Practical design and investigation of the breakwater OWC facility in China

Zhen Liu[1, 2, 3] Hongda Shi[1, 3] and Beom-Soo Hyun[2]

[1] Department of Ocean Engineering,
Ocean University of China,
23# Songling Road, Qingdao, 266-100, China
E-mail: qdsanxian@hotmail.com

[2] Division of Naval Architecture and Ocean System Engineering,
Korea Maritime University,
1# Dongsam-Dong, Yeongdo-gu, Busan, 606-791, Korea

[3] Key Laboratory of Ocean Engineering of Shandong Province,
23# Songling Road, Qingdao, 266-100, China

Abstract

The breakwaters are utilized for absorbing wave energy to provide suitable berthing conditions for the harbors. The caisson breakwater can be modified as the air chamber of the Oscillating Water Column (OWC)-Wave Energy Conversion (WEC) facilities. In the present paper, the integrated structure of Caisson breakwater- OWC chamber is practically designed. The experiments are performed in the wave flume to obtain the oscillating amplitude of inner water column inside the chamber, which are usually employed to demonstrate the operating performance of the OWC chamber. A numerical wave tank based on the two-phase VOF model is established to generate 3D incident waves. The numerical wave tank consists of the continuity equation, Reynolds-averaged Navier-Stokes equations and two-phase VOF volume fraction equations. The standard k-e turbulence model, finite volume method, NITA-PISO algorithm and dynamic mesh technique are employed. The numerical results are compared and validated by the above corresponding experimental data. The effects of several incident wave conditions and shape parameters on the wave energy converting efficiency and performance of integrated system are investigated.

Keywords: Caisson breakwater, wave energy, OWC, physical experiments, numerical simulation.

1 Introduction

In the past, the breakwaters are usually employed to provide the berthing conditions for the harbours. Recently, the rectangular caissons with compartments are widely used in the construction of breakwaters in the Chinese harbours. On the other hand, the Oscillating Water Column (OWC) facility is one of the most promising types in wave energy conversion. Most practical projects are based on this converting form. It can be pointed out that the structure of the caisson breakwaters is similar with the air chamber of OWC wave energy convertor. Therefore, the two types of structures can be integrated and constructed at the same time to realize the multifunctional development of the coastal engineering. It will save the construction expenses to reduce the producing prices of the wave energy electricity power plants.

Many efforts have been put in the research of the wave energy converting efficiency and operating performance of the oscillating water column system. Lee et al.(1996) first utilized low order 3D boundary element methods to predict the response of an isolated OWC accounting for the appropriate interior free surface boundary condition[1]. Physical model with different bottom slopes was constructed and tested in a wave tank under regular wave conditions by Wang et al. (2002) [2]. Hong et al. (2004) calculated the motions and time-mean horizontal drift forces of floating backward-bent duct buoy wave energy absorbers in regular waves taking account of the oscillating surface pressure due to the pressure drop in the air chamber above the oscillating water column within the scope of the linear wave theory[3]. Hong et al. (2007) performed an experiment concentrating on the effects of several shape parameters of OWC chamber in wave energy absorbing capability[4]. Josset and Clement (2007) applied the low order boundary element method for efficient hydrodynamic modeling of generic bottom mounted OWC power plants to estimate the annual performance of the wave energy plant on Pico Island[5]. Jayashankar et al. (2009) presented a numerical model

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to predict the flow characteristics in the components of an oscillating water column (OWC) system used for the wave energy capture[6].

It should be noted that most of the former researches only focus on the air chamber of OWC wave energy convertor, which are utilized individually. Although the concept has been proposed in the 1980s, the integrated structures of breakwater OWC haven't been studied systematically.

In the present paper, the integrated structure of Caisson breakwater- OWC chamber is practically designed. The experiments are performed in the wave flume to obtain the oscillating amplitude of inner water column inside the chamber, which are usually employed to demonstrate the operating performance of the OWC chamber. A numerical wave tank based on the two-phase VOF model is established to generate 3D incident waves. The numerical results are compared and validated by the above corresponding experimental data. The effects of several incident wave conditions and shape parameters on the wave energy converting efficiency and performance of integrated system are investigated numerically.

2 Practical Design of Breakwater-OWC Integrated System

The breakwater-OWC integrated system is practically designed under the guidance of the Chinese codes. The environmental and incident wave conditions are derived from the statistic data of the Qingdao Port, which is the one of the largest container ports in China. The water depth exceeds 10m and mean wave height is higher than 1.5m. Most of the structures of docks and breakwaters are rectangular caissons.

The sketch of the caisson breakwater-OWC integrated system is shown in Fig. 1-4. As displayed in Fig.1, the caisson is divided into nine compartments. The green parts in Fig. 1 are employed as rubble-filled compartments same as the normal caisson. They provide the stability of the whole structure. The red part is set against the incident waves, and the beam is used as the bracing components for the chamber. The blue parts are the air ducts which connect the air embraced above the free surface inside the chamber and the environmental atmosphere. The opening (Orange Part) at the bottom of the chamber front panel is illustrated in Fig. 2.

The stability of the caisson has been calculated according to the designing conditions and wave forces at the extreme high and low water level derived from the experiments, which satisfied the corresponding Chinese design code of the coastal engineering.

3 Experimental Set-up

The experiments were all carried out in the wave flume of the Ocean Engineering Key Laboratory of Shandong Province, China.

The flume is 50m long, 0.8m wide and 1.2m deep. A piston type wave making system is installed at the end of the wave flume while a wave absorber at the opposite end.

The chamber-caisson model was fixed at 45m distance from the wave maker. The models are made of acryl to provide more clear visibility. The scale ratio of the model for experimental test to prototype is 1/30 and the mean water depth in prototype scale is 12m. The wave height inside the chamber denoted by *h* measured at the centre of chamber using a wire-type capacitance wave gauge and the incident wave were measured at 20 away from the wave maker as well.

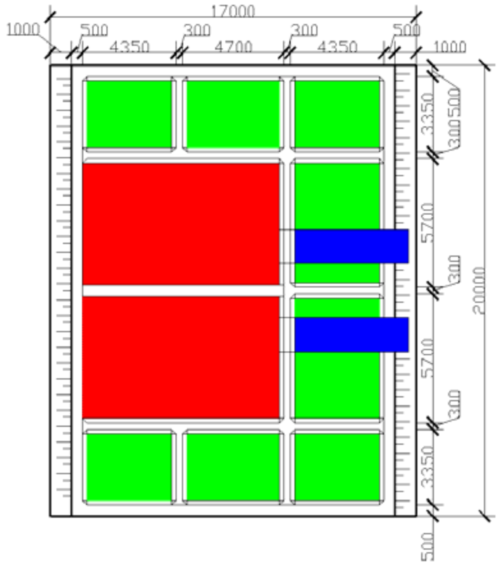

Figure 1: Top view of breakwater-OWC system

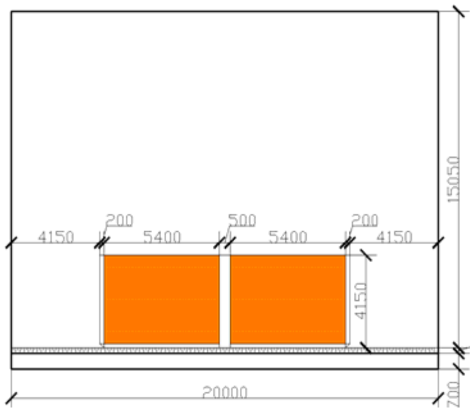

Figure 2: Front view of breakwater-OWC system

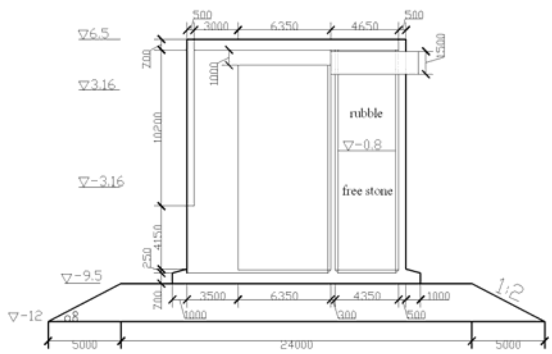

Figure 3: Side view of breakwater-OWC system

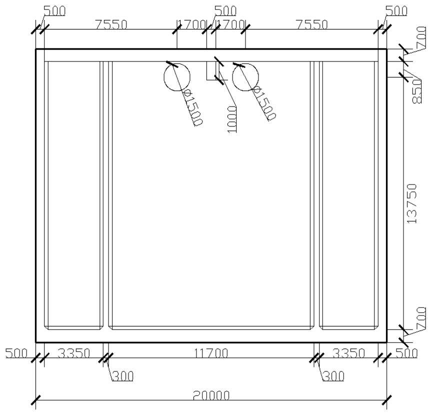

Figure 4: Back view of breakwater-OWC system

The schematic of the caisson-chamber model is shown in Fig. 5. Test conditions to examine effects of shape parameters of caisson chamber and incident wave conditions are summarized in Table 1, where d_w denotes the mean water depth, d_s the draft of chamber skirt, l_f the chamber width and l_d the diameter of the air duct. h_0 represent the incident wave height. 5 regular waves whose period varies from 5s to 12s are applied for each case. Furthermore, different cases are tested by experimental and (or) numerical methods.

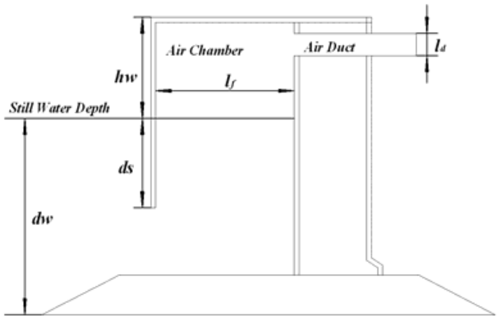

Figure 5: Schematic of caisson-chamber model

case	d_w(m)	d_s (m)	h_w (m)	l_d (m)	h_0 (m)	*Testing*
1	12.0	2.9	5.8	1.5	1.5	Exp,Num
2	13.6	2.9	4.2	1.5	1.5	Exp,Num
3	10.4	2.9	7.4	1.5	1.5	Exp,Num
4	12.0	2.9	5.8	1.5	1.0	Exp
5	12.0	2.9	5.8	1.5	2.0	Exp
6	12.0	4.4	5.8	0.5	1.5	Num
7	12.0	4.4	5.8	1.0	1.5	Num
8	12.0	4.4	5.8	1.5	1.5	Num

Table 1: Testing cases

4 Numerical Wave Tank

In the present study, the fluids are incompressible and immiscible. At the interface of two fluids, no phase change and no-slip between fluids are assumed. The propagating waves are generated by the wave maker plate at the left end, and the opening boundary is set at the other end. The governing equations are the continuity equation and RANS equations for impressible fluid:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t_i} + u_i \frac{\partial u_i}{\partial x_i} + u_j \frac{\partial u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + f_{x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j} - \overline{u_i' u_j'}\right) \quad (2)$$

where x_i, u_i represent the coordinate directions and corresponding velocity components; ρ, p, ν, f_{xi} are the fluid density, the fluid pressure, the kinematic viscosity coefficient and the body force, respectively.

The component $\overline{u_i' u_j'}$ defined as the Reynolds Stress induces *a* new turbulence model to enclose the equations. The standard *k-ε* model, which is widely used in engineering application, is employed to describe the turbulence phenomenon in the water and air dynamic motions.

The tracking of the interface between the air and water phases is accomplished through the Volume of Fluid (VOF) method proposed by Hirt and Nichols (1981) [7]. The volume fractions of water and air in the computational cell sum to unity. If the volume fraction of water is defined as a_w, then the following three conditions are possible: 1). a_w=0, the cell is empty of water; 2). a_w=1, the cell is full of water. 3). 0< a_w<1, the cell contains the interface. The volume fraction a_w is computed as:

$$\frac{\partial a_w}{\partial t} + \frac{\partial (a_w u_i)}{\partial x_i} = 0 \quad (3)$$

In addition, the face fluxes through the cells are obtained as the geometric reconstruction approach. The interface between two fluids is calculated using the piecewise-linear scheme (Youngs, 1982), which assumes the linear slope in each cell.

The regular linear wave is applied in the investigation of this paper, and the motion of the piston wave maker is determined from the following equation:

$$x(t) = \frac{S_0}{2}(1 - e^{-5t/2T})\sin \omega t \quad (4)$$

where S_0 is the maximum displacement of the wave maker; T is the period of the incident wave, and $\omega = 2\pi / T$.

On the opening boundary, the Sommerfeld radiation boundary condition (Sommerfeld, 1949) is used to obtain the relation between the horizontal velocity component and the free surface elevation[8]. The wave absorption can be performed by controlling the motion of the opening boundary within the velocities opposite to the water particles adjacent to the opening boundary on the x-direction.

The motion of the wave generating and absorbing boundaries can be achieved by defining UDF (User-Defined Function) programs. Fluent also provides the layering remeshing method in dynamic mesh model to govern the grid reconstruction adjacent to the moving boundaries. The geometries and meshes are created by the grid generation software Gambit V 2.2, and the grids at the fluid interface have been refined to predict the free surface accurately.

The governing equations are solved by using Finite Volume Method (FVM). Second-order upwind discretization is considered for the convection terms. The pressure-velocity coupling is calculated by the NITA (None-Iterative Time Advancement) – PISO (Pressure Implicit with Splitting of Operators) algorithm compatible with VOF model, which requires only one global iteration per time step, and reduces solution time significantly.

It has been proved that the VOF numerical wave tank can simulate the complex free surface interaction, and predict not only the wave motion but also the pressure distribution and air flow motion. It has been successfully employed in the investigation both the OWC and overtopping wave energy converting facilities by Liu et al. (2007) [9]and Liu et al. (2008) [10]. The geometry and grid structure of the caisson-chamber model in the numerical simulation is given in Fig. 6.

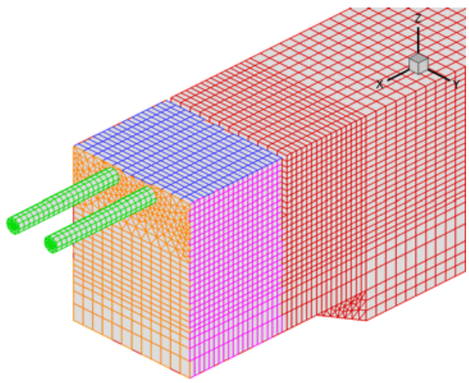

Figure 6: Geometry and Grid Structure in Numerical Study

5 Results and Discussion

Effects of incident wave conditions are illustrated in Fig. 7. Five incident wave periods and three wave heights are employed for the regular wave experimental test.

It can be seen that the relative wave height distributions against the wave period are same for the different wave heights. The relative heights will increase as the period increase at the short-period domain. The relative heights converge to 2.0 when the period is larger than 10.0s and approach to infinity because of the standing wave formation at the front wall. Futhermore, it can be seen that the relative height inside the chamber will increase as the incident wave height decrease, especially at the long-period domain. Although the efficiency of wave energy converting for small wave height is higher, the amount of energy absorbed by the facility is less than that of the higher wave height. The above results are still valuable for the assessment of the wave energy amount and distribution around the location of the power station.

Fig. 8 displays effects of still water depth on the operating performance of caisson-chamber system. The numerical prediction is also validated by the experimental results. At the short-period domain, the relative wave height shows little difference. Furthermore, the relative height will increase within the still water depth increasing and converge to 1.8 at the long-period domain. The numerical results show good agreements with the experimental data, which demonstrate that the present numerical model is suitable for the operating performance investigation on the caisson-chamber system. Both the numerical and experimental results show the same distribution characteristics of wave energy converting along the incident wave periods. On the other hand, the chamber with higher still water depth can absorb more wave energy than that with low depth especially at the long-period domain.

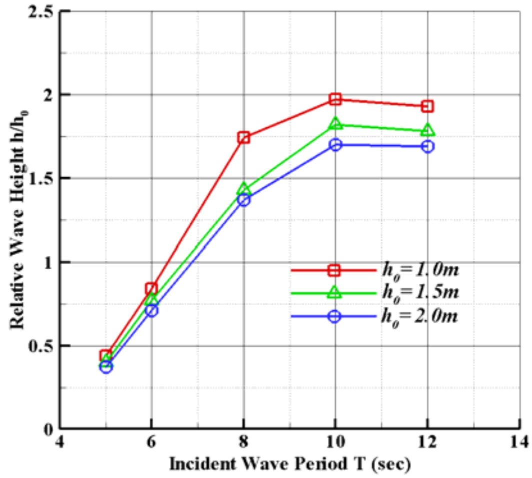

Figure 7: Effects of wave conditions on energy absorption

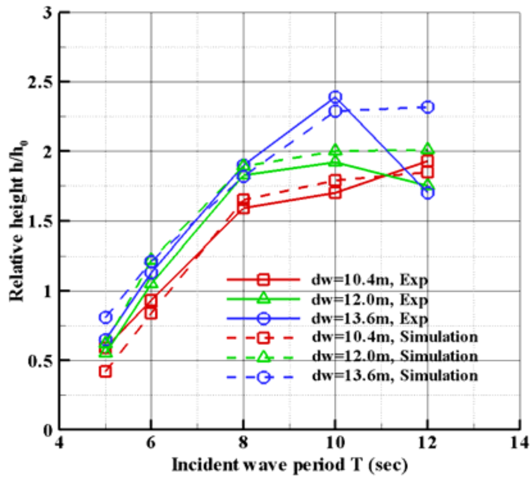

Figure 8: Effects of still water depth on energy absorption

The effects of air duct diameter on energy absorption are shown in Fig. 9. It can be seen that the obvious difference among relative heights of various air duct diameters. The relative heights of caisson-chamber system will decrease as the air duct diameters decrease. However, it is hard to say that large-diameter air duct can improve the operating performance of wave energy convertor. Although the flow rates are not large for the duct within small diameters, the air flow velocity is high which is valuable for the air turbines to drive the electricity generator. Therefore, it is necessary to choose the reasonable value of the air duct diameters based on the air flow and turbine to achieve the optimal energy converting coefficients.

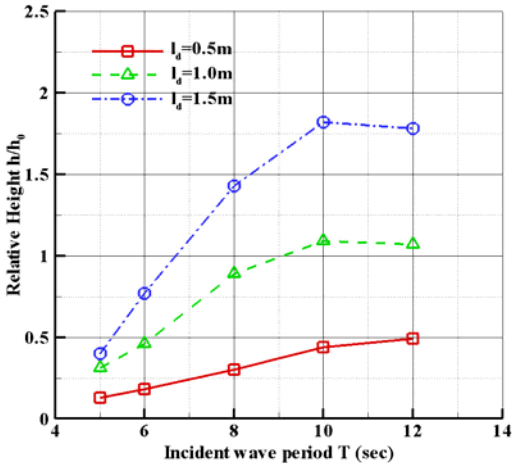

Figure 9: Effects of air duct diameter on energy absorption

6 Conclusions

The integrated structure of Caisson breakwater-OWC chamber is practically designed, which is suitable for the environmental conditions of the sea area in China.

The experiments are performed in the wave flume to obtain the oscillating height of inner water column inside the chamber to demonstrate the operating performance of the OWC chamber and provide the validating data for the numerical simulation. The numerical wave tank based on the two-phase VOF model is established to generate 3D incident waves for the performance investigation.

It can be seen that the incident wave periods, wave heights, still water depth and air duct diameters all have significant effects on the relative heights inside the caisson-chamber system. The long-period domain, high wave height, large still water depth can improve the operating performance of the system.

For the air duct, it needs more studies to choose the suitable value to achieve the optimal results for the caisson breakwater-OWC system design in the engineering application. It is also necessary to monitor and simulate the air pressure inside the chamber and air flow in the duct in the future to get more accurate results.

Acknowledgements

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