

Numerical Simulation of Wave Flow over the Spiral-Reef Overtopping Device

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ABSTRACT

In this paper, computational fluid dynamics (CFD) simulations are carried out for the purpose of finding the optimal design parameters of a spiral-reef overtopping device. In order to maximize the overtopping flow rate, geometrical parameters of the device were systematically examined in numerical computations. In all simulations, the commercial CFD program FLOW3D was used. In this study, regular waves with a period range of 4~6 seconds (which are very common in the Korean southern sea) are considered. In the first phase of the study, two-dimensional parameters including device ramp angle, ramp shape and draft were investigated. Fully three-dimensional CFD simulations were then conducted to understand wave flow over the device and the guide-vane effect on overtopping on it. The calculation results show different overtopping processes between 2D and 3D simulations, and optimal design parameters were identified based on numerical results. These findings can be incorporated in the design of an overtopping device to obtain better overtopping performance.

KEY WORDS: Spiral-reef overtopping device, CFD, overtopping discharge, ramp, guide-vane.

INTRODUCTION

There are many kinds of wave energy converters. They can be categorized as being one of three basic types; a movable body type, an oscillating water column (OWC) type and a wave overtopping type. The overtopping type makes use of the potential energy of overtopping water via water turbines.

Only a few overtopping wave energy converters have been studied. Among them, the Wave Dragon (Nielsen & Kofoed, 1997) is the most practical and pioneering model. It consists of two wave reflectors, a reservoir and a number of hydro turbines. The wave reflectors focus the incoming waves towards a ramp, and a reservoir captures the overtopping water above sea level. Low-head hydro turbines generate power by using the hydraulic head of the stored water. The Wave Dragon is a floating converter that is placed in an offshore area with a mooring line. Another new conception of the overtopping wave energy converter is the Seawave Slot-Cone Generator (Vicinanza & Frigaard, 2008). This converter has multiple reservoirs and a multi-stage turbine, which results in a higher overall efficiency compared to a single

reservoir structure.

In this study, a spiral-reef overtopping wave energy converter (shown in Fig.1) was investigated. Spiral-reef overtopping devices are fixed circular-shaped structures. Consequently, the converter's performance is identical with respect to waves from all directions. The device is composed of a sloped ramp, an inner reservoir and substructures. The substructure is a mono-pile type or jacket type. On the ramp, guide-vanes are attached to reinforce wave overtopping. In the reservoir, the overtopping water is accumulated and drained out through a center hole.

In this study, basic research on the spiral-reef overtopping device was conducted using CFD simulations. The primary purpose of numerical simulations is to find an optimum device shape with respect to overtopping flow rate (discharge). For this purpose, two and three dimensional numerical simulations were conducted by using a commercial CFD program, FLOW3D. Firstly, flow patterns of the overtopping procedure were observed. Several geometrical parameters, such as draft, ramp shape, and guide-vane shape, were then changed and the effects of the parameters were systematically investigated through numerical simulation.

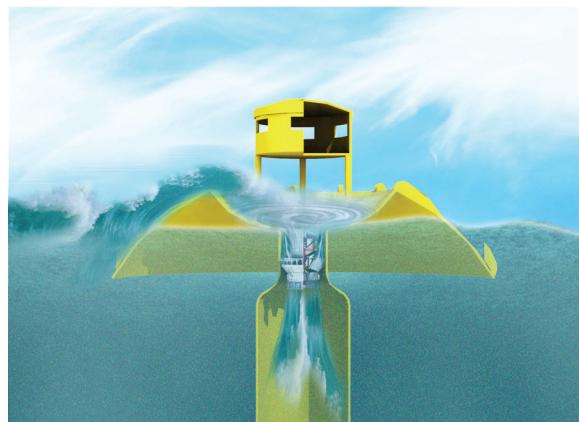


Fig.1 Spiral-reef overtopping wave energy converter

MAIN DESIGN PARAMETERS

The overtopping discharge of the device depends on geometrical parameters such as crest freeboard, draft, ramp shape, and guide vane shape. Draft and ramp shape are studied in 2D simulations while guide-vane shape is investigated in 3D simulations. In this study, the device is fixed and the crest freeboard was 2m. The main design parameters can be summarized as follows:

- 2D Parameters
 - crest freeboard (fixed)
 - draft
 - ramp angle
 - ramp shape
- 3D Parameters
 - number of guide vanes
 - guide vane height
 - guide vane angle

Wave conditions are also a main concern in wave energy converter design. In consideration of the conditions in the southern sea of Korea, the following wave parameters were selected:

- Wave type: regular
- Wave height: 2~3 m
- Wave period: 4~7 s

Wave direction is not a significant parameter because of the axisymmetric device shape.

NUMERICAL SIMULATION

In this study, all numerical simulations were carried out by using the FLOW3D program. FLOW3D is based on a finite difference method and a volume of fluid (VOF) scheme. This program is adequate for the simulation of free-boundary problems. For computational mesh, FLOW3D adopted a structured grid system with a FAVOR (Fractional Area/Volume Obstacle Representation) scheme. The FAVOR scheme is capable of very efficient and flexible grid generation only with CAD files. Numerous nodes are required to express exact geometries and to observe sensitive quantities near the body of the device. Fig. 2 shows a typical FLOW3D mesh system in two-dimensional simulations. Further details about the VOF and FAVOR scheme of FLOW3D are found in Hirt & Nichols (1981) and Hirt & Sicilian (1985).

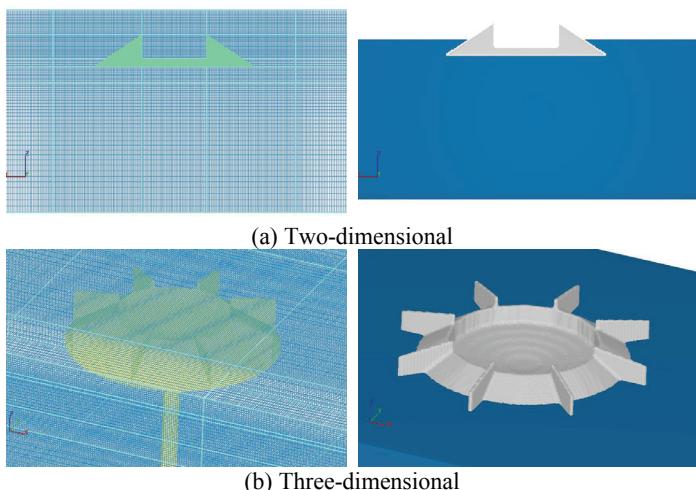


Fig. 2 Mesh system and domain of FLOW3D simulation using FAVOR scheme

In order to estimate overtopping discharge, the initial transient stage and strong reflection stage are removed from the total analysis time. Typical overtopping discharge in 2D simulations is shown in Fig. 3

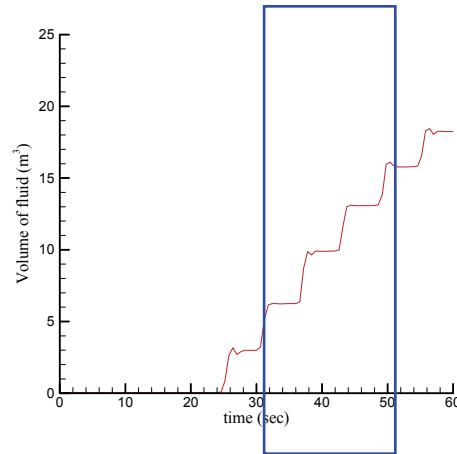


Fig. 3 Typical overtopping discharge in 2D simulations

In general, overtopping discharge is a sensitive quantity. Mesh is a significant factor in the estimation of overtopping discharges. A convergence test of overtopping flow for 2D cases was carried out as shown in Fig. 4. A total of five meshes from 23370 nodes to 55250 nodes were tested. If the total number of node is greater than 40000, overtopping discharges are converged within a 10% error bound.

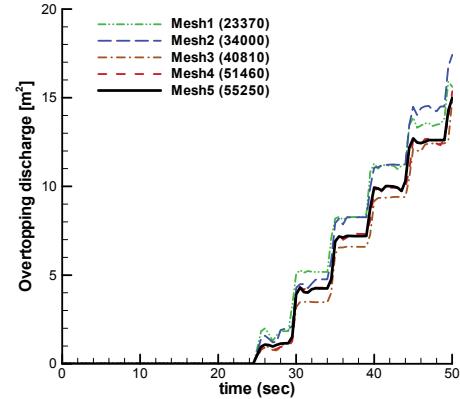


Fig. 4 Convergence test for overtopping discharges

RESULTS AND DISCUSSIONS

2-D Simulations

Figure 5 shows the main design parameters of the two-dimensional model. L_f is crest freeboard and L_d is draft. L_x and L_y are the horizontal and vertical lengths of the ramp. α and R are reservoir length and ramp angle, respectively. In this study, crest freeboard, L_f , is fixed at 2m and reservoir length, R , is fixed at 8m for all numerical simulations.

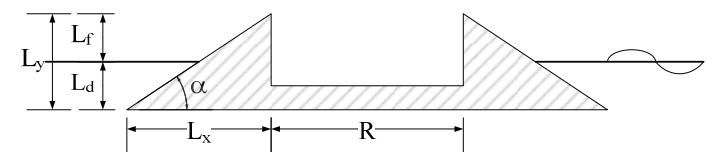


Fig. 5 Two dimensional parameters

A typical two-dimensional overtopping procedure is shown in the four snapshots of Fig. 6. An incoming wave approaches the device from the right side as shown in figure 6(a). The next figure shows the wave is piling up and breaking. The water then quickly runs up over the device ramp. Finally, overtopping occurs when the flows pass over the crest freeboard.

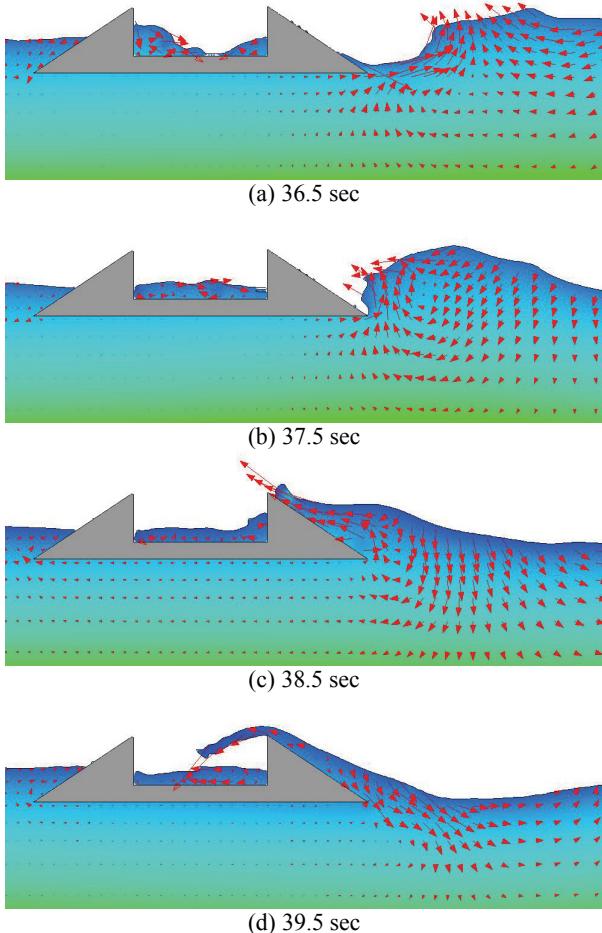


Fig.6 Typical two-dimensional overtopping procedure
($L_x=6m$, $Ly=4m$, $T=5sec$, $H=3m$)

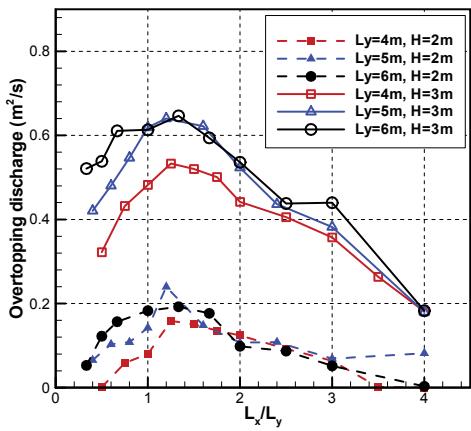


Fig. 7 Comparison of overtopping discharge due to different draft and ramp angles ($\lambda=55m$)

(1) Ramp angle

The ramp angle is a key parameter that must be specified to optimize overtopping, as the slope of the ramp affects wave amplification and the mass transport velocity of the wave (Shin & Hong, 2005). A few researchers have made suggestions with respect to the optimal ramp angle, and these fall between 30° and 50° (summarized in Kofoed (2002) and Shin & Hong (2005)). Among the suggestions for an optimal ramp angle, 30° ($L_x : L_y = \sqrt{3} : 1$) and 33.69° ($L_x : L_y = 3 : 2$) are frequently discussed in many papers. Fig. 7 shows overtopping discharges for different device ramp angle with a fixed draft. According to FLOW3D simulation, maximum overtopping occurs when device slope (L_x / L_y) is between 1.0 and 1.6. That is, slope angle between 32° and 45° induces maximum overtopping discharges.

Kofoed (2002) modified the expression by Van der Meer and Janssen (1995) to suggest a new overtopping formula for non-breaking waves in Eqs. 1~3.

$$\frac{q}{\lambda_\alpha \lambda_{dr} \lambda_s \sqrt{g H_s^3}} = 0.2 e^{-2.6 \frac{R_c}{H_s}} \quad (1)$$

$$\lambda_\alpha = \cos^3(\alpha - \alpha_m) \quad (2)$$

$$\lambda_{dr} = 1 - 0.4 \frac{\sinh(2k(d - d_r)) + 2k(d - d_r)}{\sinh(2kd) + 2kd} \quad (3)$$

where q is the average overtopping discharge. R_c , H_s , and g are crest freeboard, significant wave height and acceleration due to gravity respectively. λ_s is a correction factor which is defined as given in Kofoed (2002). λ_α , λ_{dr} are influence factors for influence of ramp angle and draft. α_m is the optimal slope angle. k is wave number. d and d_r are water depth and draft respectively. In this study, α_m is set to 33.69° and the wave height of regular wave is used as H_s . Fig. 8 shows the comparison of overtopping discharges from CFD calculations and the overtopping formula. The agreement is fairly good except the range of low ramp angle. The effect of ramp angle and draft is clearly shown in formula results since correction factors λ_α and λ_{dr} are included.

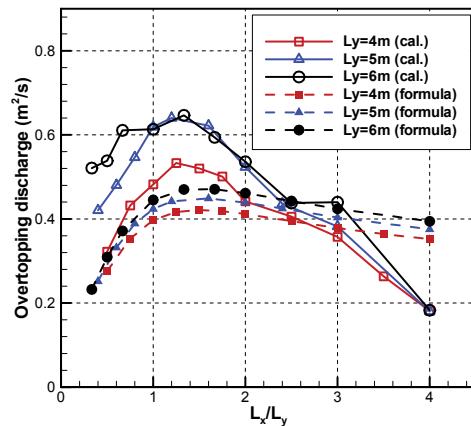


Fig. 8 Comparison of overtopping discharge with overtopping formula ($\lambda=55m$, $H=3m$)

(2) Draft

When an overtopping device has a deeper draft within a fixed ramp angle, the incoming wave is more amplified due to the shoaling effect. Fig. 9 shows the change of overtopping discharges as the draft is deepened. Until the draft reaches 3m, the overtopping discharges increase in the case of wave period 5~6 sec. However, when the draft of the device is greater than 4m, the trend of overtopping discharges is not consistent. From a practical point of view, since a deeper draft caused larger hydrodynamic forces and a larger structure entails greater cost, a deeper draft is not preferable.

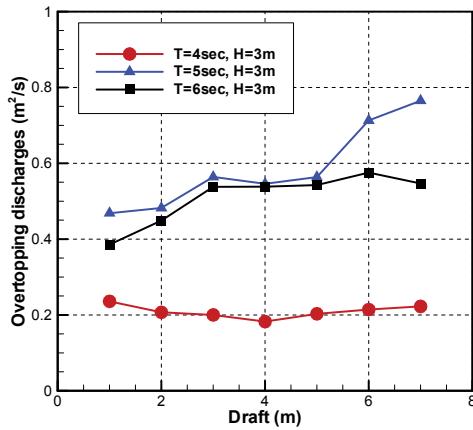
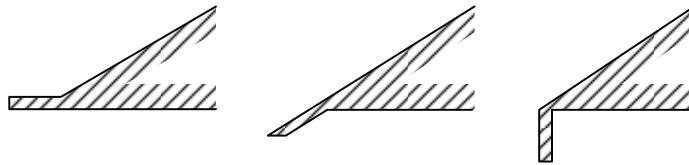


Fig. 9 Draft effect on overtopping discharge ($L_x : L_y = 3 : 2$)

(3) Plate

In order to increase overtopping, an auxiliary plate can be attached to overtopping device. Three types of plates—horizontal, sloped and vertical—are considered in this study. Among them, the vertical plate is most efficient in inducing overtopping flow, as shown in Fig. 11. In this case, sloped and vertical plates play roles similar to that of a deeper draft.



(a) Horizontal plate (b) Sloped plate (c) Vertical plate
Fig. 10 Plate configurations (plate length is approximately 2m.)

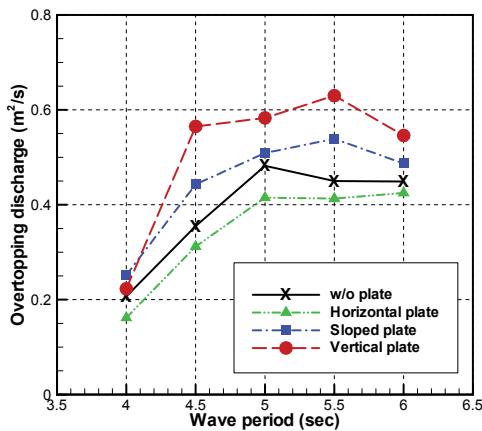


Fig. 11 Plate effect of overtopping discharges ($H=3m$, $L_x : L_y = 3 : 2$)

(4) Ramp shape (profile)

Ramp shape is another main parameter affecting the 2D overtopping device. Kofoed (2002) points out that a ramp with a convex upper part that has an elliptical shape results in an overall increase in overtopping discharge of 18% (based on laboratory tests). Among many possible examples, two modifications of ramp shape are shown in Fig. 12. The C1 model is similar to the basic model equipped with horizontal plates. The C2 model has a weak convex ramp shape. C1 produces a small increase of overtopping discharge as shown in Fig. 13. However, the increase of overtopping discharge due to ramp shape variations is not significant. After testing many variations of ramp shape, it was found that an excessively concave or convex ramp results in the reduction of the overtopping discharge compared to a straight ramp. Under the most conditions, the straight ramp is fairly efficient.

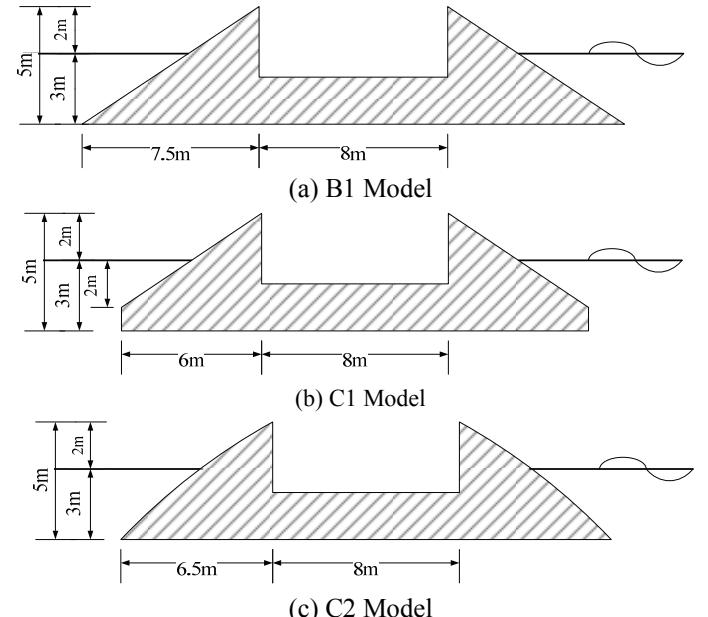


Fig. 12 Models with different slope profiles

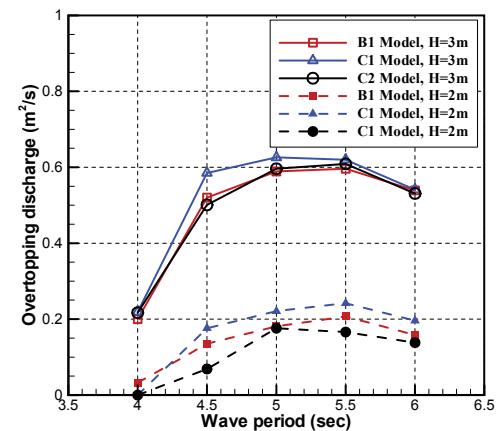


Fig. 13 Comparison of overtopping discharges with slope shape variations

3-D Simulations

The effect of the guide vane was investigated primarily through three-dimensional simulations. Guide vane angle, guide vane height and the number of guide vanes were considered in numerical simulations. Fig.

14 shows the main design parameters of the three-dimensional structure. In this study, reservoir diameter R is fixed at 15m and slope dimensions, L_r and L_z are 6m and 4m respectively (slope angle 33.69°). Only the guide vane heights (h_1, h_2) and guide-vane angle (α) are changed in the following sections.

The overtopping process in 3D simulation is slightly different from that in a 2D simulation. Fig. 15 shows numerical results of overtopping process and photographs of experiment. Experiments were carried out in an ocean engineering basin in MOERI. The basin is 56m(L)*30m(B)*4.5m(D). A 1/10 model was used in the experiments. Three stages can be identified in three-dimensional overtopping. First, an incident wave arrives at the overtopping device. Overtopping then occurs and water flows into the internal reservoir. In contrast to two-dimensional simulations, wave breaking prior to overtopping usually does not occur in 3D simulations. This validates the usage of non-breaking wave formula to predict overtopping discharge in 3D marine structures. Lastly, wave flow progresses around the device and revisits the backside of the device. Sometimes the revisited wave overflows again.

A well-designed guide vane can help an incoming wave to flow through into reservoir. However, a poorly designed guide vane can block incoming waves and reduce overtopping discharge. Fig. 16 shows four snapshots of 3D simulations with 8 guide vanes. In this case, flow over the device is effectively guided into the reservoir and overtopping discharges increase significantly.

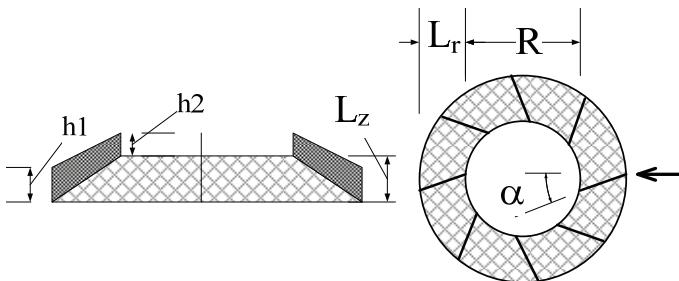


Fig. 14 Three dimensional parameters

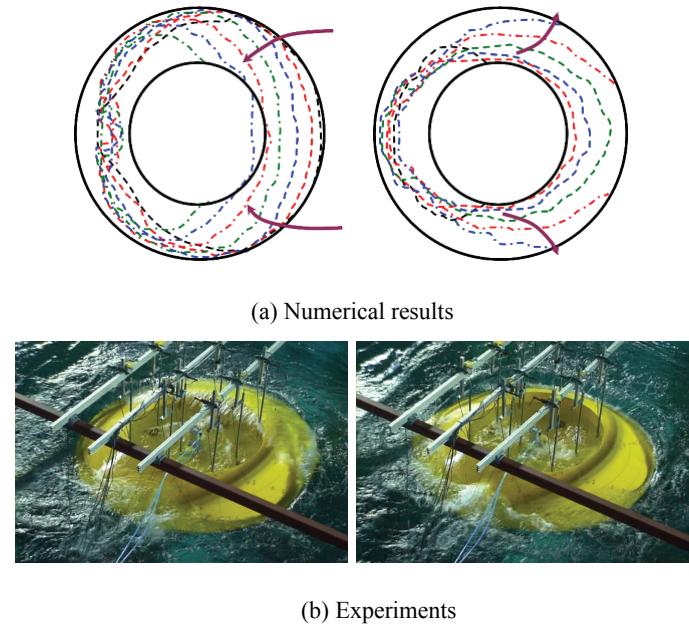


Fig. 15 Overtopping process in 3D simulations without a guide vane

(1) Guide vane angle

A straight guide vane and two spiral guide vanes were tested. The two spiral guides have angles of attacks (α) of 46.7 degrees and 55.4 degrees respectively. Fig. 17 shows the overtopping discharges of each guide vane and the numerical results are compared with those of experiments. The numerical results suggest that as the angle of attack becomes smaller, overtopping discharge increase. To maximize overtopping discharge, a straight guide vane is preferable to a spiral guide vane or none at all. Numerical predictions are similar to experimental measurements, especially in the case of the straight-guide vane. However, experiments show that a spiral guide-vane (55.4 deg.) yields worse results compared to the basic model without a guide vane. In contrast, the numerical results show an opposite trend.

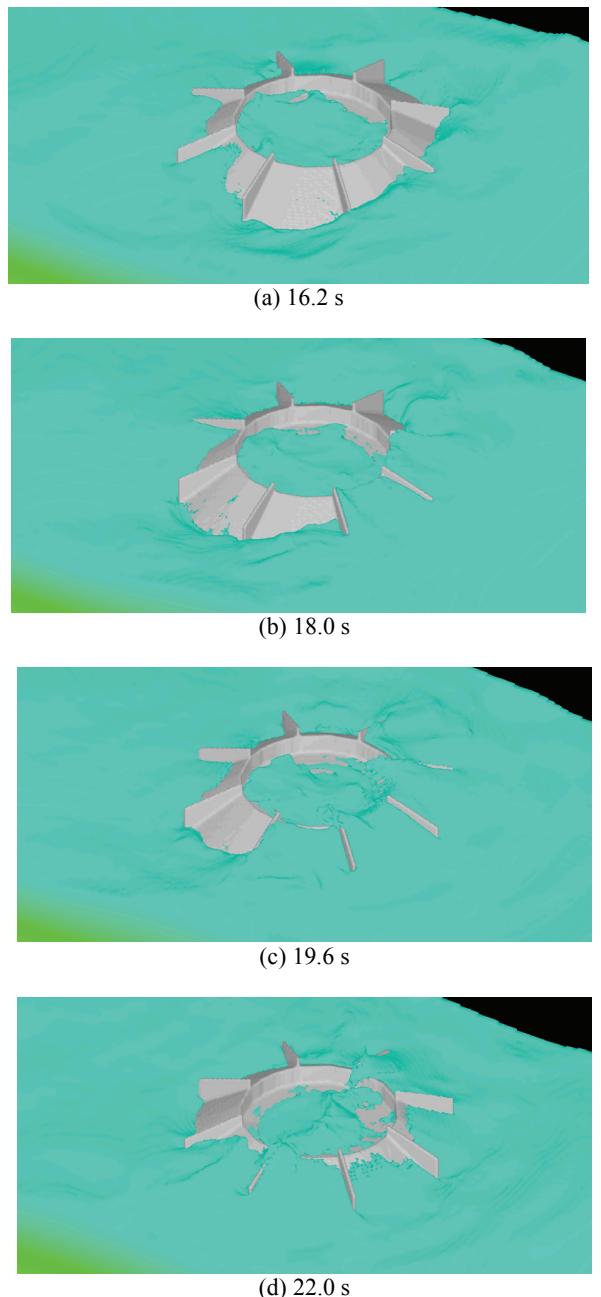


Fig. 16 Snapshots of three-dimensional simulations with a guide vane

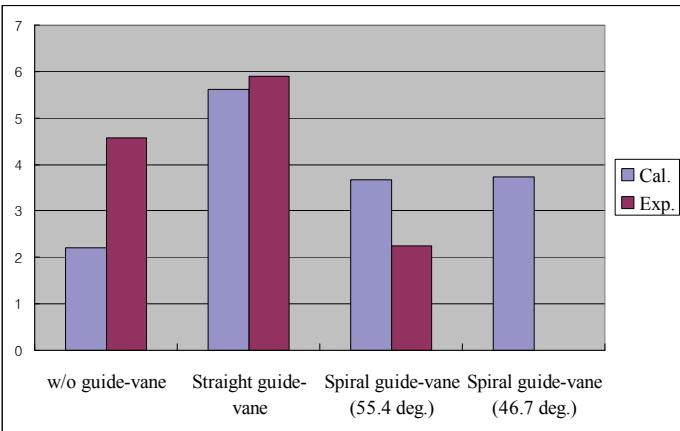


Fig. 17 Guide vane angle effect on overtopping discharges

(2) Guide vane height

The height of the guide vane also affect on overtopping discharges. The effective height of the guide vane is closely related to the maximum wave elevation around the device. In this study, four different guide-vane heights were considered. A dramatic increase was found between the straight I model and the straight II model. After straight II, there is little variance with respect to overtopping device according to guide vane height.

Table 1. Effect of guide-vane height for overtopping discharges

Model	h_1 (m)	h_2 (m)	Q (m^3/s)
w/o guide-vane	-	-	2.2090
Straight I	0.5	0.5m	2.3715
Straight II	3.0	1.0	5.4798
Straight III	4.0	1.0	5.6196
Straight IV	4.0	2.0	5.6624

(3) Number of guide vanes (opening effect)

The number of guide vanes is closely related to the opening effect because a center angle between two adjacent guide vanes is determined by guide vane number. After varying the numbers of guide vanes, it was concluded that 8~10 guide vanes is most effective number for increasing overtopping discharges.

Table 2. Effect of guide vane height for overtopping discharges

Model	Center angle (deg.)	Q (m^3/s)
w/o guide-vane	-	2.2090
10 Straight guide-vane	36	7.2425
8 Straight guide-vane	45	5.6196
6 Straight guide-vane	60	3.9940
4 Straight guide-vane	90	3.4454

CONCLUSIONS

In this study, various design parameters of a spiral-reef wave overtopping device were tested through two- and three-dimensional

CFD simulations. In order to maximize the overtopping flow rate (discharge) of the device, the optimal geometrical shape is investigated and some favorable trends for overtopping were identified as follows:

- When the ratio of horizontal length to vertical length (ramp angle) is in the range of 1:1 and 1.6:1, overtopping flow rate is maximized
- As the draft becomes deeper, the overtopping flow rate increases.
- An Auxiliary sloped plate or vertical plate results in the increase of overtopping flow rate, while a horizontal plate produces unfavorable effect with respect to overtopping.
- Certain variations of ramp shape can increase overtopping flow rate. However, expecting a large increase in overtopping flow rate due to a change in ramp shape (from a straight ramp) is problematic.
- A Straight guide vane is more efficient than a spiral (or curved) guide vane.
- A higher guide vane increase overtopping flow rate.
- The appropriate number of guide vane is between 8~10.

ACKNOWLEDGEMENTS

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