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# An experimental investigation of hydrodynamics of a fixed OWC Wave Energy Converter

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## Abstract

The hydrodynamic performance of a fixed Oscillating Water Column (OWC) wave energy device under various wave conditions and geometric parameters was tested experimentally in a wave flume. The measured water surface elevation at the chamber center, the air pressure in the chamber of the OWC device and the hydrodynamic efficiency are compared well with the published numerical model results in Ref. [22]. Then the effects of various parameters including incident wave amplitude, the chamber width, the front wall draught, the orifice scale and the bottom slope on the hydrodynamic efficiency of the OWC device were investigated. It is found that the opening ratio  $\varepsilon$  ( $\varepsilon = S_0/S$ , where  $S_0$  and  $S$  are the cross-sectional areas of the orifice and the air chamber, respectively) has a significant influence on the maximum hydrodynamic efficiency of the OWC device. The optimal efficiency occurs at the opening ratio of  $\varepsilon=0.66\%$ . Although bottom slope has little influence on the resonant frequency, the optimal hydrodynamic efficiency increases with the increase of bottom slope. A proper bottom slope can provide a work space in the OWC chamber almost independent on the sea wave conditions. The spatial variation of the water surface inside and outside the chamber was also examined. And the results indicate that the water motion is highly dependent on the relative wave length  $\lambda/B$  (where  $\lambda$  is the wave length and  $B$  is the chamber width). Seiching phenomenon is triggered when  $\lambda/B=2$  at which the hydrodynamic efficiency is close to zero.

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25 **Key words:** OWC; Wave energy; Model testing; Hydrodynamic efficiency; Water motion.

## 26 **1. Introduction**

27 To cope with the increasing costs of fossil fuels and the environmental problems derived from the  
28 extraction and the use of fossil fuels, renewable energy sources are believed to play a more and more  
29 important role to mitigate these effects [1]. Wave energy is certainly a significant component of the  
30 renewable energy [2] due to its high energy density [3] and less negative environmental impact [4, 5].  
31 More than one thousand wave energy converter patents had been registered by 1980 and the number  
32 has increased markedly since then [6], in which the OWC device has been extensively studied and  
33 implemented due to its mechanical and structural simplicity [7]. Generally, a land-fixed OWC device  
34 consists of two parts: a partially submerged land back chamber and an open below the mean sea level.  
35 They are used to trap a column of air above the free surface. As the waves impinge on the device, the  
36 oscillating motion of the internal water free surface makes the air to flow through a turbine that  
37 drives an electrical generator [8]. A number of full sized OWC prototypes have been installed and  
38 tested world widely, including Tofteshallen in Norway (500 kW), Sakata in Japan (60 kW), Pico in  
39 Portugal (400 kW), Limpet in Scotland (500 kW), and more recently Mutriku in Spain (300 kW) [9].  
40 However, OWC technology has not been fully commercialized yet [10]. The main reason is that the  
41 hydrodynamics of the OWC devices has not been fully understood. Further hydrodynamic  
42 investigations on OWC device still need to be carried out theoretically, numerically and  
43 experimentally.

44 Although significant efforts have been made to investigate the hydrodynamic performance of  
45 OWC devices theoretically at the early stage, such as McCormick [11], Evans [12], Falcão and  
46 Sarmiento [13], Evans [14] and Falnes and McIver [15] etc, majority of OWC theories are based on  
47 linear wave theory and neglect the viscosity, spatial variation of water surface elevation in the  
48 chamber. The hydrodynamic efficiency is generally over-predicted based on the simple theoretical  
49 solutions [8, 22, 25].

50 Recent development of numerical techniques and increasing computer power has significantly  
51 increased the efficiency and accuracy of numerical studies of the hydrodynamic performance of

52 OWC devices. Based on the potential flow model, Count and Evans [16] developed a numerical  
53 model by coupling the three-dimensional (3-D) boundary integral method outside the OWC device  
54 and with the eigenfunction expansion method in the rectangular inner region. Wang et al. [17]  
55 validated numerical computations with experimental measurements and found the topographical  
56 effects of bottom slope and water depth is important to the performance of an OWC. Delauré and  
57 Lewis [7] applied the first-order BEM to simulate the hydrodynamic performance of a 3D fixed  
58 OWC device and discussed its accuracy. Josset and Clément [18] developed a time-domain  
59 numerical model of OWC wave power plants to predict the annual performance of the wave energy  
60 plants on Pico Island, Azores, Portugal. Nunes et al. [19] analyzed an off-shore OWC device  
61 numerically and studied the techniques that could improve energy extraction efficiency. It was  
62 proved that it is possible to achieve a resonant response for sinusoidal waves with a frequency  
63 different from the device's natural frequency. Falcão et al. [20] analyzed the performance of an OWC  
64 spar buoy wave energy converter in the frequency domain for both regular and irregular waves.  
65 Iturrioz et al. [10] presented a simplified time-domain model for a fixed detached OWC device and  
66 validated numerical computations by comparison with experimental data. Gkikas and Athanassoulis  
67 [21] presented a nonlinear system identification method for modeling the pressure fluctuation inside  
68 the chamber of an OWC wave energy converter under monochromatic excitation. Ning et al. [22]  
69 developed a two-dimensional (2-D) fully nonlinear numerical wave flume (NWF) based on a  
70 time-domain higher-order boundary element method (HOBEM) and used it to investigate the  
71 hydrodynamic performance of a fixed OWC wave energy device. Rezanejad et al. [23] investigated  
72 the performance of dual chamber OWC devices in the stepped sea bottom condition.

73 Recently, researchers have also developed viscous-flow model based on the N-S equations to  
74 analyze the OWC device. Marjani et al. [24] simulated the flow characteristics in the chamber of an  
75 OWC system using the FLUENT software. They found that the energetic performances are higher in  
76 the case of the inhalation mode than in the case of the exhalation mode. Zhang et al. [25] developed a  
77 2-D two-phase numerical wave tank (NWT) using a level-set immersed boundary method to study  
78 the flow field, surface elevation and air pressure in an OWC chamber. They investigated the effects  
79 of the geometric parameters on the OWC power capture efficiency. Teixeira et al. [9] applied the

80 Fluinco numerical model to simulate an OWC device and investigate the effects of the chamber  
81 geometry and the turbine characteristics on the device performance. López et al. [26] implemented a  
82 2-D numerical model based on the RANS equations and the VOF surface capturing scheme  
83 (RANS-VOF) to study the optimum turbine-chamber coupling for an OWC. Luo et al. [27]  
84 developed a 2-D, fully nonlinear CFD model and analyzed the efficiency of fixed OWC-WEC  
85 devices with linear power take off systems. Iturrioz et al. [28] simulated a fixed detached OWC  
86 device using OpenFOAM to test capability of CFD simulations in analyzing the OWC device.  
87 However, it is still difficult to perfectly simulate the nonlinear wave interaction with an OWC device  
88 in any previous numerical models due to the complicated coupling process of air and water in the  
89 chamber.

90 In addition to the numerical modelling, a number of experiments have been carried out to study  
91 the performance of OWC devices. Tseng et al. [29] presented the concept of a breakwater and a  
92 harbor resonance chamber which can extract energy from the ocean and protect the shore at the same  
93 time. A 1/20 model of this type of system was constructed and tested in a wave tank and the  
94 experimental data were compared with the previous theoretical results. Afterward, Boccotti et al. [30]  
95 carried out an experiment to study the hydrodynamic performance of harbor resonance chambers.  
96 Morris-Thomas et al. [8] experimentally studied the energy efficiency of an OWC focused their  
97 study on the influence of front wall geometry on the OWC's performance. Gouaud et al. [31] carried  
98 out experiments to investigate the hydrodynamic performance of an OWC device and compared the  
99 experimental data to numerical results. Liu [32] studied the operating performance of an OWC air  
100 chamber both experimentally and numerically. Dizadji and Sajadian [33] carried out an experimental  
101 study on the geometrical design of an OWC system and optimized the set up for the maximizing the  
102 energy harness. He et al. [34] experimentally investigated an integrated oscillating water column type  
103 converter with floating breakwater and found that the integrated system can widen the frequency  
104 range for energy extraction. Imai et al. [35] studied the total conversion process of an OWC device  
105 with a turbine theoretically, and carried out experiment to validate the theoretical results.

106 Above literature review shows that a number of investigation methods have been developed and  
107 applied to study the hydrodynamic performance of the OWC device. Various numerical models have

108 been established based on either potential-flow or viscous-flow model. However, the related  
109 experimental studies on land-fixed OWC devices are still limited, especially those on the influence  
110 of wave nonlinearity, turbine damping and bottom slope on the performance of the OWC devices.  
111 Moreover, no sufficient attention has been paid to the water motion in the chamber. The large  
112 difference between the internal and external surface elevations of the chamber can cause the dynamic  
113 pressure on the front wall, which may be a threat to the safety operation of the OWC device [36]. To  
114 complete the previous studies, the primary goal of this study is to experimentally investigate the  
115 effects of wave nonlinearity, the orifice scale and the bottom slope on the hydrodynamic efficiency of  
116 land-fixed OWC devices and the characteristics of water motion in the air chamber.

117 The rest of the present paper is organized as follows: The experimental procedure is described  
118 in section 2. Experimental data is compared with the solutions of the higher-order boundary element  
119 method (HOBEM) in Section 3. In Section 4, the effects of the incident wave amplitude and  
120 geometric parameters on the hydrodynamic efficiency of the OWC device are discussed. In Section 5,  
121 the spatial variation of the free surface in the air chamber is analyzed. Finally, the conclusions of this  
122 study are summarized in Section 6.

123 **2. Experiments**

124 **2.1 Experimental set-up**

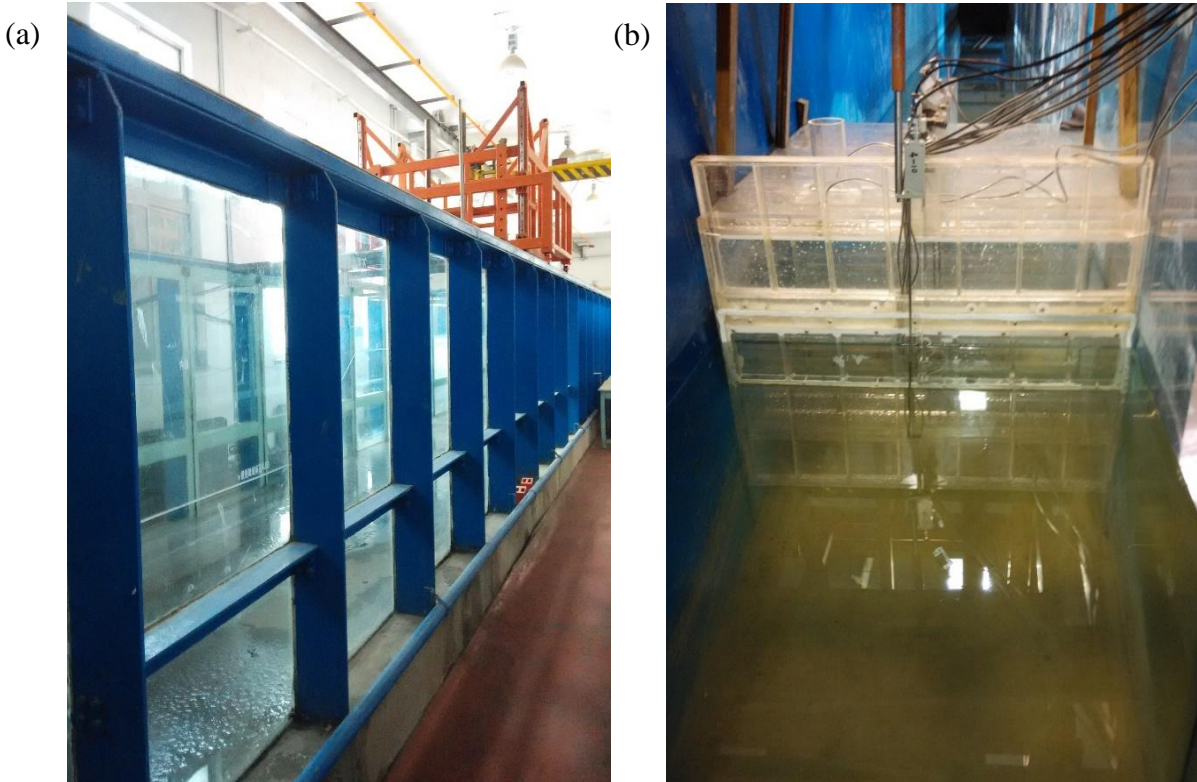
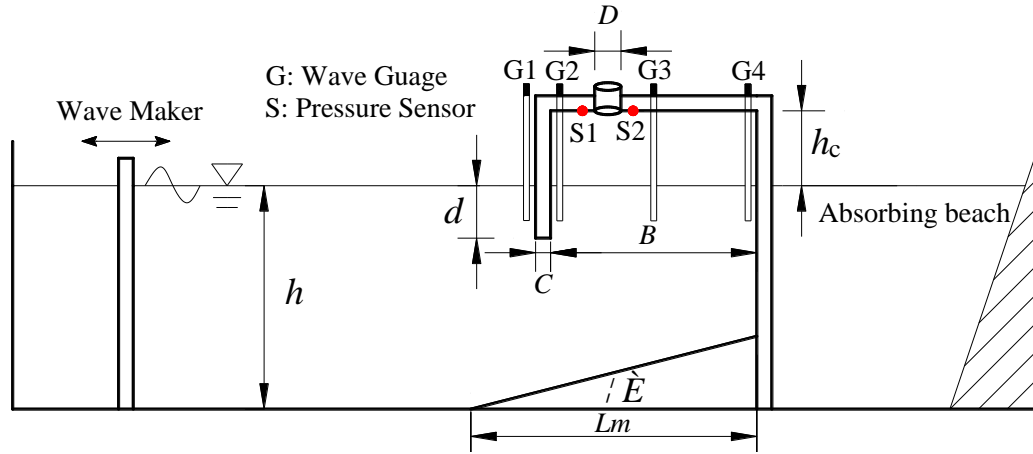
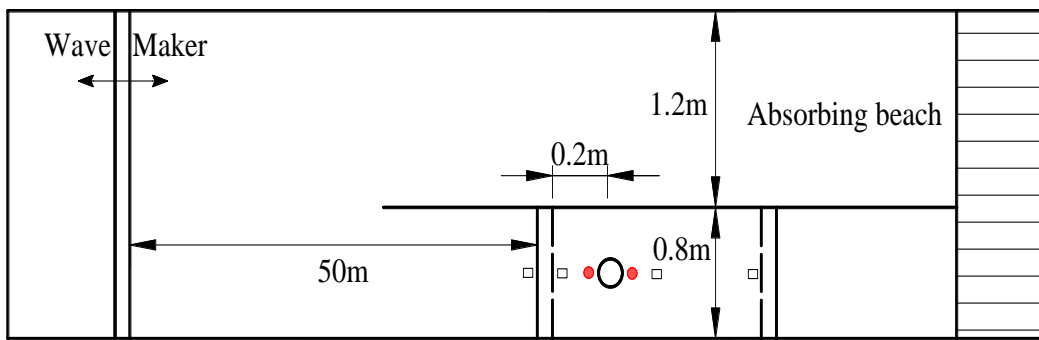


Fig. 1 Photos of (a) Laboratory wave flume and (b) OWC device.

The physical model tests were carried out in the wave-current flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The glass-walled wave flume is 69 m long, 2 m wide and 1.8 m deep as shown in Fig. 1 (a). The piston-type wave maker is installed at one end of the flume, and a wave-absorbing beach is located at the other end to absorb the outgoing waves. The wave maker is able to generate regular and irregular waves with periods from 0.5 s to 5.0 s. The test section of the flume was divided into two parts along the longitudinal direction, which were measured as 1.2 m and 0.8 m in width, respectively. The OWC model was installed in the 0.8 m wide part and 50 m away from the wave maker (see Fig. 2 (b)). To avoid wave energy transfer through the device, the model was designed to span across the width and depth of the flume. The main body of the model was made of 8-mm thick transparent Perspex sheets, in order to have a clear view of the internal free-surface of the water.



(a) Side view



(b) Plan view

Fig. 2 Schematic of the experimental setup.

138  
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140  
141  
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143 The power take-off was implemented through a circular orifice situated on the roof of the  
 144 chamber and 0.2 m from the front wall (see Fig. 2). The sketch of the experimental setup is shown in  
 145 Fig. 2, in which  $h$  denotes the static water depth,  $B$  the chamber width,  $C$  the thickness of the front  
 146 wall,  $D$  the diameter of the orifice,  $d$  the immergence of the front wall,  $L_m$  the base length of the sea  
 147 bottom slope,  $\theta$  the slope angle of the bottom, and  $h_c$  the height of the air chamber (i.e., distance  
 148 between the still water surface and the ceiling). In the experiments, four resistance-type wave gauges  
 149 (G1, G2, G3, G4) with resolution of 0.01 cm were used to measure the instantaneous surface  
 150 elevations at different locations. One exterior wave gauges was situated 0.02 m from the outer side of  
 151 the front wall to measure and record the time series of free-surface wave elevation outside the  
 152 chamber. Three were situated inside the OWC chamber, in which one was 0.02 m from the inner side  
 153 of the front wall, the second one was at the mid-point of the chamber and the last one was 0.02 m  
 154 from the rear wall. Two pressure sensors (S1 and S2) were used to measure the air pressure inside the  
 155 chamber, which were placed rigidly 0.02 m from the edge of the orifice (see Fig. 2). Their average



156 value is regarded as the air pressure in the chamber. Both the surface and pressure signals are  
 157 sampled at 50 Hz. A high-speed CCD camera was used to record the whole water surface motion in  
 158 the chamber with a frame rate of 100 fps.

159 Five sets of experiments were carried out to investigate the effects of the incident wave  
 160 amplitude, chamber width, front wall draught, orifice diameter and bottom slope on the  
 161 hydrodynamic performance of the OWC. The front wall thickness  $C=0.04$  m and the chamber height  
 162  $h_c=0.20$  m were remained constant in the experiments. Parameters  $B=0.55$  m,  $d=0.14$ m,  $\theta=0^\circ$ , and  
 163  $D=0.06$  m were chosen as the references. Then only one corresponding parameter would be varied in  
 164 each set of experiment and the others were kept constant. The geometric parameters chosen for the  
 165 experiment are shown in Table 1.

166

167

Table1 Geometric parameters used in the experiments

$B(\text{m})$	$d(\text{m})$	$\theta(^{\circ})$	$C(\text{m})$	$D(\text{m})$	$h_c(\text{m})$	$L_m(\text{m})$
0.55	0.14	0	0.04	0.04	0.2	1.0
0.70	0.17	10	0.04	0.06	0.2	1.0
0.85	0.20	20	0.04	0.08	0.2	1.0
-	-	30	0.04	-	0.2	1.0

168

169 By keeping the still water depth constant at  $h=0.8$  m, different wave conditions with wave  
 170 amplitudes  $A_i$  varied in the range of (0.02 m, 0.07 m) and 14 wave periods  $T$  in the range of (0.95 s,  
 171 2.35 s) were considered. In the cases for the effects of the geometric parameters on the OWC  
 172 efficiency, the incident wave amplitude was fixed at  $A_i=0.03$  m. Total 177 tests were carried out to  
 173 study the hydrodynamic performance of the OWC device.

174 **2. 2 Data analysis**

175 Influenced by the incident waves, the water surface in the chamber is not flat and the water column  
 176 may experience both sloshing and piston motions, which influence the natural frequency of the OWC  
 177 system. The mean power absorbed by the OWC device depends primarily on the heave motion of the  
 178 water column and air pressure inside the air chamber. Brendmo et al. [37] reported that when  
 179 wavelength is long enough in comparison with the characteristic horizontal dimension of the inner

180 OWC surface, surface motion at one point can represent the whole surface variation in the chamber.  
 181 In the present paper, the horizontal dimension of the interior chamber of the OWC is small when  
 182 compared with the prevailing wavelength. The water surface motion at the mid-point (G3) is used to  
 183 represent the internal surface fluctuation for calculating the hydrodynamic efficiency.

184 The hydrodynamic efficiency of an OWC device is determined as [8]

$$185 \quad \xi = \frac{P_0}{P_w w}, \quad (1)$$

186 where  $P_w$  is the time-average energy flux of the incident waves,  $w$  is the width of the flume section  
 187 used and  $P_0$  is the hydrodynamic energy absorbed from the waves by the OWC device during one  
 188 wave period, which is calculated by

$$189 \quad P_0 = \int_{S_f} \overline{p(t) \cdot u(t)} dt = \frac{Bw}{T} \int_t^{t+T} p(t) \cdot u(t) dt, \quad (2)$$

190 where  $p(t)$  is the air pressure in the chamber,  $u(t)$  is the normal vertical velocity of interior free  
 191 surface (represented by the surface at the chamber center),  $S_f$  is the cross-section area of the free  
 192 surface in the chamber and  $B$  is the width of the chamber.

193 According to linear wave theory, the average energy flux per unit width in the incident wave is  
 194 given by

$$195 \quad P_w = \frac{1}{2} \rho g A_i^2 c_g, \quad (3)$$

196 where  $\rho$  is the water density,  $g$  is the gravitational acceleration,  $A_i$  is the incident wave amplitude and  
 197  $c_g$  is the group velocity of the incident wave defined as

$$198 \quad c_g = \frac{c}{2} \left( 1 + \frac{2kh}{\sinh 2kh} \right), \quad (4)$$

199 where  $k$  is the wave number;  $c$  is the incident wave velocity

$$200 \quad c = \frac{\omega}{k}, \quad (5)$$

201 and the angular frequency  $\omega$  satisfies the following dispersion relation

$$202 \quad \omega^2 = gk \tanh kh. \quad (6)$$

### 203 3. Comparisons between experimental data and numerical results

204 A two-dimensional fully nonlinear numerical model based on the potential theory and the  
 205 time-domain HOBEM by Ning et al. [22] is used to simulate the proposed hydrodynamic  
 206 performance of an OWC device and the numerical results are compared with the experimental data.  
 207 In the numerical model study, the incident wave is generated by the inner-domain sources whose  
 208 strength is dependent on the incident wave velocity. A damping layer with a coefficient  $\mu_1(x)$  at the  
 209 inlet of the numerical flume is implemented to absorb the reflected wave from the OWC device as  
 210 shown in Fig. 3. The reflected waves from the structure can pass through inner-domain sources (i.e.,  
 211 the incident surface) and then absorbed at the inlet damping layer with nearly none re-reflection. The  
 212 relative study is given in the Appendix A detailedly. The governing equation is changed from Laplace  
 213 equation to Poisson equation. To model the viscous effect due to water viscosity and flow separation  
 214 in the potential flow model, the linear damping term can be used in the free surface boundary of a  
 215 sloshing container [38] or a narrow gap between twin floating objects [39, 40]. In the study [22], an  
 216 artificial viscous damping term with a coefficient  $\mu_2$  is applied to the dynamic free surface boundary  
 217 condition inside the OWC chamber. Then, velocity potential also satisfies the following modified  
 218 fully nonlinear free surface boundary conditions

$$219 \begin{cases} \frac{dX(x, z)}{dt} = \nabla \phi - \mu_1(x)(X - X_0) \\ \frac{d\phi}{dt} = -g\eta + \frac{1}{2}|\nabla \phi|^2 - \frac{p}{\rho} - \mu_1(x)\phi - \mu_2 \frac{\partial \phi}{\partial n} \end{cases}, \quad (7)$$

220 where  $X_0=(x_0, 0)$  denotes the initial static position of the fluid particle. The damping coefficient  $\mu_1(x)$   
 221 is defined by

$$222 \mu_1(x) = \begin{cases} \omega \left( \frac{x-x_1}{L} \right)^2, & x_1 - L < x < x_1, \\ 0, & x \geq x_1 \end{cases}, \quad (8)$$

223 where  $x_1$  is the starting position of damping zone,  $L$  is the length of the damping zone at the left  
 224 flume-end and equals to one incident wavelength in the present study. The artificial viscous damping  
 225 coefficient  $\mu_2$  is determined by trial and error (the detailed determination process is shown in

226 Appendix B) and only implemented inside the chamber.

227 The air pressure  $p$  on the water free surface is set to be zero (i.e., atmospheric pressure) outside  
 228 of the chamber. Inside the chamber, the pneumatic pressure is given by

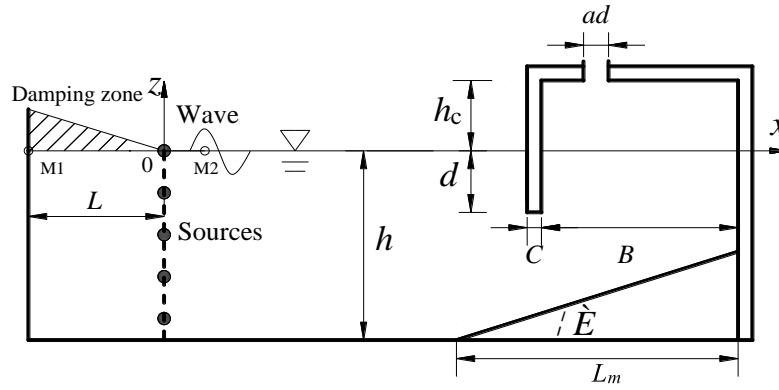
$$229 \quad p(t) = C_{dm} U_d(t), \quad (9)$$

230 where  $C_{dm}$  is linear pneumatic damping coefficient and  $U_d(t)$  the air flow velocity in the orifice.

231 The energy absorbed by the OWC device in the numerical model can be calculated by

$$232 \quad P_0 = \frac{1}{T} \int_t^{t+T} Q(t) p(t) dt = \frac{1}{T} \int_t^{t+T} B \bar{\eta}(t) p(t) dt = \frac{1}{T} \int_t^{t+T} C_{dm} U_d(t) A U_d(t) dt, \quad (10)$$

233 where the flow rate  $Q(t) = B \bar{\eta}(t) = A U_d(t)$ .  $\bar{\eta}(t)$  is the time mean vertical velocity of the free  
 234 surface inside the chamber. More details regarding the numerical model can be found in [22].



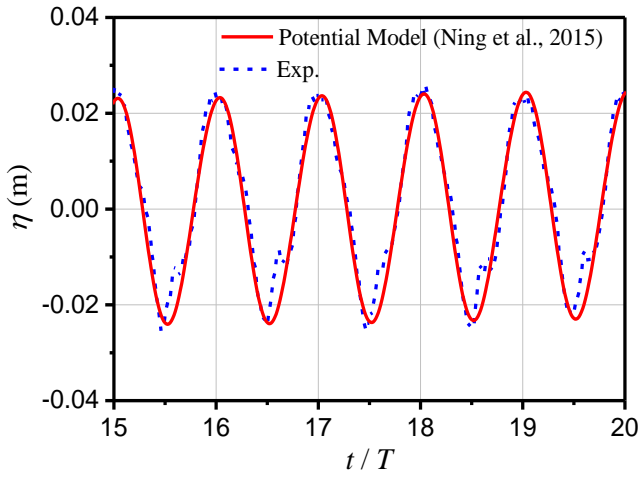
235  
 236 Fig. 3 Sketch of the numerical wave flume.

237 The numerical results with the parameters: chamber width  $B=0.55$  m, front wall thickness  
 238  $C=0.04$  m, front wall draught  $d=0.14$  m, bottom slope  $\theta=0^\circ$  and the orifice diameter  $D=0.06$  m, are  
 239 compared with the experimental data. In the numerical model, the air duct width  $ad$  is set as  $0.0036$   
 240 m, which is of the same area with the circular air orifice in the experiment, and the other four  
 241 parameters are the same as those used in the experiment. The incident wave amplitude is  $A_i=0.03$  m.  
 242 The viscous coefficient and the linear pneumatic damping coefficient in Eqs. (7) and (9) are set as  
 243  $\mu_2=0.2$  and  $C_{dm}=9.5$ , respectively. The length of the numerical flume is set to  $5\lambda$ , in which  $1.0\lambda$  at the  
 244 left side is used as the damping layer. And the size of the boundary elements in the horizontal  
 245 direction is  $\Delta x = \lambda/30$ . For each case, 30 periods of waves are simulated with a time step of  $\Delta t = T/80$ .

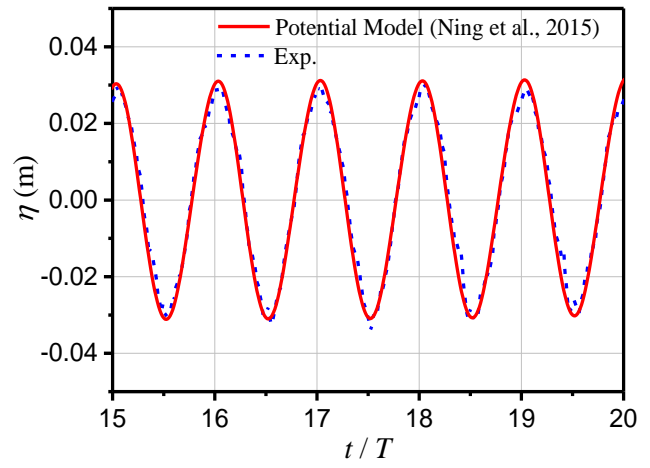
246 Figs. 4 (a) and (b) show the time series of the surface elevation at the chamber center for  
 247  $T=1.366$  s and  $T=1.610$  s, respectively. Overall, the measured and predicted surface elevation

248 compare well with each other. However, the numerical model did not capture the secondary  
249 harmonic peaks observed in the experiment in Fig. 4 (a). This is likely due to the fact that the present  
250 pneumatic model is linear, therefore, is unable to predict the higher harmonics generated by the  
251 interaction between the high frequency wave and the inhaled air flow. To verify this point, Figs. 5 (a)  
252 and (b) show the surface elevation spectrums at points outside the chamber (G1) and inside the  
253 chamber (G3) for  $T=1.366$  s. Fig. 5 (a) indicates good agreement between the numerical model and  
254 experiment at G1 outside the chamber, where the highest harmonic energy occurs at the second  
255 harmonic frequency without the pneumatic influence in the chamber. However, the highest harmonic  
256 energy occurs at the fourth harmonic frequency as observed at G3 by experiment in Fig. 5 (b), which  
257 is due to the pneumatic effect by comparison with the result in Fig. 5 (a) and are not resolved by the  
258 present linear pneumatic model. Figs. 6 (a) and (b) presents the time series of air pressure in the  
259 chamber for  $T=1.366$  s and  $T=1.610$  s, respectively. Better agreements between the observed and  
260 predicted results are obtained.

261 Fig. 7 gives the variation of the hydrodynamic efficiency with the dimensionless wave number  
262  $kh$ . The comparisons between the experimental data and the potential numerical results with  $\mu_2=0.0$   
263 (i.e., no considering the viscous effects) and  $\mu_2=0.2$  (i.e., considering the viscous effects) are shown  
264 in the figure. It can be seen that the pure potential solutions (i.e.,  $\mu_2=0.0$ ) over-predict the  
265 hydrodynamic efficiency because it neglects the viscous damping, but the resonant frequencies  
266 predicted by the potential model with and without the damping term agree well with each other. The  
267 viscous effect on the hydrodynamic efficiency is more obvious in the resonant zone (i.e.,  $1.2 < kh < 2.2$ )  
268 than at the other wave number ranges. In addition, the shape of the calculated hydrodynamic  
269 efficiency curves are similar to each other. Overall, the potential model results with a certain  
270 damping term agree well with the experimental data. It is also noted that there are two experimental  
271 data lying in between the two potential results near  $kh=2.5$ , which may be due to the experimental  
272 error or a larger damping coefficient  $\mu_2$  defined. Furthermore, it can be seen that both the numerical  
273 results with the viscous term and experimental data indicate that the optimal point is around  $kh=1.58$   
274 with the hydrodynamic efficiency of 0.83 for this geometry.



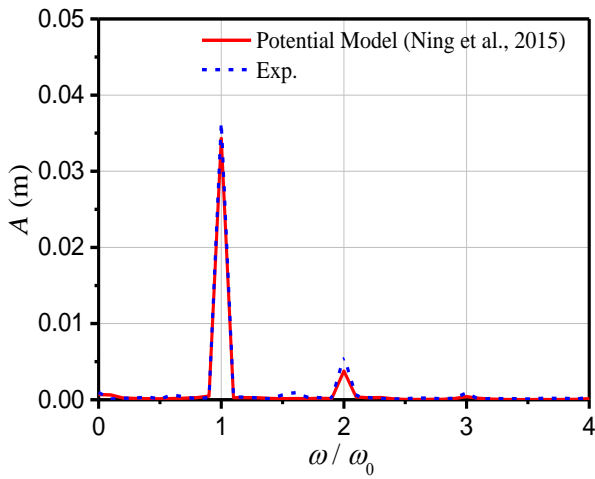
(a)  $T=1.366$  s



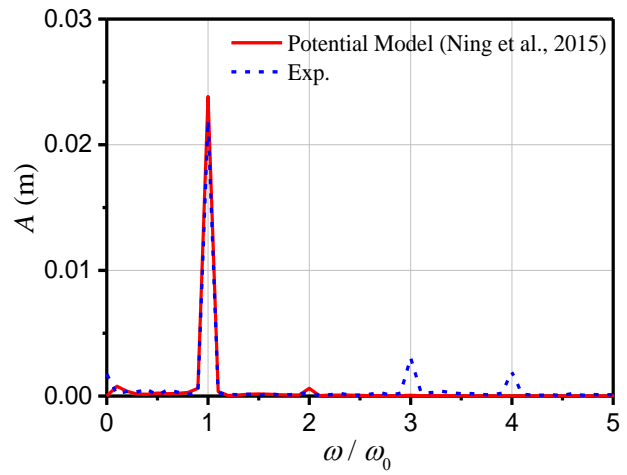
(b)  $T=1.610$  s

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277 Fig. 4 Time series of the predicted (solid line) and observed (dashed line) surface elevation at the  
278 chamber center at  $T=1.366$  s and  $1.610$  s



(a) at G1

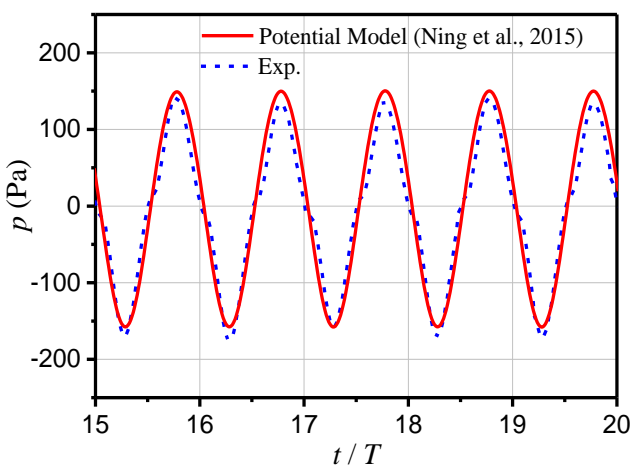


(b) at G3

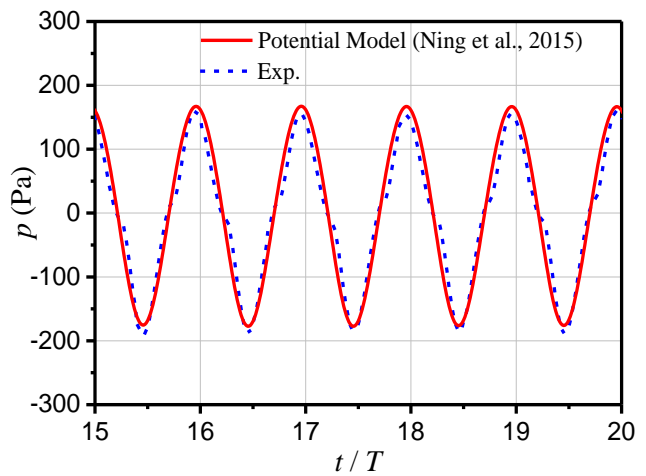
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281 Fig. 5 Spectrum analysis of surface elevations at outside the chamber (G1) and chamber center G3 for  
282  $T=1.366$  s



(a)  $T=1.366$  s

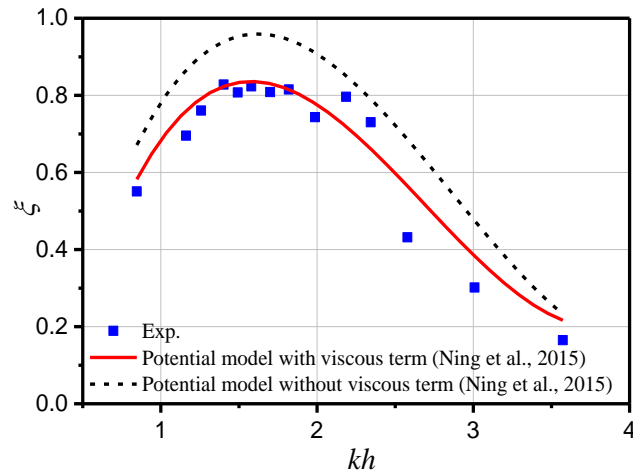


(b)  $T=1.610$  s

283  
284

285 Fig. 6 Time series of the predicted (solid line) and observed (dashed line) air pressure in the chamber

286 at  $T=1.366$  s and  $1.610$  s.



287  
288

Fig. 7 Variation of the predicted and observed hydrodynamic efficiency with  $kh$ .

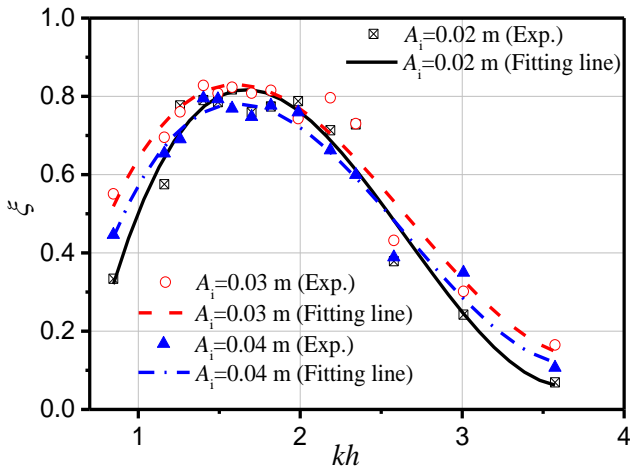
## 289 4. Effects of wave and geometric parameters

290 The influences of the incident wave amplitude (i.e., wave nonlinearity) and the OWC geometric  
291 parameters including the chamber width, the front wall draught, the orifice scale and the bottom  
292 slope on the hydrodynamic efficiency are examined in this section. Both the experimental data and  
293 their cubic fitting curves are included in the relevant figures. The similar fitting method can be found  
294 in Zhang et al. [25].

### 295 4.1 Incident wave amplitude

296 To investigate the effect of the wave nonlinearity on the hydrodynamic efficiency of the OWC device,  
297 the experiments were carried out with different incident wave amplitudes and constant other  
298 parameters:  $B=0.55$  m,  $d=0.14$  m,  $D=0.06$  m and  $\theta=0^\circ$ . Fig. 8 shows the variation of the  
299 hydrodynamic efficiency with  $kh$  for the incident wave amplitudes  $A_i = 0.02$  m,  $0.03$  m and  $0.04$  m. It  
300 can be seen that wave amplitude has little influence on the resonant frequency and the efficiency  
301 curve shape. While the resonant frequencies for all the three wave amplitudes occur at  $kh=1.58$ , the  
302 hydrodynamic efficiencies for  $A_i = 0.02$  m,  $0.03$  m and  $0.04$  m are of  $0.81$ ,  $0.83$  and  $0.78$ , respectively.  
303 In addition, it can be observed that the overall hydrodynamic efficiency increases as the wave  
304 amplitude  $A_i$  increases from  $0.02$  m to  $0.03$  m, and decrease as  $A_i$  increases from  $0.03$  m to  $0.04$  m.  
305 The maximum efficiency is at  $A_i = 0.03$  m among these three wave amplitudes.

306 To further illustrate the relationship between the wave nonlinearity and the hydrodynamic  
 307 efficiency, Fig. 9 shows the variation of the hydrodynamic efficiency with the incident wave  
 308 amplitude at three frequencies of  $kh=1.40$ ,  $1.58$  and  $1.82$ . It can be observed that the hydrodynamic  
 309 efficiency firstly increases with increasing wave amplitude, and reaches the maximum at a critical  $A_i$ ,  
 310 then decreases as wave amplitude further increases. Such behavior is in agreement with the  
 311 numerical results presented by Ning et al. [22]. When studying OWC in irregular waves, López et al.  
 312 [41] also observed that the capture factor increases with the wave steepness at low wave frequencies  
 313 and decreases at high wave frequencies. But the critical wave amplitude  $A_i$  corresponding to the peak  
 314 efficiency was not presented in their work. In addition, the peak efficiency at the resonant frequency  
 315 (i.e.,  $kh=1.58$ ) decreases more quickly with increasing amplitude than those at  $kh=1.40$  and  $kh=1.82$ .



316  
 317 Fig. 8 Hydrodynamic efficiency versus dimensionless  
 318 wave number for  $A_i=0.02$  m,  $0.03$  m and  $0.04$  m.  
 319

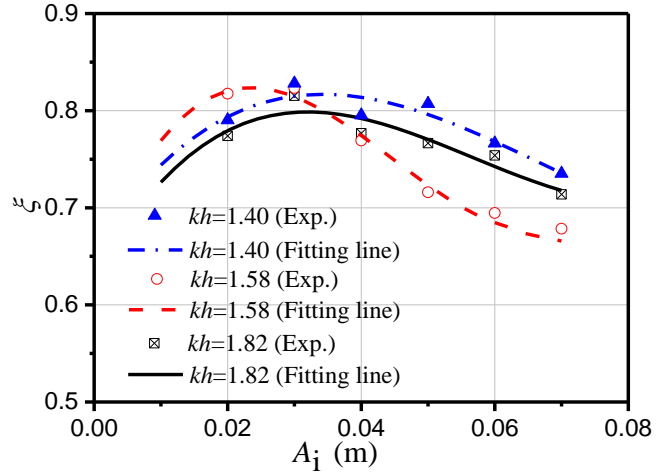


Fig. 9 Hydrodynamic efficiency versus  
 incident amplitude  $A_i$  for  $kh=1.40$ ,  $1.58$   
 (resonant frequency) and  $1.82$ .

## 320 4. 2 Chamber width

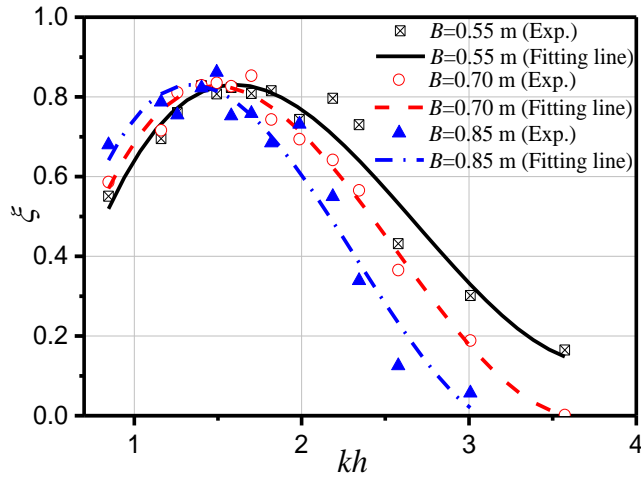
321 Fig. 10 shows the hydrodynamic efficiency of the OWC device for three different chamber widths:  
 322  $B= 0.55$  m,  $0.70$  m and  $0.85$  m and constant wave amplitude of  $A_i=0.03$  m. The other parameters are  
 323 kept the same as those in Fig. 8. From the figure, it can be seen that the chamber width has a  
 324 significant influence on the hydrodynamic efficiency of the OWC device. The hydrodynamic  
 325 efficiency increases with the increase of chamber width  $B$  in the low-frequency region (about  
 326  $kh<1.5$ ), but follows a completely opposite trend in the high-frequency region. What's more, the  
 327 resonant frequency decreases with the increase of  $B$ . The optimal points are around  $kh=1.58$  ( $B=0.55$



328 m),  $kh=1.50$  ( $B=0.70$  m) and  $kh=1.36$  ( $B=0.85$  m) with the same hydrodynamic efficiency of 0.83,  
 329 respectively. The reason is due to that the inertia of the OWC water column increases with chamber  
 330 width. The approximated nature piston frequency formula by Veer and Thorlen [42] for the water  
 331 mass oscillating in a moonpool is calculated as follows:

$$332 \quad \omega_n = \sqrt{\frac{g}{d + 0.41\sqrt{Bw}}} \quad (11)$$

333 The coefficient 0.41 in the above formula is empirical and hence does not necessarily provide  
 334 accurate results in the case of OWC device. However, the dependence of the natural frequency on the  
 335 width of the chamber can be clearly seen in Eq. (11).

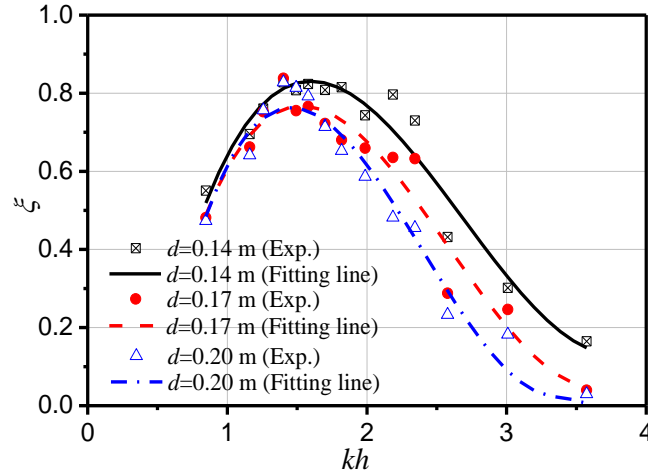


336  
 337 Fig. 10 Hydrodynamic efficiency versus dimensionless wave number for different chamber widths

### 338 4. 3 Front wall draught

339 Fig. 11 illustrates the hydrodynamic efficiency of the OWC device obtained from different front wall  
 340 draughts of  $d=0.14$  m, 0.17 m and 0.20 m with  $A_i=0.03$  m and other parameters remaining the same  
 341 as those in Fig. 8. Firstly, it can be observed that both the resonant frequency and the peak efficiency  
 342 decrease with the increase of the submerged depth  $d$ . They occur at  $kh=1.59$  ( $d=0.14$  m), 1.50  
 343 ( $d=0.17$  m) and 1.41 ( $d=0.20$  m) corresponding to the hydrodynamic efficiency of 0.83, 0.77 and  
 344 0.76, respectively. This characteristic is caused by the increased mass of water column in the  
 345 chamber. The hydrodynamic efficiency reduces significantly with increasing  $d$  in the high-frequency  
 346 zone (about  $kh>1.75$ ) and is not sensitive to the change of draught  $d$  in the low-frequency zone  
 347 (about  $kh<1.0$ ). An explanation to such a phenomenon is that while in the low-frequency long wave

348 region, compared with the wave length, the draught of the front wall is small enough, so that the  
 349 variation of the long wave length is insensitive to the submerged depth. In contrast, in the  
 350 high-frequency short wave region, the draught of the front wall is not small relative to the  
 351 wavelength, so the variation of the short wave length is sensitive to the immergence depth [22].

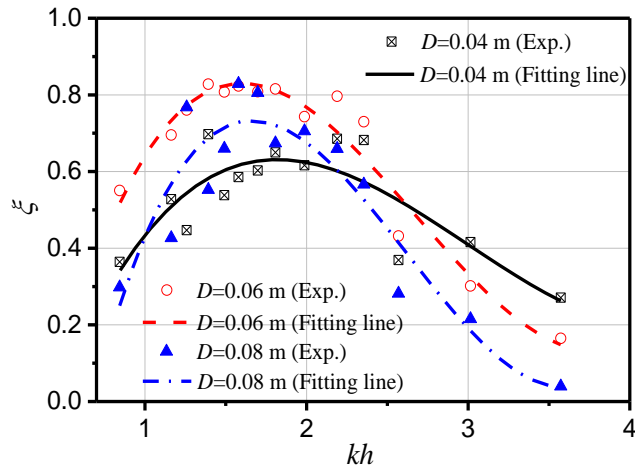


352  
 353 Fig. 11 Hydrodynamic efficiency versus dimensionless wave number  $kh$  for different draught  $d$

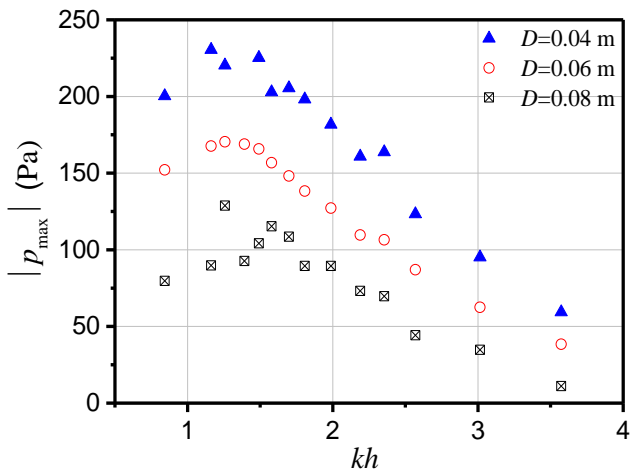
#### 354 4. 4 Orifice scale

355 As shown in Fig. 12, three circular-shaped openings were tested in the experiments. The size of  
 356 an opening can be described by the opening area ratio  $\varepsilon = S_0/S$ , where  $S_0$  and  $S$  are the cross-sectional  
 357 areas of the orifice and the air chamber, respectively. In this set of experiments, the incident wave  
 358 amplitude was set as  $A_i = 0.03$  m and other parameters were kept the same as those in Fig. 8. Three  
 359 diameters of the orifice  $D = 0.04$  m,  $0.06$  m and  $0.08$  m correspond to the opening ratios of 0.29%,  
 360 0.66% and 1.17%, respectively. The optimal hydrodynamic efficiency  $\zeta$  is highly influenced by the  
 361 opening ratio with  $\zeta = 0.63$  ( $\varepsilon = 0.29\%$ ),  $0.83$  ( $\varepsilon = 0.66\%$ ) and  $0.74$  ( $\varepsilon = 1.17\%$ ). Moreover, the  
 362 hydrodynamic efficiency  $\zeta$  for  $\varepsilon = 0.66\%$  reaches the largest among the three opening ratios except  
 363 those in the high-frequency zone (about  $kh > 2.6$ ). He and Huang [43] obtained a similar conclusion in  
 364 their experimental study of pile-supported OWC-type structure. They found that the circular-shaped  
 365 opening with an opening ratio of 0.625% could achieve the smallest transmission coefficient. To  
 366 further explain such phenomenon, Figs. 13 and 14 present the comparisons of the air pressure in the  
 367 chamber and the maximum water surface elevation at the chamber center for different opening ratios,  
 368 respectively. The water column motion is influenced by the oscillation of the air pressure inside the

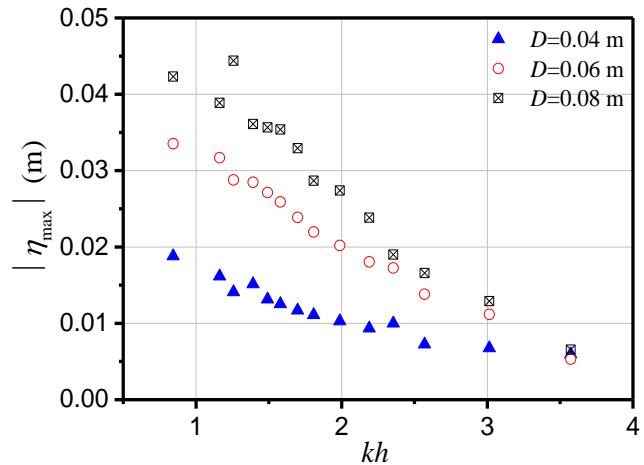
369 chamber. Experimental results show that internal air pressure decreases with increasing opening ratio,  
 370 while the maximum surface elevation changes with an opposite trend. For the smallest opening ratio  
 371  $\varepsilon=0.29\%$  (i.e.,  $D=0.04$  m), the largest pressure fluctuation in the chamber leads to the smallest  
 372 oscillation amplitude of the water column. For the largest opening ratio  $\varepsilon=1.17\%$  (i.e.,  $D=0.08$  m),  
 373 the pressure fluctuation in the chamber is the smallest with the largest surface elevation. The wave  
 374 energy extraction attributes to the product of air pressure and volume variation in the chamber  
 375 according to Eq. (2). Thus the optimal ones correspond to the opening ratio  $\varepsilon=0.66\%$  (i.e.,  $D=0.06$  m)  
 376 from Figs. 12, 13 and 14. The present analysis may help to determine the turbine damping of the  
 377 OWC device to achieve the optimal energy extraction.



378  
 379 Fig. 12 Variation of hydrodynamic efficiency for different diameter of the air orifice  $D=0.04$  m  
 380 (open ratio  $\varepsilon=0.29\%$ ),  $0.06$  m (open ratio  $\varepsilon=0.66\%$ ) and  $0.08$  m (open ratio  $\varepsilon=1.17\%$ ).



381  
 382 Fig. 13 Variation of the air pressure in the chamber  
 383 for different diameter of the air orifice.



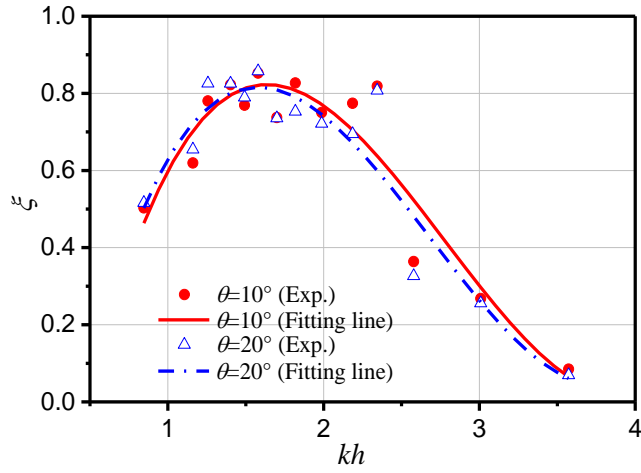
384 Fig. 14 Variation of the surface elevation at  
 the chamber center for different diameter of the  
 air orifice.

#### 385 4. 5 Bottom slope

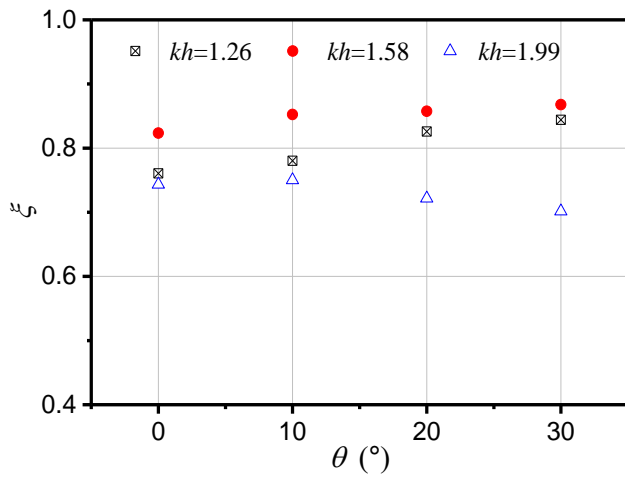
386 To investigate the influence of the bottom slope on the performance of the OWC device, physical  
387 tests are carried out for different bottom slopes with the parameters  $A_i=0.03$  m,  $B=0.55$  m,  $d=0.14$  m,  
388  $D=0.06$  m and  $L_m=1.0$ m being constant. As shown in Fig. 15, the results indicate that the efficiency  
389 curve is shifted slightly to the left with the increase of the slope angle  $\theta$ . The resonant frequency is  
390 basically unchanged and occurs at about  $kh=1.58$ . Rezanejad et al. [23] reported that the efficiency  
391 curve slightly shifts to the lower wave period with the decrease of the bottom slope in the case  
392 without stepped bottom in their study of the dual-chamber OWC. Ashlin et al. [44] experimentally  
393 studied the performance of an OWC device with different bottom profiles subject to random waves  
394 and found that the nature frequency is independent of the bottom profile.

395 Fig. 16 shows the variation of the hydrodynamic efficiency versus bottom slope for different  $kh$ .  
396 The largest efficiency occurs at the resonant frequency (i.e.,  $kh=1.58$ ) and slightly increases with the  
397 bottom slope in the proposed scope of  $\theta \leq 30$  degree. This attributes to the largest product of the  
398 surface variation rate  $(\eta_{\max} - \eta_{\min})/T$  and air pressure variation rate  $(p_{\max} - p_{\min})/T$  in the chamber  
399 at resonant frequency (see Figs. 17 (a) and (b)). For the low-frequency ( $kh=1.26$ ), the hydrodynamic  
400 efficiency increases with increasing slope angle. This is because the water depth in the chamber  
401 decreases with increasing slope angle, which can enhance the shallow water effect and strengthen the  
402 piston motion in the chamber. For the high-frequency ( $kh=1.99$ ), the increase of the slope angle can  
403 lead to a stronger reflection from the sloping bottom for the short waves with a weak transmission  
404 capability. Thus, the hydrodynamic efficiency decreases with increasing slope angle.

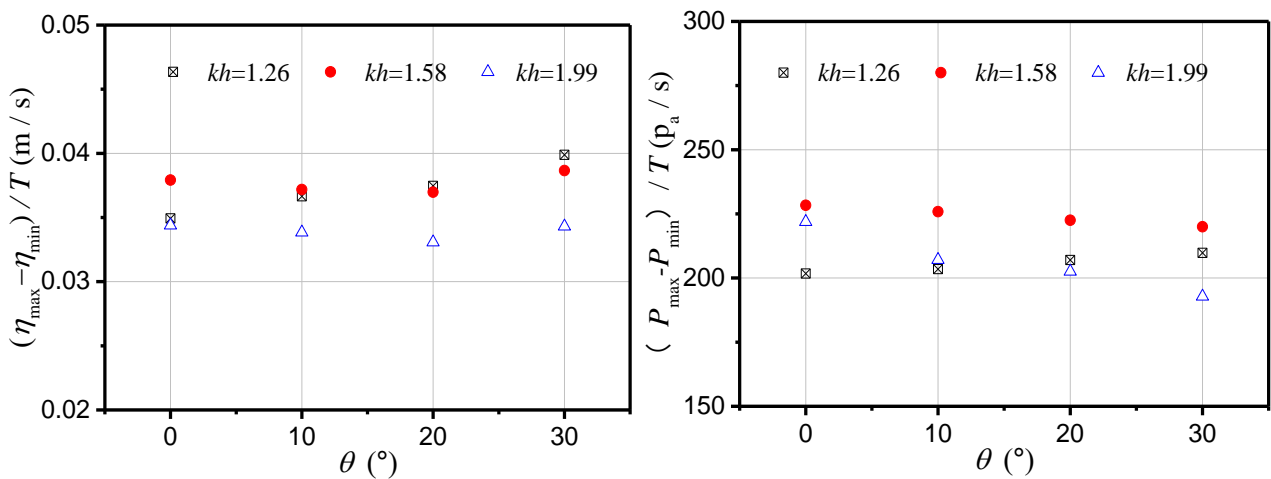
405 From Fig. 17, it can be seen that the difference in between surface variation rates for different  
406  $kh$  is small for some special bottom slopes. The result indicates that a proper bottom slope can  
407 provide a work space in the OWC chamber almost independent on the sea wave conditions. This is  
408 important for the structure safety and operation stability. Because the real sea bottom is not plan, this  
409 will provide a good reference to explore a proper site for the OWC wave energy converter to be  
410 constructed.



411 Fig. 15 Variation of the hydrodynamic efficiency for different bottom slope  $\theta$ .  
 412  
 413



414 Fig. 16 Variation of the hydrodynamic efficiency versus  $\theta$  for different  $kh=1.26$ , 1.58 (resonant  
 415 frequency) and 1.99.  
 416  
 417



418 (a) Free surface variation rate

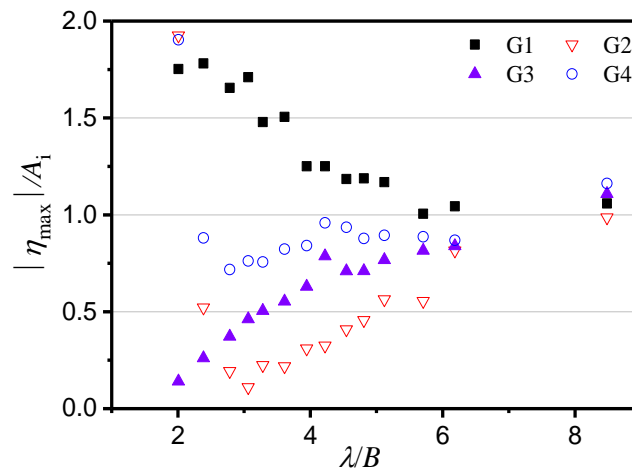
419 (b) Air pressure variation rate

420 Fig. 17 Variation of the free surface and air pressure rate in the chamber versus  $\theta$  for different  
 421  $kh=1.26$ , 1.58 (resonant frequency) and 1.99.

422 **5. Water motion outside and inside the chamber**

423 To investigate the spatial variation of the free surface, four wave gauges were used to measure the  
 424 wave elevations at locations as described in Fig. 2. The free surface motion in the chamber is quite  
 425 complicated and strongly influenced by the chamber geometry and the incident wave conditions. The  
 426 following parameters, including wave amplitude  $A_i=0.03$  m, chamber width  $B=0.70$  m, front wall  
 427 draught  $d=0.14$  m, orifice diameter  $D=0.06$  m and bottom slope angle  $\theta=0^\circ$ , are chosen in this  
 428 section.

429 Fig. 18 shows the relative maximum surface amplitude  $|\eta_{\max}|/A_i$  at each gauging point versus the  
 430 dimensionless wave length  $\lambda/B$ . It can be seen that the three maximum surface amplitudes inside the  
 431 chamber increase with the increase of wave length, while the surface amplitude outside the chamber  
 432 presents an opposite trend. This is because that the long wave possesses a strong transmission  
 433 capability and a large part of the wave energy is transmitted into the chamber. The maximum surface  
 434 amplitudes at G2 and G4 reach the largest at  $\lambda/B=2$  (i.e.,  $T=0.950$ ,  $\lambda=1.40$  and  $B=0.70$ ), but the  
 435 relating surface amplitude at chamber center, i.e., G3, is near to zero. This is due to the so called  
 436 seiching phenomenon excited when  $\lambda/B=2$ . A similar phenomenon was ever reported by Liu et al. [45]  
 437 numerically.



438  
 439 Fig. 18 Variation of the relative maximum surface amplitude with the dimensionless wave length at  
 440 four gauges.

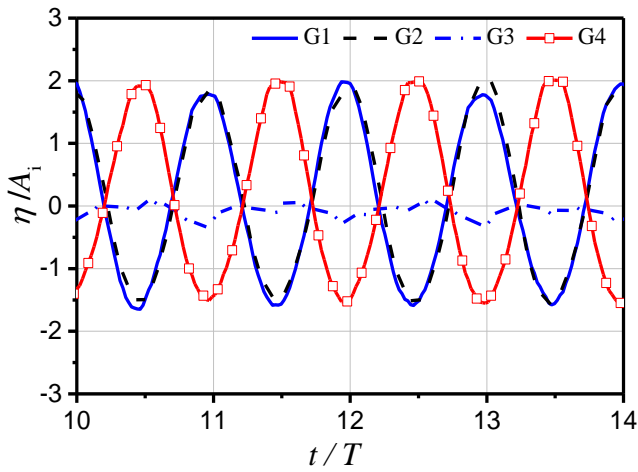
441 Fig. 19 (a) and Fig. 20 (a) may help to further explain this special seiching phenomenon. Fig. 19  
 442 (a) shows the time series of the surface elevation at the gauges with a wave period  $T=0.950$  s

443 ( $\lambda/B=2.01$ ). It is found that, there is a phase difference of half period (i.e.,  $T/2$ ) between G2 and G4,  
444 and the amplitudes at G2 and G4 are nearly twice the incident wave amplitude. However, the surface  
445 elevation at G3 has a very weak fluctuation and its mean value is below the still water surface. This  
446 is because of the pneumatic pressure resulting in the lower mean surface in the chamber. Fig. 20 (a)  
447 shows the snapshot of surface elevation in the chamber with  $T=0.950$  s. It can be seen that, the water  
448 surface in the chamber is rising at one wall and falling at the other wall and the intersection node of  
449 two lines lies at the chamber center. This is the typical standing wave characteristics. Furthermore,  
450 the total mass inside the chamber is not changed [45] and the air pressure is also kept constant which  
451 is close to the atmospheric pressure. Thus, no energy can be extracted from the waves, which can be  
452 seen the dashed line for case of  $B=0.70$  m in Fig. 10 (i.e., the hydrodynamic efficiency is near to zero  
453 for  $kh=3.57$  corresponding to  $T=0.950$ s and  $\lambda/B=2.01$ ). Therefore, such seiching phenomenon should  
454 be avoided in the OWC design.

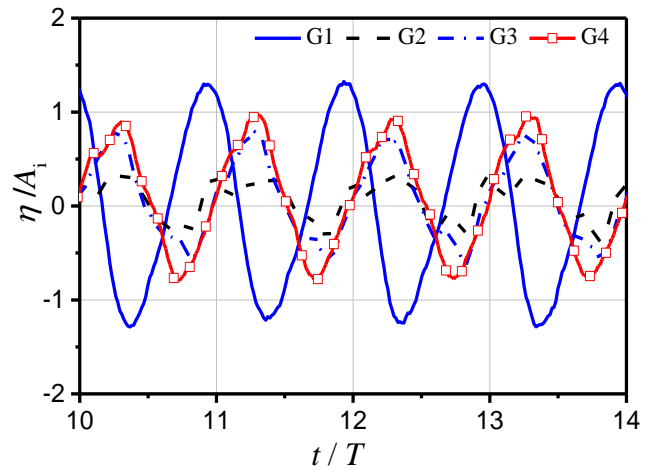
455 In addition, from Fig. 19 (b), (c) and (d), it can be seen that the phase difference between the G1  
456 and G2 decreases with the increase of wave length. That is to say, the long wave generates more  
457 synchronized surface motion inside and outside the chamber than the short wave. This is benefit to  
458 the safety of the OWC device to avoid the large wave pressure on the front wall caused by the  
459 apparent phase difference between the internal and external surface elevation of the chamber.

460 Overall, it is evident from Figs. 18, 19 and 20 that the surface elevation at the three observed  
461 points inside the chamber become closer to each other with the increase of wave length. It means that  
462 the interior water surface tends to a horizontal line, which proves that it is feasible to use a point to  
463 represent the water column motion inside the chamber for long waves in Eq. (2). From Fig. 7, it can  
464 also be seen that there is good match between the measured efficiency and the improved potential  
465 solution for long waves in the low-frequency zone. However, due to the spatial variation of surface  
466 elevation in the chamber, there exists the apparent discrepancy between them for short waves in the  
467 high-frequency zone. It means that there may be some errors in calculating the experimental  
468 hydrodynamic efficiency by using the chamber center to represent the average motion of the water  
469 column in the chamber for some short waves.

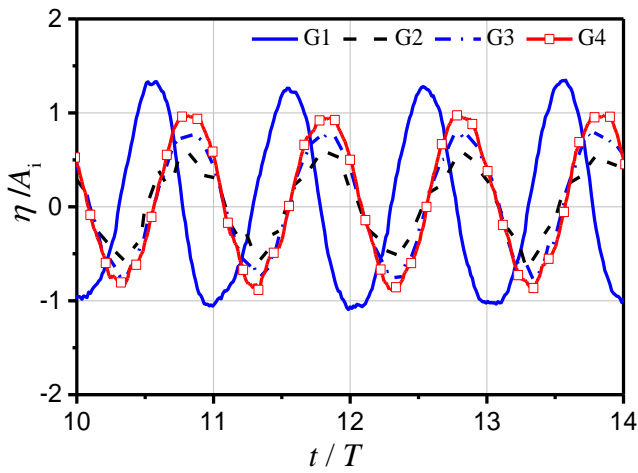
470



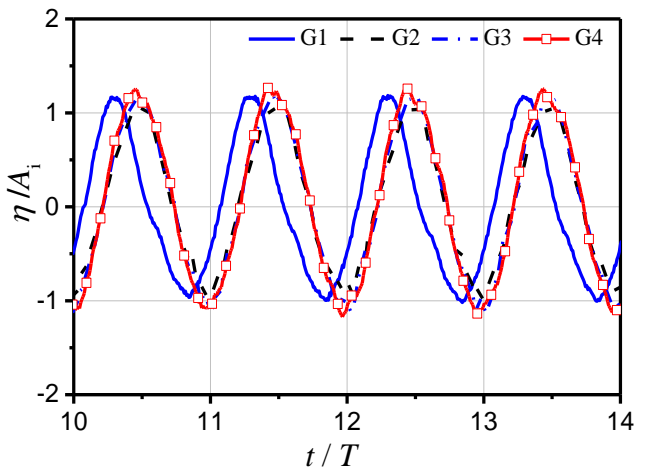
(a)  $T=0.950$  s,  $\lambda/B=2.01$



(b)  $T=1.366$  s,  $\lambda/B=3.95$

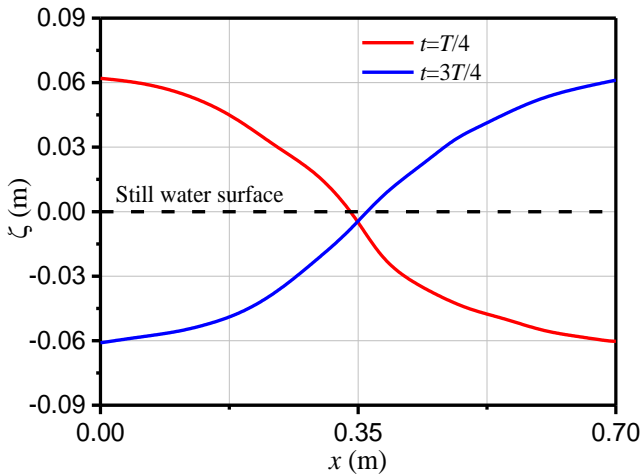


(c)  $T=1.610$  s,  $\lambda/B=5.12$

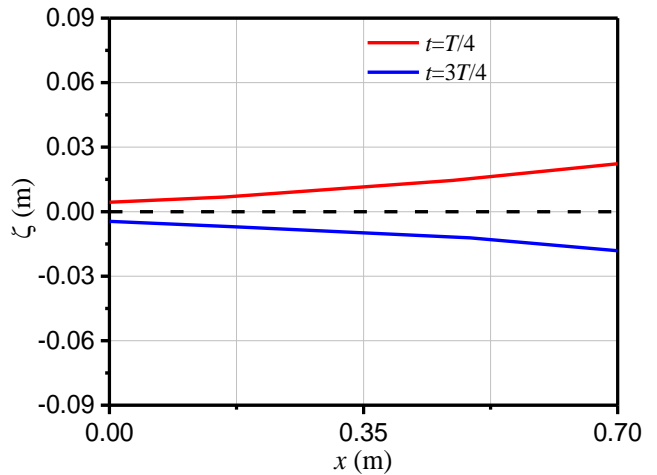


(d)  $T=2.350$  s,  $\lambda/B=8.48$

Fig. 19 Time series of surface elevations at four wave gauges for  $A_i=0.03$  m,  $B=0.70$  m,  $d=0.14$  m,  $D=0.06$  m and  $\theta=0^\circ$ .

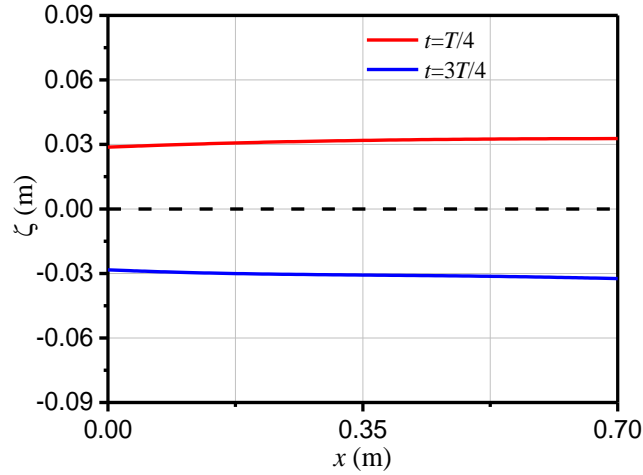


(a)  $T=0.950$  s,  $\lambda/B=2.01$



(b)  $T=1.366$  s,  $\lambda/B=3.95$





(c)  $T=2.350$  s,  $\lambda/B=8.48$

479

480

481 Fig. 20 Snapshots of surface elevations profiles in the chamber taken by CCD camera for wave  
 482 periods  $T=0.950$  s,  $1.366$  s and  $2.350$  s.

## 483 6. Conclusions

484 In the present work, the hydrodynamic performance of a fixed OWC Wave Energy Converter is  
 485 experimentally investigated. The effects of the incident wave amplitude and geometric parameters on  
 486 the hydrodynamic efficiency and water motion inside and outside the chamber were examined. The  
 487 measured surface elevation at the chamber center, the air pressure in the chamber and the  
 488 hydrodynamic efficiency agree well with the improved potential numerical model.

489 The incident wave amplitude has little influence on the resonant frequency and the hydrodynamic  
 490 efficiency. However, the hydrodynamic efficiency increases firstly to a peak value and then decreases  
 491 with the increase of the incident wave amplitude. The hydrodynamic efficiency decreases rapidly  
 492 after the peak value with increasing the incident wave amplitude at the resonant frequency. With  
 493 increasing the chamber width  $B$ , the hydrodynamic efficiency increases in the low-frequency region,  
 494 and it follows a completely opposite trend in the high-frequency region. Meanwhile, a lower resonant  
 495 frequency occurs due to the greater water mass in the chamber for a larger width  $B$ . Larger  
 496 submerged depth  $d$  leads to a lower hydrodynamic efficiency  $\zeta$  and a lower resonant frequency. The  
 497 opening ratio has a significant influence on the peak value of the hydrodynamic efficiency. The  
 498 present results show that the optimal hydrodynamic efficiency occurs at the opening ratio  $\varepsilon=0.66\%$ .  
 499 In the range of  $\theta \leq 30^\circ$ , the bottom slope has little influences on the resonant frequency, but the  
 500 optimal efficiency increases with the increase of bottom slope. A proper bottom slope can provide a

501 work space in the OWC chamber almost independent on the sea wave conditions.

502 The water surface motion in the chamber is highly dependent on the relative wave length  $\lambda/B$ .  
503 Seiching phenomenon, which leads to no energy extracted from the waves, can be excited when the  
504 relative wave length is  $\lambda/B=2$ . This phenomenon should be avoided in the design of an OWC device.  
505 With the increases of the relative wave length ( $\lambda/B >2$ ), the mode of sloshing motion decreases and  
506 the mode of piston motion increases. Meanwhile, the phase difference of free surface between the  
507 inside and outside the chamber also decreases.

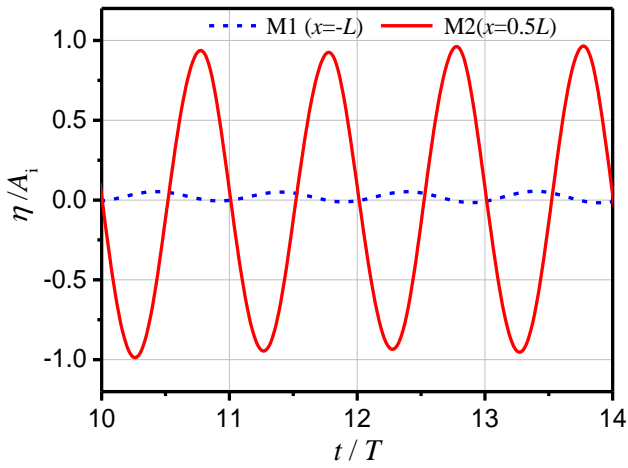
508 The present investigation can be a guideline to assist in the geometry optimization design, site  
509 selection, and safety analysis of the land-based OWC devices and provide experimental data for  
510 validating numerical models.

## 511 **Acknowledgements**

512 The authors also would like to gratefully acknowledge financial support from the National Natural  
513 Science Foundation of China (Grant Nos. 51179028, 51222902, 51490672), the Program for New  
514 Century Excellent Talents in University (Grant No. NCET-13-0076) and the Joint Project between  
515 NSFC and RS (Grant No. 51411130127).

## 516 **Appendix A: Absorption ability of the damping layer**

517 The absorption ability of the damping layer was tested in a case with the following parameters  
518  $A_i=0.03$  m,  $T=1.610$  s,  $B=0.55$  m,  $D=0.06$  m,  $d=0.14$  m and  $\theta=0^\circ$ . Fig. A1 shows the time series of  
519 surface elevations at two different positions (i.e., M1 and M2) as marked in Fig. 3. M1 is at the left  
520 flume-end (i.e., the ending position of the damping layer,  $x=-L$ ) and M2 is at  $x=0.5L$ . It can be seen  
521 that the relative wave amplitude at the left flume-end (M1) is less than 0.03, which means that most  
522 of reflected wave energy was absorbed in the damping layer. Fig. A2 shows the relative wave height  
523 ( $H/2A_i$ ) distribution along the damping layer. The wave height attenuates rapidly to a very small  
524 value (less than 3% of the incident wave height) along the damping layer. This indicates that the  
525 damping layer can absorb the reflected wave effectively and the re-reflection phenomenon can be  
526 ignored.



527  
528 Fig. A1 Time series of surface elevations at different  
529 positions in the numerical flume.

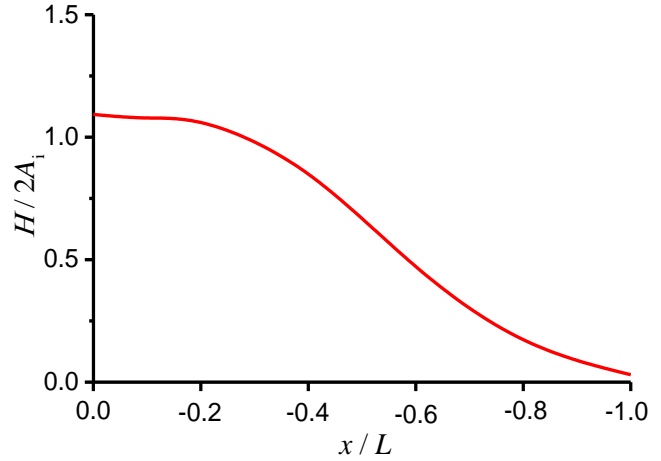
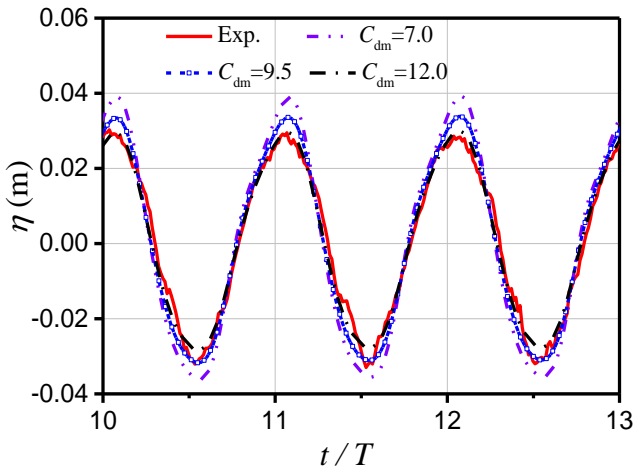


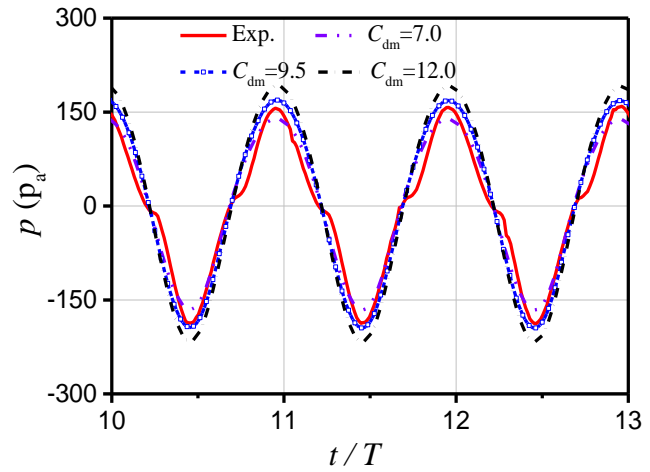
Fig. A2 Wave height distribution along the  
damping layer.

530 **Appendix B: Determination of the pneumatic damping coefficient  $C_{dm}$  and artificial damping**  
531 **coefficient  $\mu_2$**

532 The controlling variables method is applied to determine the adaptable pneumatic damping  
533 coefficient  $C_{dm}$  and artificial damping coefficient  $\mu_2$ . The same case in Appendix A was taken as an  
534 example. Firstly, we set the value of  $\mu_2$  as zero and change the value of  $C_{dm}$ . Fig. B1 shows that the  
535 smallest  $C_{dm}=7.0$  overestimates the surface elevation and underestimates the air pressure, it is vice  
536 versa for the largest  $C_{dm}=12.0$ . It can be noted that the numerical results are closest to the  
537 experimental data for  $C_{dm}=9.5$ . Then, the value of  $C_{dm}$  is fixed as 9.5 and the value of  $\mu_2$  is varied.  
538 From Fig. B2 we can see that the existence of viscous damping can reduce the amplitudes of both the  
539 surface elevation and air pressure. It can be seen that the numerical results show good agreement  
540 with the experimental data for  $\mu_2=0.2$ . Therefore, the coefficients  $C_{dm}=9.5$  and  $\mu_2=0.2$  are determined  
541 and the error between the numerical results and experimental data is within 5% with these two  
542 conformed parameters. Such trial and error process can be looped until the most adaptable  
543 coefficients  $C_{dm}$  and  $\mu_2$  are obtained.

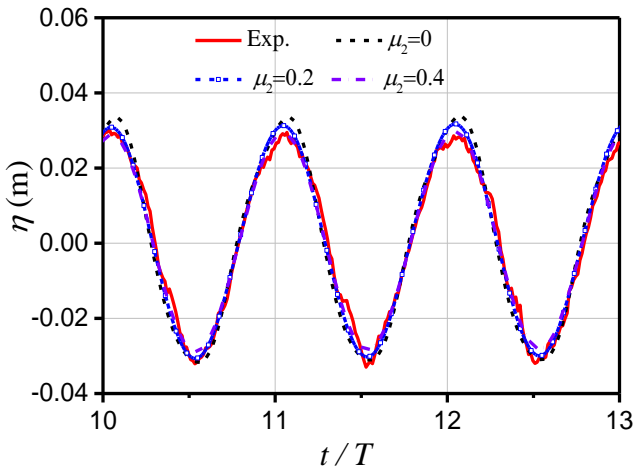


544  
545 (a) surface elevations

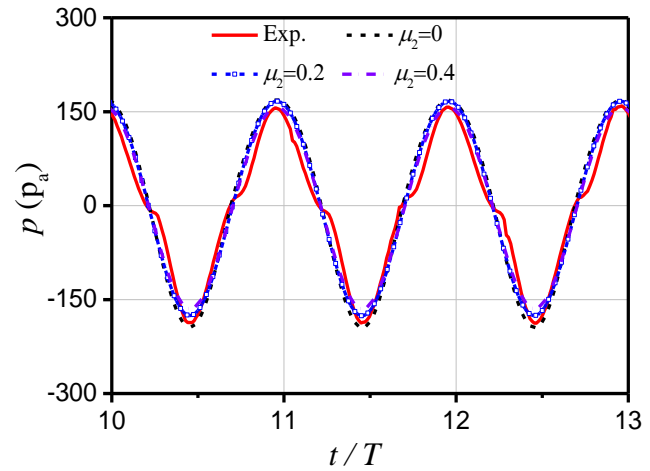


(b) air pressure

546 Fig. B1 Time series of surface elevation at the chamber center and air pressure inside the chamber for  
547 different  $C_{dm}$  with  $\mu_2=0$ .



548  
549 (a) surface elevations



(b) air pressure

550 Fig. B2 Time series of surface elevation at the chamber center and air pressure inside the chamber for  
551 different  $\mu_2$  with  $C_{dm}=9.5$ .

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