short period waves. In addition, as the immersed depth d of the drooping plate increases in Figure 8, the minimum reflection coefficient of the breakwater occurs at longer wave period (larger wavelength L and smaller relative wave chamber width B / L).

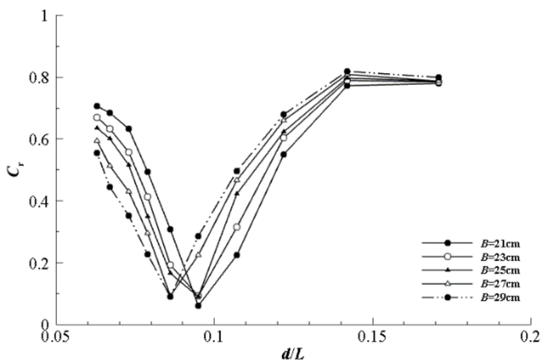


Figure 7 Variation of C_r versus d/L（d=21 cm, θ=45°）

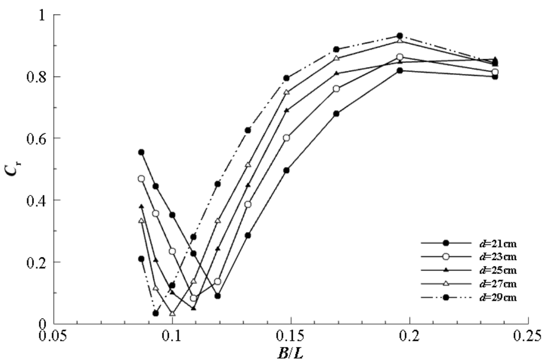
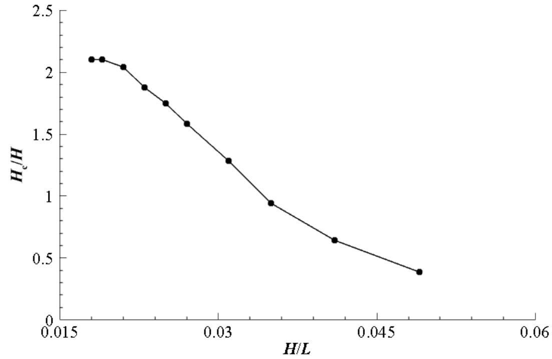


Figure 8 Variation of C_r versus B/L（B=29 cm, θ=45°）

Figure 9 gives numerical results to show the effect of the wave steepness H / L on the relative wave height H_c / H inside the wave chamber. It can be seen from this figure that the value of H_c / H increases with the decreasing H / L (the increasing incident wavelength L). This is natural as more wave energy can penetrate into the wave chamber for longer period waves. Figure 10 shows the effect of angle θ at the bottom of the drooping plate on the reflection coefficient C_r. It is noted from this figure that the reflection coefficients of curtain breakwater at positive and negative angles (θ = 45° and –45°) are close. In addition, a drooping plate with a shaper corner generally can dissipate more incident wave energy (has smaller reflection coefficient).



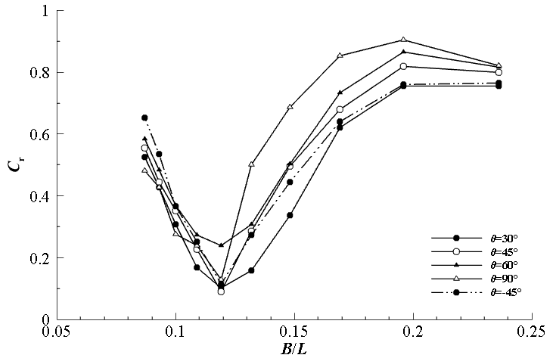
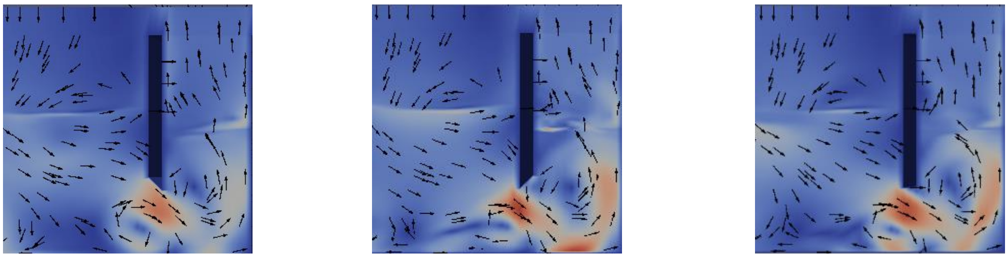


Figure 9 Variation of H_c/H versus H/L(B=29 cm, d=21 cm, θ=45°) **Figure 10 Variation of C_r versus B/L(B=29 cm, d=21 cm)**

In order to further examine the energy dissipation mechanism of the breakwater, the flow fields around the drooping plate with the same wave period (T = 1.4 s) which corresponds to the smallest reflection coefficients in Figure 10 for different angles θ (θ = 45°,–45° and 90°) at the same time (t = 35 s) are shown in Figure 11. In this figure, vortex flows at the bottom of the drooping plate can be clearly observed, and the incident wave energy is dissipated by the vortex flows effectively. It is noted that the flow fields around the drooping plate in Figure 11 are similar, which results in close minimum reflection coefficients at about B / L = 0.12 for the three different cases.



θ = 45° **θ = –45°** **θ = 90°**

Figure 11 The flow fields around the drooping plate (B = 29 cm, d = 21 cm, t = 35 s)

4 Conclusion

In this study, the interaction between the curtain breakwater and regular waves has been studied using the numerical solution based on OpenFOAM. The numerical results of the reflection coefficient and the free surface elevation inside the wave chamber of the curtain breakwater are in a good agreement with the experimental data in literature. Numerical results have shown that for reaching a low reflection coefficient, the wave chamber width of the curtain breakwater should be designed as about one tenth of the incident wavelength. The positive and negative sloping angles at the drooping plate bottom cannot bring significant difference on dissipating incident wave energy. The present numerical solution based on OpenFOAM can well estimate the hydrodynamic performance of the curtain breakwater, and the irregular wave action on the curtain breakwater will be examined in the next study.

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