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포물선형 월류파력발전장치에 대한 수치해석

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Computational Analysis of Parabolic Overtopping Wave Energy Convertor

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요 약

월파형 파력발전장치는 월류된 파랑으로 인하여 발생한 수두차를 이용하여 터빈을 구동하는 일종의 파랑에너지 변환장치로써 파랑에너지를 전기 에너지로 변환하는 장치이다. 본 연구는 상용 CFD코드 인 Fluent를 사용하여 수치조파수조를 구현하여 월파형 파력발전장치의 해석에 도입을 하여 입사파 조건과 형상에 대한 계산을 수행하였다. 최적의 월류성능을 나타내는 구조물 사면형상을 도출하기 위하여 직선형과 포물선형을 채택하여 비교분석을 수행한 결과 포물선형 사면경사를 갖는 구조물이 더 우수한 월류성능을 보인다는 것을 확인 하였다.

Abstract – Overtopping Wave Energy Convertor (OWEC) is an offshore wave energy convertor for collecting the overtopping waves and converting the water pressure head into electric power through the hydro turbines installed in the vertical duct which is fixed in the sea bed. The numerical wave tank based on the commercial computational fluid dynamics code Fluent is established for the corresponding analysis. Several incident wave conditions and shape parameters of the overtopping device are calculated. The straight line type and parabolic type of the sloping arm are compared in the optimal designing investigation of the overtopping characteristics and discharge for OWEC device. The numerical results demonstrate that the parabolic sloping arm is available for wave running up and the overtopping discharge increasing.

Keywords: Overtopping wave energy convertor(월파형 파력발전변환장치), VOF model(VOF 모델), Numerical wave tank(수치조파수조), Straight type(직선형), Parabolic type(포물선형), Overtopping discharge(월류량)

1. INTRODUCTION

Among various ocean renewable resources, wave energy is most abundantly available and applicable in most coastal and offshore areas. Plenty of wave energy absorption devices and plants have been invented, and several of them have been utilized in the electricity generation. Overtopping Wave Energy Convertor (OWEC) has some distinct advantages over other types of wave energy converting devices. It produces a relatively small fluctuation in the derived electricity because it converts wave energy to potential energy in the calm water of the reservoir.

TAPCHAN is the first overtopping type prototype onshore generator which was installed on a remote Norwegian island in 1985 described by (Falnes *et al.* [1991]). (Kofoed et al. [2006]) proposed a floating wave energy convertor of the overtopping type, Wave Dragon. It consists of two patented wave reflectors focusing the wave towards the ramp, linked to the wave reservoir. The wave reflectors have the verified effects of increasing the significant wave height substan-

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tially and thereby increasing the energy capture. Waves focused by the reflectors overtop the ramp and fill the reservoir, which is situated at a higher level than the surrounding sea. The SSG (Sea Slot-cone Generator) is a new wave energy converter of the overtopping type proposed by (L. Margheritini *et al.* [2009]). The structure consists of a number of reservoirs one on the top of each other above the mean water level in which the water of incoming waves is stored temporary. In each reservoir, expressively designed low head hydro turbines are converting the potential energy of the stored water into power.

The computational analysis method has been widely employed in the investigation of the wave structure interaction especially the overtopping motion. The VOF model coupled with the Navier-Stokes equations now are applied in the wave propagation and flow structures, which focus on the prediction of the precise free water surface and intense air-water interaction. (Isobe et al. [2001], Lin and Liu [1998] and Hieu et al. [2004]) proposed several numerical wave tank (NWT) based on VOF model. The NWT all have the capability on simulation of the wave propagation in the shallow water, including the processes of wave shoaling, breaking, reflection and air movement.

In the present paper, a 2D numerical wave tank utilizing two-phase VOF model is established to study the overtopping characteristics and discharge for OWEC device. Several incident wave conditions and shape parameters of the overtopping device are calculated. The straight line type and two types of parabolic shape of the sloping arm are compared in the optimal designing investigation of the OWEC device.

2. OVERTOPPING WAVE ENERGY CONVERTOR

The 2D schematics of the Overtopping Wave Energy Convertor (OWEC) devices with various types of sloping arms are illustrated in Fig. 1. The device consists of a reservoir to store wave water and the sloping arms for the waves to run up from the incident direction. The device is fixed to the sea bottom by the duct installed with the low head hydro turbines. As displayed in Fig. 1, L and h represent the projected length and height of the sloping arm in the oriental and vertical directions, respectively. The sloping ratio S of the device arm is defined as: $S=L/h$. h_u is the hydro head, and h_b is the underwater height of the sloping arm. The water depth is fixed as 20 m and the width of the reservoir is 8 m. The length projected in the oriental direction L varies with respect to the variation of the sloping ratio and the height projected in the vertical direction h.

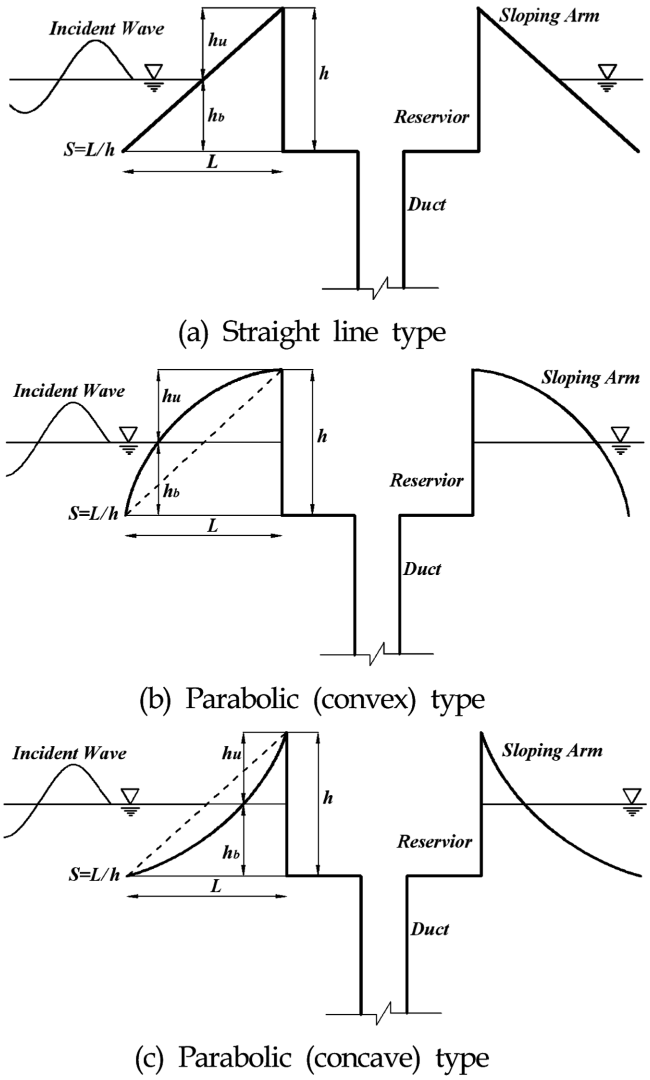


Fig. 1. 2D schematic of OWEC with various types of sloping arms.

In the present paper, 3 types of sloping arms are employed in the practical calculation of the overtopping characteristics and discharge analysis: (a) Straight line type; (b) Parabolic (Convex) type; (c) Parabolic (Concave) type. The schematic of a 2-D numerical wave tank is shown in Fig. 1. The propagating waves are generated by the wave maker plate at the left end, and the opening boundary is set at the other end.

In the numerical simulation, the OWEC device without the duct is employed because the investigating emphasis is the overtopping characteristics and comparison of discharge amounts. The length of the numerical wave tank is 300 m; the OWEC device is 200 m away from the wave maker at the left end. The opening boundary is set at the right end of the flume.

The capability of the numerical wave tank on the overtopping simulation utilized in the present paper has been validated with the corresponding experimental data by (Liu *et al.* [2008]). It has been reported by (Liu *et al.* [2008]) that the wave cannot overtop and fall into the reservoir for the wave height H_0=1.0 m when the water head is 2.0 m. Therefore, the wave height utilized in the present study is 2.0 m. Various shape parameters are employed to investigate the effects of different sloping arm type on the overtopping characteristics and discharges of the OWEC device. The testing shape parameters and incident wave conditions are summarized in Table 1. For each case, three types of 2-D sloping device arms are applied in the calculation. The effect of grid dependency is minor when the number of grid exceeds 3×10^4, as shown in Fig. 2.

In order to verify the capability of the VOF model based on the numerical wave tank, the overtopping flow rates of straight type OWEC facility within h_u=2.0 m, h_b=2.0 m, S=1:1.5 against various incident wave periods are calculated, as shown in Fig. 3. The good agreements with the corresponding experimental data (Shin *et al.* [2008]) indicate that the present numerical model can be utilized in the overtopping performance prediction and design of OWEC device.

Table 1. Testing shape parameters of OWEC and wave conditions

Case	S	H_u (m)	H_b (m)	T (sec)	H_0 (m)
01	1:1.5	2.0	2.0	6.0	2.0
02	1:2	2.0	2.0	6.0	2.0
03	1:3	2.0	2.0	6.0	2.0
04	1:2	1.0	2.0	6.0	2.0
05	1:2	3.0	2.0	6.0	2.0
06	1:2	2.0	1.0	6.0	2.0
07	1:2	2.0	3.0	6.0	2.0

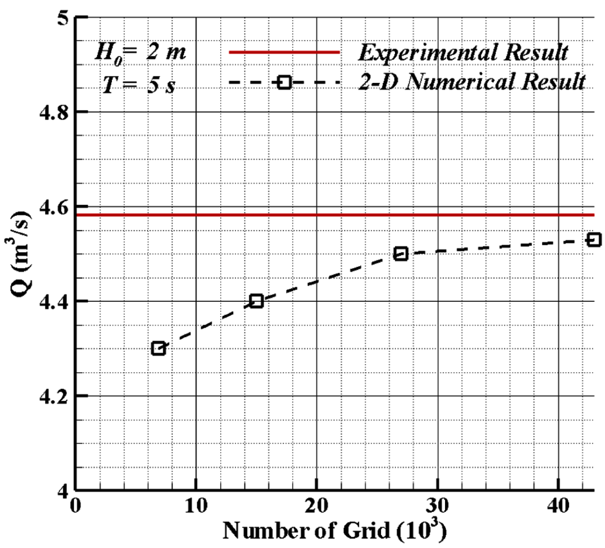


Fig. 2. The effect of grid dependency.

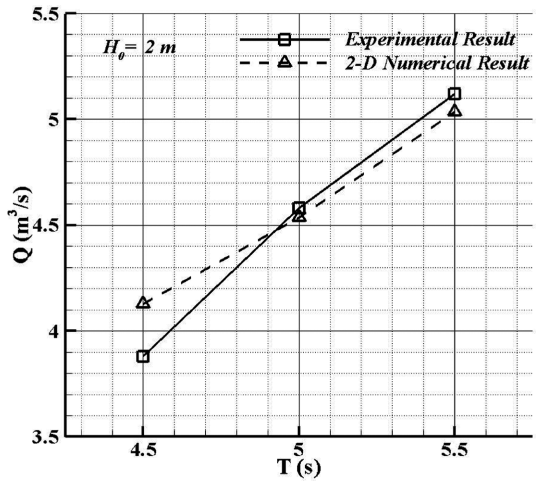


Fig. 3. Comparison of experimental and numerical results for overtopping flow rate of OWEC.

3. RESULTS AND DISCUSSION

A typical process of wave overtopping the OWEC device with straight sloping arm for Case 02 is given in Fig. 4. As displayed in Fig. 4(a) and (b), the incident waves are blocked by the sloping arm and the water column falls down during running up the arm. The air bubbles are also enclosed in the water as shown in Fig. 4(c). In Fig. 4(d), the wave water will splash and cause the energy loss. The overtopping phenomena in the other cases for the straight line type also show the similar behaviors.

The overtopping process in one period for convex sloping arms is shown in Fig. 5. It can be seen in Fig. 5(a)~(c) that the incident waves will be blocked by the sloping arm and break during climbing along the arm, which also induce the complex movement of the wave waters with much air bubbles enclosed. After the water overtops and falls into the reservoir in Fig. 5(d) and (e), the wave profile and movement is similar with the straight line type shown in Fig. 4.

Different from the above two types of sloping arms, the wave does not break during running up along the sloping arm for the concave type as shown in Fig. 6(a)~(c). It demonstrates that the concave sloping arm has minor blocking effects on the incident wave running up at the initial stage.

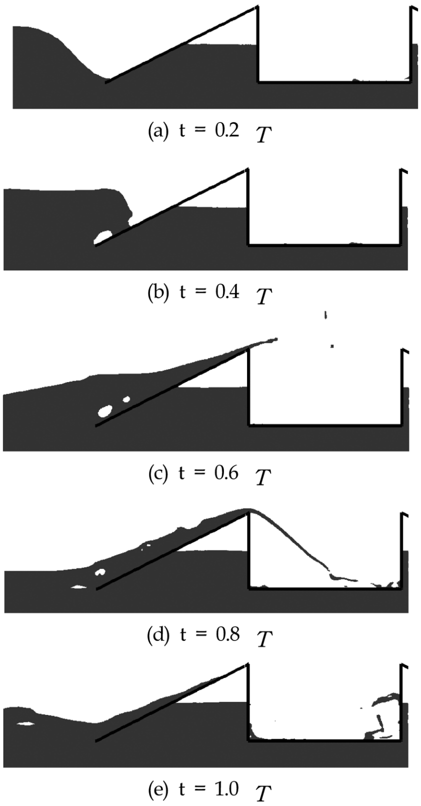


Fig. 4. Snapshot of overtopping in one period for straight type (Case 2).

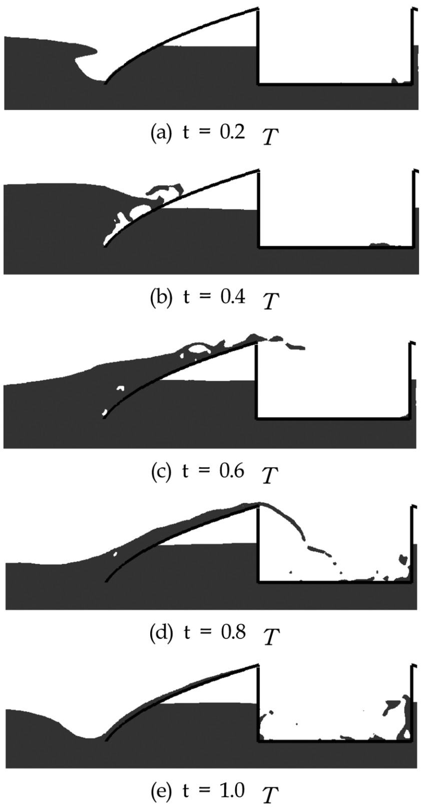


Fig. 5. Snapshot of overtopping in one period for convex type (Case 2).

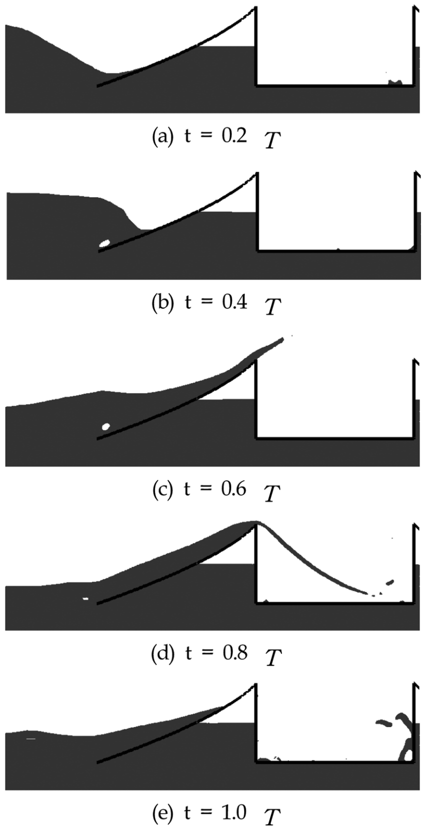


Fig. 6. Snapshot of overtopping in one period for concave type (Case 2).

The difference with the above two types of wave falling back stages is not evident as given in Fig. 6(d) and (e).

Time series of the flow rate of wave overtopping into the reservoir for Case 2 with concave sloping arm are shown in Fig. 7, which can be monitored at the highest point of sloping arm. The maximum values of the overtopping fluxes of the arriving waves are around 1 m^3/s except the first incident wave. It can be seen that the period variation of the overtopping fluxes are same as the incident wave period. The overtopping flow characteristics for other types of sloping arm also show the similar behavior.

The overtopping discharge can be obtained by integrating the flow rate curve in Fig. 7, which is illustrated in Fig. 8. The variations of overtopping discharges are more stable after the initial effects of the first incident wave.

The operating performance of OWEC device is determined by the overtopping discharge of the water column because it represents the potential energy contained by the water column in the reservoir, which can be converted to the kinetic energy of the falling water to drive the hydro turbines.

Effects of shape parameters and sloping arm types of

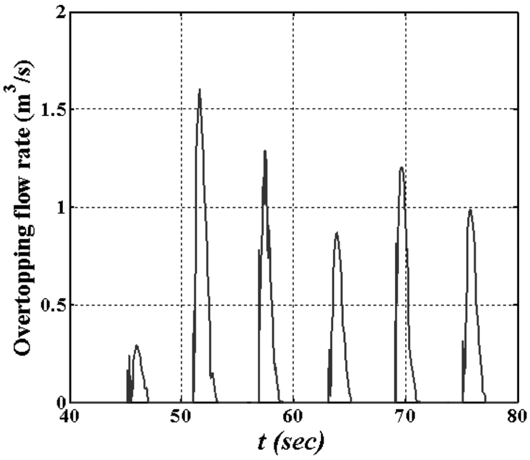


Fig. 7. Time series of overtopping flow rate for concave type (Case 2).

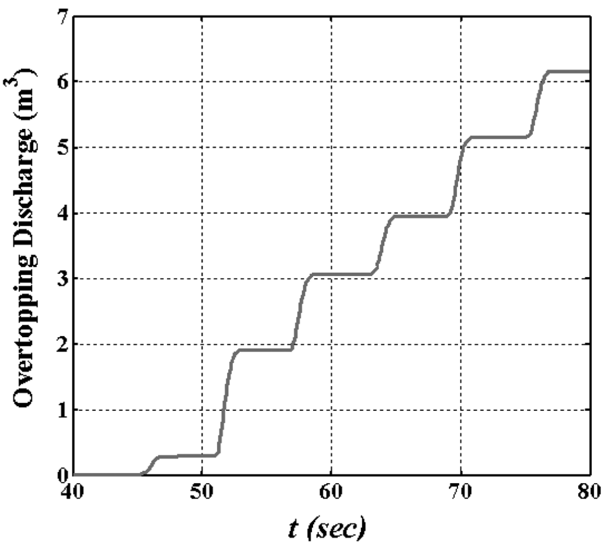


Fig. 8. Time series of overtopping discharge for concave type (Case 2).

OWEC device on the dimensionless overtopping discharges are given in Fig. 9. As shown in Fig. 9(a), the overtopping discharges in one period will decrease as the sloping ratio decreases when it is smaller than 1:2. The maximum discharge is obtained for the convex type with sloping ratio equaling to 1:2. Due to the calculating results, it is recommended that the sloping ratio should not be smaller than 1:2.

Fig. 9(b) gives the influence of the hydro head of OWEC device on the discharges. The overtopping flow discharge will decrease as h_u increases evidently. It also can be seen that the concave type of sloping arm causes the discharges reduce and the convex type shows best performance with the variation of the hydro head of OWEC device.

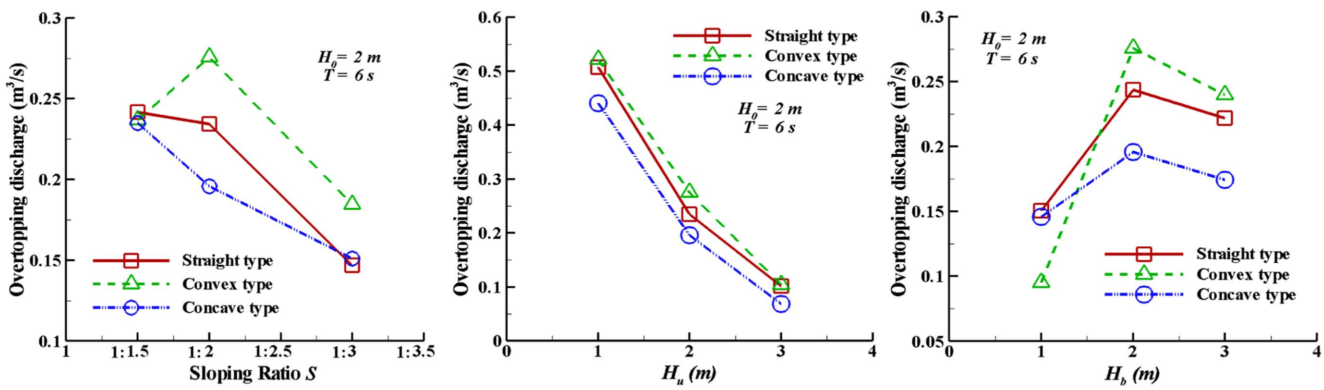
It is demonstrated in Fig. 9(c) that the effects of the underwater height of the sloping arm are minor when it is larger than 2 m for each type of sloping arms. The incident waves will be blocked obviously for the convex sloping arm when h_b is small. The maximum overtopping discharge occurs for the convex type as h_b varies.

In general, it is concluded that the convex type of sloping arms shows the best performance of the overtopping discharge of OWEC device and the concave type will reduce the overtopping fluxes within the test conditions conducted here.

4. CONCLUSIONS

The predicting capability of the numerical wave tank based on the VOF model on wave overtopping is compared with the laboratory test and experimental data. The good agreements with experimental data demonstrate that the present model can be used in the corresponding investigation of the wave overtopping problems.

Three types of sloping arms with several of shape parameters of OWEC device are calculated and compared. The straight line type and convex type shows similar characteristics as the incident waves run up the sloping arm. The



(a) Sloping ratio (b) h_u (c) h_b

Fig. 9. Effects of shape parameters and sloping arm types of OWEC device on overtopping discharges.

waves break during climbing process and the breaking phenomena are more evident for the convex type. It cannot be seen that the obvious breaking when the waves running up along the concave type of the sloping arm.

The convex type of sloping arms shows best performance on the overtopping discharges and the discharges of concave type is smaller than that of the straight line type within the test conditions conducted in the present study.

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