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Parametric Study on Oscillating Water Column Wave Energy Converter Applicable to Breakwater †

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Abstract

This paper presents a parametric study on an oscillating water column (OWC) wave energy converter (WEC). This OWC has been planned for installation in the breakwaters on isolated islands located away from the mainland. Both a numerical analysis and a model experiment are utilized for determining a proper conceptual design for this purpose. Various design parameters, including the configurations and dimensions, are evaluated through the numerical analysis, which is based on a potential flow theory, and several design concepts are then selected as candidates. The model experiment using a 2D wave flume is conducted to evaluate the effects of the design parameters and compare the performances of the candidates. Based on the overall results of the numerical analysis and model experiment, a conceptual design of the OWC WEC applicable to a breakwater is selected.

Keywords: Oscillating water column (OWC), Wave energy converter (WEC), Numerical analysis, Boundary element method, Model experiment, 2D wave flume

1. Introduction

An oscillating water column (OWC), which is a type of wave energy converter (WEC), utilizes the motions of a water column vertically oscillating in the chamber, producing a reciprocating airflow that operates a turbine connected from the chamber through a duct. An OWC WEC is easy to maintain and has reliable durability owing to its simplicity, and has thus been commonly demonstrated in real sea (Falcao and Henriques, 2016). The first large-scale OWC system developed was Kaimei, which was installed along the western coast of Japan. Eight OWC chambers with a capacity of 125 kW were equipped on a barge platform, and several turbines were applied on Kaimei (Masuda and McCormick, 1986; Hotta et al., 1988). Another OWC using a Wells turbine, with a capacity of 40 kW, was deployed for a breakwater located in Sakata port, Japan, in 1990. This was the first case of merging an OWC into a breakwater, which demonstrated some cost saving effects (Masuda and McCormick, 1986). In the same year, a bottom-fixed OWC with a capacity of 125 kW was installed in Trivandrum, India. The performances of various turbines, including an impulse type, were evaluated (Mala et al., 2009). In Europe, the Pico Plant, constructed on Pico Island, Portugal, with a capacity of 400 kW, has been undergoing testing since 1999 (Falcao, 2000), and the LIMPET OWC Plant, deployed on Islay Island, Scotland, with a capacity of 500 kW, was evaluated during a real sea test

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(Heath et al., 2000). In Korea, the construction of a bottom-fixed OWC with a capacity of 500 kW was completed in 2015, and a real sea test is being prepared.

The economic feasibility of harvesting renewable energy resources, including wave energy, is a key element directly connected to commercialization. By coupling the OWC system into a breakwater installed for the purpose of protecting a harbor, the costs of construction, operation, and maintenance can be reduced (Falcao and Henriques, 2016). In Mutriku Port, Spain, a breakwater OWC was composed of sixteen chambers and Wells turbines, each with a capacity of 18.5 kW, for a total of about 300 kW, and has been operating since 2011 (Torre-Enciso et al., 2009). In Civitavecchia Port, Italy, numerous U-OWC chambers are being merged into a newly constructing breakwater. After construction, Civitavecchia OWC is expected to produce 2,800 MWh per year with a total capacity of 2.7 MW (Arena et al., 2013a; Arena et al., 2013b).

An R&D project for the development of an OWC WEC applicable to a breakwater, which enables people living on isolated islands to receive clean energy without a grid connection from the mainland, was launched in Korea in 2016. The final objective of this research project is to conduct a real sea test for the developed OWC WEC at a selected test site. All components of the system, including the chamber, turbine, generator, power converter, power controller, and energy storage system, are being studied and designed through the project. Among these components, a chamber converting the excited motions of a water column into an airflow driving the turbine and generator is the research object of this study. It is important to design a chamber that creates a resonance based on wave characteristics at the test site because higher wave heights in the chamber result in a more massive airflow.

The research objective of the present study is to create a conceptual design of a chamber for an OWC applicable to a breakwater. To do so, a parametric study on the design variables, including the configuration and dimensions of the chamber, was conducted using a numerical analysis and model experiments through a 2D wave flume. The remainder of this paper is organized as follows. The subject of this study is first described, followed by the analysis methods including the numerical simulation and model experiment. Next, the results from both methods are discussed, and finally, some concluding remarks are provided.

2. Problem Description

2.1 Description of the OWC chamber

The chamber of the OWC is composed of rear and side walls that form a closed space within the chamber by enclosing vertical members connected from the sea bed to above the mean water level, as well as a skirt that allows waves to enter into the chamber and be excited in the opened chamber under the mean water level. The upper structures, including the upper wall, duct, turbine, and generator, are not considered in this study. Only the process in which the wave motions are converted into an airflow is considered. Fig. 1 shows a schematic diagram of an OWC. The chamber length and skirt depth determine the size of the water column trapped in the chamber, which is related to the period of resonance excited in the chamber. This type of chamber has a conventional structure, and has been most commonly adopted in past studies owing to its simplicity.

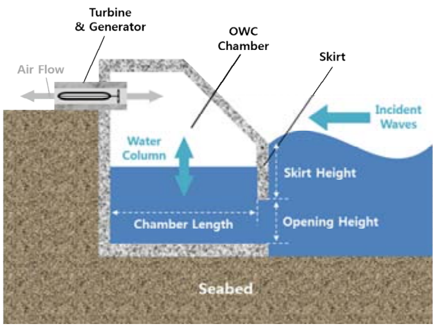


Fig. 1. Schematic diagram of an OWC

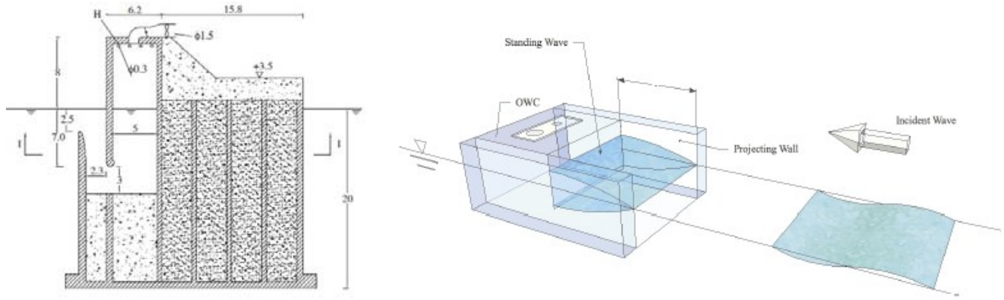
2.2 Configurations of OWC Chamber

Various studies on improving the conversion efficiency of the chamber by changing the chamber geometry have been conducted. Boccotti (2007) proposed a new type of chamber, called a U-OWC chamber, the length of which is extended using an additional vertical wall located in front of the skirt, which forms a U-shaped chamber (Fig. 2 (a)). A U-OWC can have a larger water column owing to its lengthened chamber, increasing the resonance period of the chamber with a relatively shorter chamber length. In addition, the amplitude of the pressure fluctuations at the exit of the U-OWC can be increased. To increase the efficiency of the conversion, Ikoma et al. (2013; 2012) suggested using a projecting wall attached in front of the skirt toward the incoming waves (Fig. 2 (b)). Owing to the projecting wall, standing waves are induced ahead of the chamber, causing a harbor resonance and lengthening the resonance period.

To design a cost-effective OWC chamber applicable to a breakwater, the ability to connect the chamber to the breakwater should be another important design consideration. Conventional breakwaters in Korea have a standard shape, as illustrated in Fig. 3. Tetrapods (TTPs) are cumulated on the solid base composed of a rubble-mound foundation and armor stone with a standardized slope of 1/1.5, which is effective in absorbing waves. If an OWC chamber has a sloped cross section, the slope of which is identical to the TTP slope, the construction procedures can be simplified by inserting the chamber into the TTP layer, allowing the structure to be safer and more cost-effective.

2.3 Baseline Chamber Models

In this study, a conventional, U-OWC, projecting wall, and sloped chamber are considered as the configuration variables, and in the present paper are called Types I, II, III, and IV, respectively. Cross sections of each variable are shown in Fig. 4, which also summarizes the excitation mechanism.



(a) U-OWC (Boccotti, 2007) (b) Projecting Wall (Ikoma et al., 2013)

Fig. 2. Various types of OWC chamber

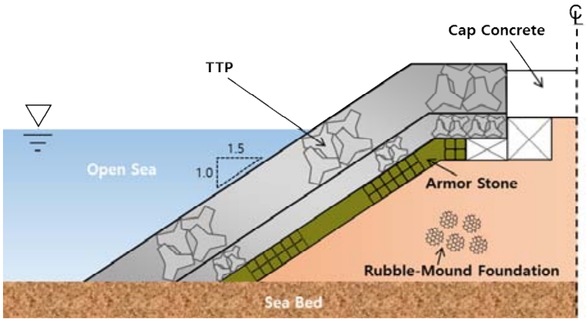


Fig. 3. Cross section of a conventional breakwater in Korea

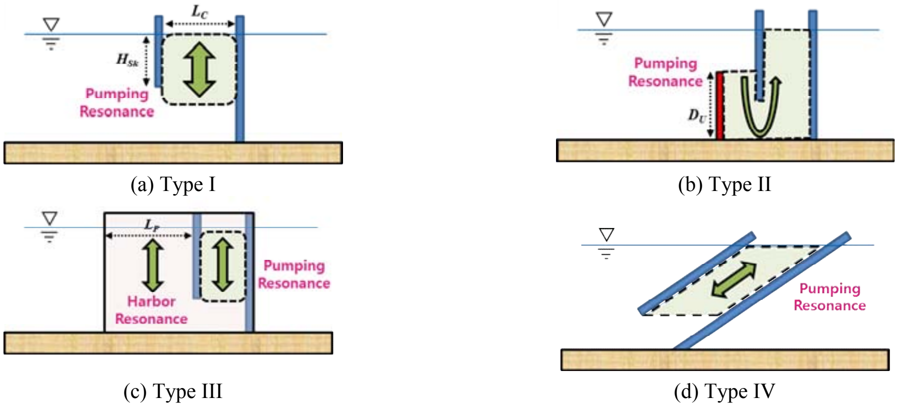


Fig. 4. Wave excitation mechanism in OWC chamber for various configuration types

3. Analysis Methods

3.1 Numerical Method

The numerical analysis was conducted using an in-house code, AdFLOW, which solves a boundary value problem, established based on a potential flow theory, using a higher-order boundary element method with Green's function for a wave equation. The detailed theoretical background was described in an advanced study (Nam et al., 2014). Using AdFLOW, a potential flow analysis in the frequency domain was conducted for each panel model, as illustrated in Fig. 5, and the relative wave height (H_R), defined as the excited wave height (H_D) estimated from the wave run-up in the chamber divided by the incoming wave height (H_I), $H_R = H_D/H_I$, was extracted as the index for evaluating the performance.

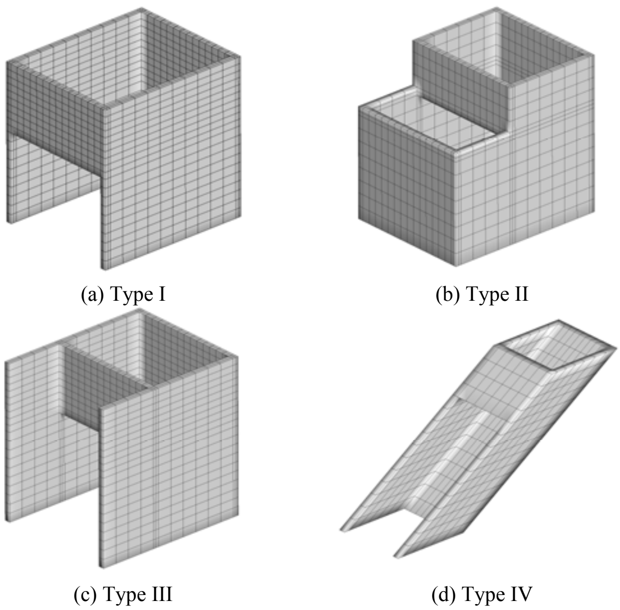


Fig. 5. Representative panel models for various types of chamber configuration

Table 1. Experiment model conditions

Test ID	Chamber Case	Chamber Length	Skirt Height
		Real / Model	Real/Model
U01	Type I	4 *m* / 0.2 *m*	4 *m* / 0.2 *m*
U02	Type I	4 *m* / 0.2 *m*	3 *m* / 0.15 *m*
U03	Type I	4 *m* / 0.2 *m*	2 *m* / 0.1 *m*
U04	Type I	5 *m* / 0.25 *m*	2 *m* / 0.1 *m*
U05	Type I	3 *m* / 0.15 *m*	2 *m* / 0.1 *m*
S01	Type IV	4 *m* / 0.2 *m*	3 *m* / 0.15 *m*
S02	Type IV	4 *m* / 0.2 *m*	2 *m* / 0.1 *m*
S03	Type IV	4 *m* / 0.2 *m*	1 *m* / 0.05 *m*
S04	Type IV	5 *m* / 0.25 *m*	1 *m* / 0.05 *m*
S05	Type IV	3 *m* / 0.15 *m*	1 *m* / 0.05 *m*

The numerical analysis applied in this study has certain limitations in that the method is unable to consider the effects of viscous damping from the chamber walls. In addition, the relative wave height estimated without any modeling of the interactions between the free surface in the chamber and the turbine may not be an indicator for a performance evaluation of the OWC. Such limitations, however, are allowed in this study because the present process of the project remains in the conceptual design stage. Actually, the qualitative performances represented by the relative wave height in the chamber were evaluated in this study. Note that an appropriate artificial damping estimated based on accumulated experience in developing the chamber was consistently used in the simulation to reduce an unrealistic response under resonance.

3.2 Experimental Setup

The model experiment was conducted in a 2D wave flume using scaled models for the selected Type I and IV chamber configurations. The wave flume, which is 40 m long, 0.6 m wide, and 1.0 m high, is equipped with a piston-type wave maker system, allowing the period to range from 0.75 to 2.4 s. The water depth was set at 0.5 m in this experiment.

Scaled models with a scale ratio of 1/20 appear in Fig. 6. They were installed at the bottom of the wave flume and fixed by additional weights. To apply the model as a 2D problem, the sidewalls of the chamber were replaced with flume walls. The design variables for the chamber length and skirt height were varied in the experiment model. Table 1 summarizes the model cases.

(a) Type I (b) Type IV

Fig. 6. Photographs of the experiment models installed in the 2D wave flume

Table 2. Characteristics of generated regular waves in 2D wave flume

Wave ID	T (Model) [s]	T (Real) [s]	H/λ
W01	1	4.47	0.044
W02	1.15	5.14	0.034
W03	1.3	5.81	0.025
W04	1.45	6.48	0.021
W05	1.6	7.16	0.018
W06	1.75	7.83	0.015
W07	1.9	8.50	0.012
W08	2.05	9.17	0.01

Capacitive wave height meters were installed in the chamber to measure the excited wave height, as shown in Fig. 7.

Each chamber was exposed to regular waves generated by the wave maker with a scaled wave period ranging from 1.0 to 2.05 s, and the relative wave height in the chamber was extracted. The characteristics of the regular waves generated are summarized in Table 2.

4. Results

4.1 Numerical Results

Fig. 8 shows the results of the relative wave height in the chamber for the incoming wave period for the Type I, II, and III configurations. The water depth conditions, considering the conventional tidal difference in Korea, are marked in the figure. LAT, Mean, and HAT indicate the low astronomical tide (3.6 m), mean water level (5.28 m), and high astronomical tide (6.96 m) at the site, respectively. The panel models used in the simulation for each water depth condition are listed in the above curves in order, and the symbols, L_C and H_{Sk}, represent the chamber length and skirt height, as described in Fig. 4. Note that an opening height, which is defined as the distance between the bottom of the skirt and the seabed, depends on the skit height owing to the water depth provided.

The effects of the chamber length and skirt height on the performance can be discussed by comparing Figs. 8 (a) and (b). The longer chamber length and higher skirt height delay the resonance period because these design variables increase the size of the water column trapped in the chamber. This should be considered in the chamber design to match the chamber resonance period to the characteristic period at the target site.

Simulation results for the Type II configuration are shown in Fig. 8 (c). Note that D_U is the distance between the water level and the top of the front wall for a U-OWC. The wave in the chamber was highly excited around the resonance period under the Mean conditions, but suppressed under HAT conditions. Under this situation, when a HAT arrives, the front wall is too low. This means that the U-OWC is quite sensitive to the change in water depth and tidal difference, although a high level of performance occurs within a specific range of period.

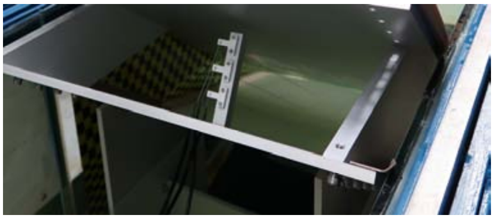
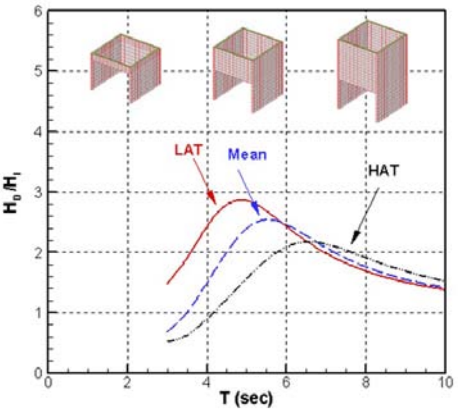
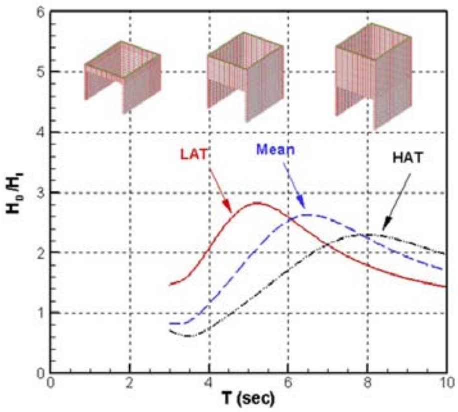


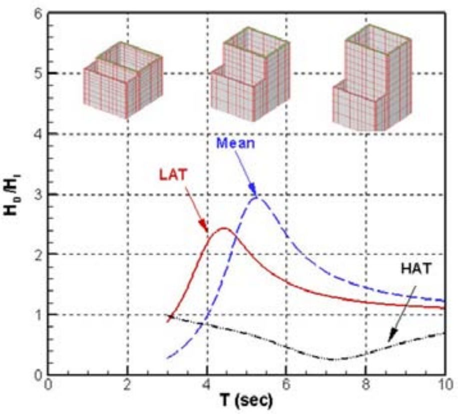
Fig. 7. Installed capacitive wave height meters



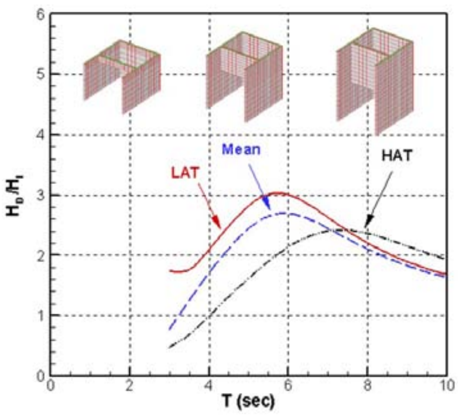
(a) Type I, L_C = 4.0 m, H_{Sk} = 0.6 m / 2.28 m / 3.96 m



(b) Type I, L_C = 5.0 m, H_{Sk} = 0.6 m / 2.28 m / 3.96 m



(c) Type II, L_C = 3.0 m, H_{Sk} = 1.6 m / 3.28 m / 4.96 m, D_U = 0.32 m / 2 m / 3.68 m



(d) Type III, L_C = 3.0 m, H_{Sk} = 0.6 m / 2.28 m / 3.96 m, L_P = 2 m

Fig. 8. Numerical simulation results for Type I, II, and III configurations

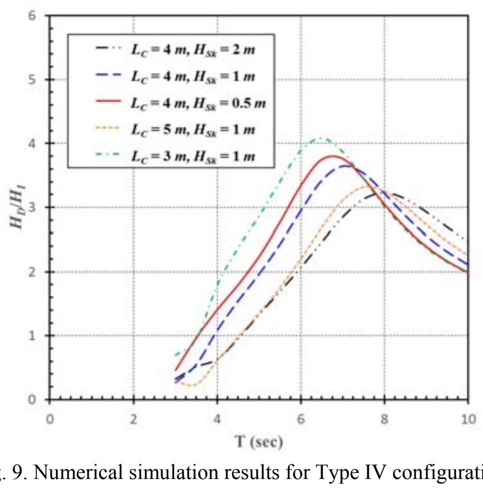


Fig. 9. Numerical simulation results for Type IV configuration

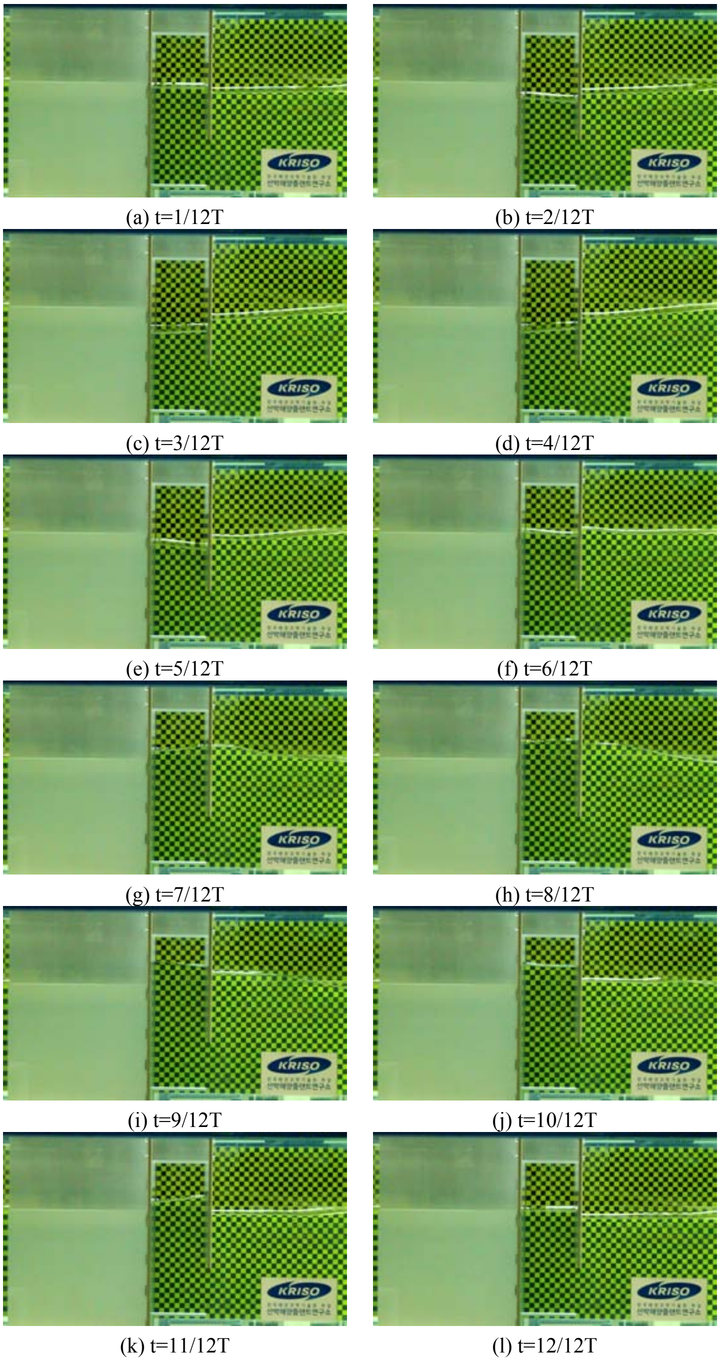
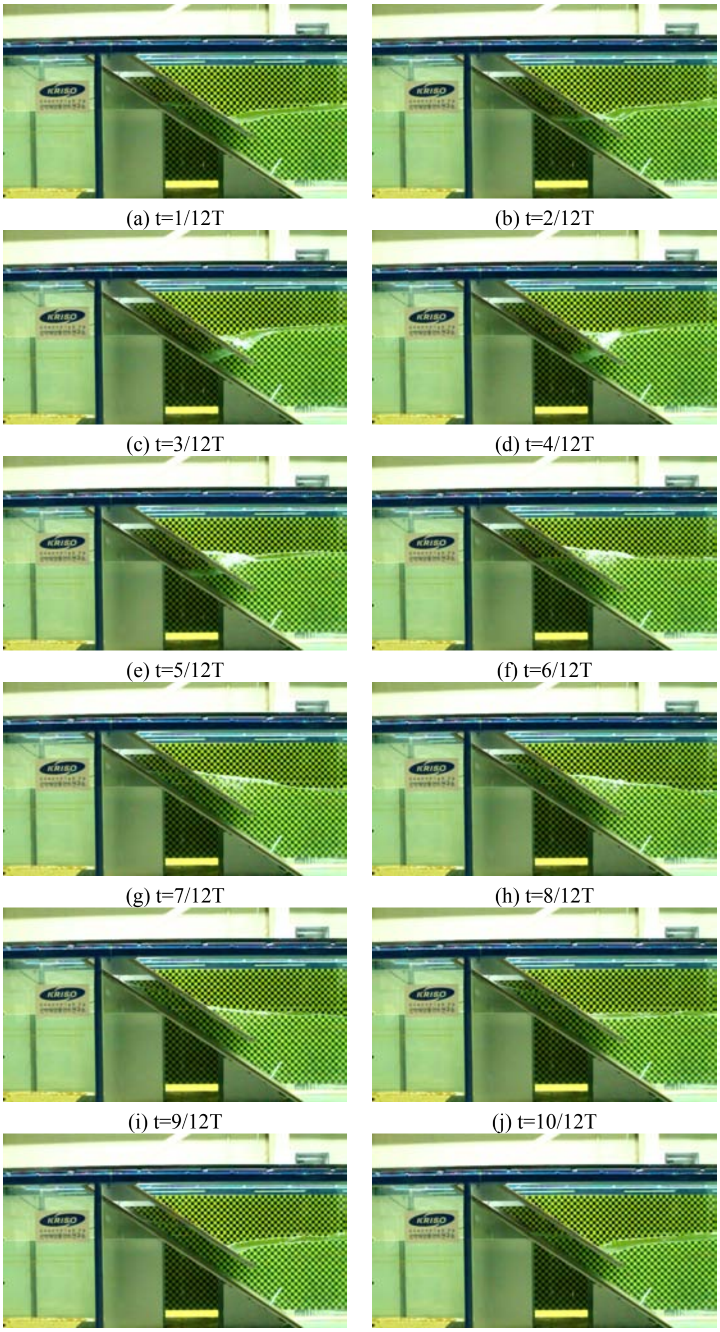


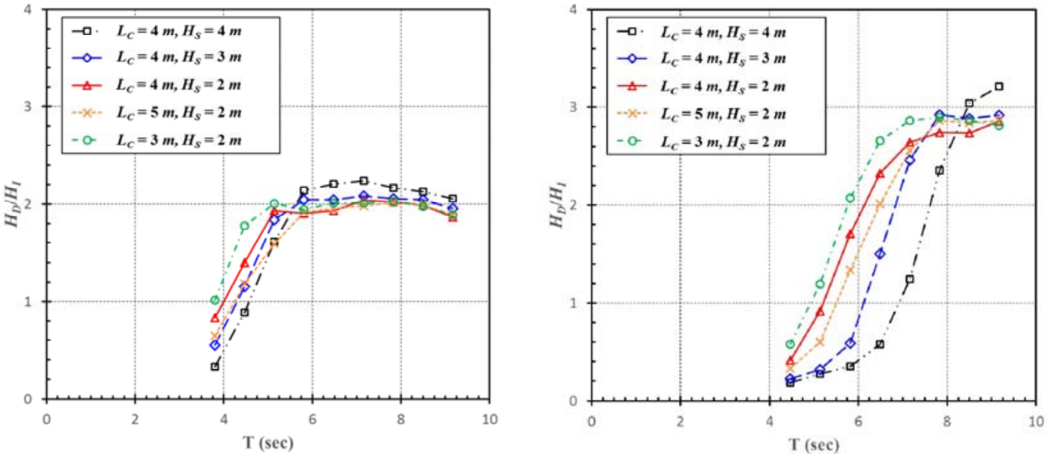
Fig. 10. Snapshots showing behavior of an excited wave in the Type I chamber captured during one cycle (U01 and W05)

The relative wave height in the chamber for the Type III configuration is shown in Fig. 8 (d). Note that L_P is the length of the projecting wall. A comparison between Figs. 8 (b) and (d) shows that the resonance period of the chamber was formed similarly despite the chamber length of Type III being shorter than that of Type I. This means that the projecting wall delayed the resonance period of the chamber by generating both harbor resonance and pumping resonance. Moreover, the relative wave height increased owing to the harbor resonance. However, the projecting wall seems to be weak when it is up against oblique waves under extreme weather conditions.



(a) t=1/12T (b) t=2/12T
(c) t=3/12T (d) t=4/12T
(e) t=5/12T (f) t=6/12T
(g) t=7/12T (h) t=8/12T
(i) t=9/12T (j) t=10/12T
(k) t=11/12T (l) t=12/12T

Fig. 11. Snapshots showing behavior of an excited wave in the Type IV chamber captured during one cycle (S01 and W06)



(a) Type I (b) Type II

Fig. 12. Measured relative wave height for Type I and Type IV

The results for the Type IV configuration are shown in Fig. 9. The chamber length (L_C) and skirt height (H_{Sk}) were varied during the simulation. The resonance period of the chamber depended on the chamber length and skirt height, similar to those for the Type I configuration. Note that the resonance period for Type I, which is L_C = 4.0 m and H_{Sk} = 0.6 m, is about 5 s, as shown in Fig. 8 (a), whereas that for Type IV, which is L_C = 4.0 m and H_{Sk} = 0.5 m, is about 7 s. There is a difference in the resonance period even if the design variables are almost the same for the Type I and IV configurations. As the reason for this, the slope for a Type IV configuration makes a difference in the size of the water column trapped in the chamber.

Based on the simulation results, the Type I and IV configurations are reasonable for an OWC chamber applicable to a breakwater, and thus were selected as candidates for the conceptual design considered in the model experiment.

4.2 Experimental Results

The model experiment was conducted in a 2D wave flume using the model cases listed in Table 1. Figs. 10 and 11 show snapshots of the behavior of the excited waves in the chamber for the Type I and IV configurations, respectively. In the snapshots, the behaviors during one cycle for wave periods of 7.16 s and 7.83 s, respectively, were captured. As shown in the snapshots, the excited wave height was approximately doubled for Type I and tripled for Type IV compared to the incoming wave height. This can be qualitatively identified through a comparison of the grid occupied by waves. The grid has a square section, the space of which is 2 cm.

The relative wave heights measured at the chamber center for the cases listed in Table 1 are shown in Fig. 12 (a) and (b) for the Type I and IV configurations, respectively. It was verified that the longer chamber and higher skirt delay the resonance period, which corresponds to the results from the numerical analysis. In addition, an increase in the relative wave height during a longer period for a deeper skirt height was confirmed through the results. As the reason for this, a deeper skirt reduces the viscous damping effects caused by a vortex generated at the tip of the skirt owing to its isolation from the free surface.

It was estimated that a Type IV configuration excites the waves in the chamber more than Type I, and thus was selected for the conceptual design of an OWC chamber applicable to a breakwater; however, the parametric study presented in this paper has a limitation in that the effects of the interactions between the free surface and the turbine were not modeled.

4. Concluding Remarks

Various configurations of an OWC chamber including conventional, U-OWC, projecting wall, and sloped configurations were analyzed through a parametric study using a numerical method and a model experiment. In the numerical analysis, the U-OWC chamber showed an improvement in the performance within a specific range of wave periods; however, the operable conditions could be limited at a site with high tide differences. An increase in performance within a wide range of wave periods was shown for a projecting wall; however, a weakness with regard to the structural safety was expected owing to its long arm being exposed to the open sea. A model experiment using a 2D wave flume was also conducted for the selected candidates, namely, conventional and sloped chambers, which showed reasonable performances in the numerical results in addition to a structural simplicity. According to the experiment results, the sloped chamber showed quite a good performance as well as good constructability, and was therefore selected as the conceptual design for an OWC chamber applicable to a breakwater.

To complement several limitations of the numerical method and model experiment, a CFD analysis, which makes it possible to consider the viscous damping effect and free surface interaction by the airflow through the duct, and 3D model experiments, which enable the 2D wall effect of the wave flume to be excluded, are planned for the future, and the design procedures will be continued based on these analysis methods.

Acknowledgements

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