Experimental investigation on water exchange performance through a hollow buoy driven by wave overtopping

Ze Gao YIN1,2, Huan ZHANG2, Liu YANG2, Cheng Yan GAO2 and Hui XU2
1Shandong Province Key Laboratory of Ocean Engineering, Ocean University of China, Qingdao, 266100, China;
2Engineering College, Ocean University of China, Qingdao, 266100, China
Email: yinzegao@ouc.edu.cn

Abstract: A series of regular wave overtopping experiments for a hollow buoy is conducted, and its water exchange behavior is investigated. The variation of its response amplitude, flow rate and net flow rate through the buoy under different wave conditions is analysed. It was found that: 1) The wave height response amplitude in the buoy increases with increasing incident wave period and the incident wave height, respectively. 2) The flow rate through the hollow buoy varies periodically, and its period is consistent with the wave period. The duration of upward flow rate is higher, and its peak value is smaller. In comparison, the duration of downward flow rate is smaller, and its peak value is higher. 3) For the incident wave period smaller than 2 s, the net flow rate is very small, even it closes to zero; for the incident wave period higher than 2 s, the net flow rate increases obviously, and the water exchange efficiency increases. For a regular wave with higher period and height, the net flow direction is upward. For a regular wave with higher period and smaller height, the net flow direction is downward. The work provides insights to the development and optimization of water exchange device.

1. Introduction
Wave energy utilization has become a growing concern of many countries. A great deal of investigation has been contributed to the wave power take-off and energy conversion. M. Folley and Whittaker [1] analysed the nearshore wave energy resource using SWAN wave model, and the North Atlantic wave energy resource at different water depths was modelled. They pointed out that nearshore sites offer similar potential for wave energy exploitation resource as offshore sites. A. Al-Habaibeh et al. [2] introduced an innovative approach for waves energy generation, and presented a complete description of the system including the general concept, configurations, mechanical design, electrical system, modeling techniques and expected power output. To achieve better constructive effects, Chen et al. [3] designed a large wave power plant consists of a series of wave energy converters, and studied the interaction effects among them. Viet et al. [4] developed a floating energy harvester to harvest the energy from intermediate and deep water waves, and its structure is designed by connecting a mass-spring system to two piezoelectricity-lever devices. Sierra et al. [5] analyzed the wave energy resource along the Atlantic coast of Morocco using a 44-year series of data obtained from numerical modeling, a multi-criteria analysis is carried out considering different factors in order to select the best places for wave energy converters deployment.

Water exchange is an important guarantee for a good water quality between surface water and bottom water. Due to the seawater stratification and eutrophication, the bottom seawater hypoxia occurs frequently [6], and it plays a negative role in the population, growth and reproduction of aquatic
organism as well as the seawater environment. In order to improve the water exchange between sea surface and bottom, Stommel et al. [7] proposed to pump water vertically through a pipe, and hence nutrient-rich water can be pumped up to the surface. Based on the Stommel’s hypothesis, Shigenao Maruyama et al. [8] conducted a field observation in the Philippines Sea as well as the numerical simulation. The upwelling of a perpetual salt fountain was confirmed as expected, and the chlorophyll concentration at the pipe outlet was extremely greater than that in the surrounding surface seawater. Lucia Margheritini et al. [9] presented a floating and overtopping device to collect overtopping wave water to oxygenate the bottom water suffering from eutrophication. Similarly, Antonini et al. [10] proposed a floating device OXYFLUX, and it induced a downward water flux by collecting incident waves. In order to further the investigation on the behavior of water exchange between surface and lower layers, a hollow buoy driven by wave is designed, a series of experiments were conducted with different wave scenarios, and the relationship was explored.

2. Physical model test

In order to analyze the hydrodynamic behavior, a series of experiments was conducted in a wave flume at the Hydraulic Laboratory of Ocean University of China. The length, width and height of wave flume are 30 m, 0.6 m and 1.2 m, respectively. At the start position of the wave flume, a piston-type wave generator was used to generate the desired regular waves. Its operating frequency and the stoke length were controlled to obtain the wave parameters as required. At the end of the wave tank, a porous material was used to absorb the incident waves, as shown in Figure 1.

Figure 1 Experimental sketch

The circular hollow buoy is made of polylactic acid (PLA) lightweight material with the inner diameter of 0.13 m, the height of 0.34 m and the mass of 0.475 kg. In order to increase the overtopping water, a 0.04 m high slope is mounted on the top of the buoy, see Figure 2 (a). An elastic rope is used to bind the buoy at the middle of stationary frame, as shown in Figure 2 (b).

Figure 2 The buoy
Before the start of an experiment, the buoy is fixed at 1/3 times wave flume length from the wave generator, a wave height gauge was used to measure the wave history inside the buoy. An ADV is used to measure water velocity in the buoy, and then the flow rate is calculated. The fresh tap water is pumped into the tank, and the still water depth \( d \) was controlled as 0.4 m for all the experiments. The vertical distance from still water surface to the device top is defined as \( R_c \), and \( R_c=0.02 \) m as shown in Figure 2 (a). In our experiments, the incident wave height \( H \) varied from 0.06 m, 0.08 m, 0.10 m, 0.12 m to 0.14 m, respectively, and the incident wave period \( T \) varied from 1.0 s, 1.5s, 2.0 s, 2.5s to 3.0 s, respectively.

3. **Water exchange principle**

When a regular wave goes through the buoy, it consists of the main procedures as follows.

3.1 **Wave trough to crest**

When wave goes through the buoy in trough time before overtopping, \( R_c \) is positive, the wave surface outside increases, so the hydrostatic restoring force of buoy increases, the buoy will move upward coupling with the wave exciting force. The inside water level is lower than outside, and the inside water will go upward due to internal and external pressure difference;

When the wave overtops the slope, a deal of water flows over it, \( R_c \) becomes negative, a lot of water flows into the buoy, and the water flows downward due to the water head difference between inside and outside water.

3.2 **Wave crest to trough**

When \( R_c \) is negative, the buoy has a complex downward movement, because of buoy upward movement inertia leading to a larger downward elastic force of the rope than the upward hydrostatic restoring force, so the buoy moves down;

When \( R_c \) begins to be positive until trough arrives, hydrostatic restoring force decreases, the downward force of elastic rope is greater than the upward hydrostatic restoring force, then buoy moves down coupling with the downward wave exciting force. In this process, the water level outside the buoy moves down, may be lower than inside, the water inside the buoy will flow down due to internal and external pressure difference.

The upward or downward flow of the water in the buoy can effectively improve the water exchange capacity vertically.

4. **Results and discussion**

Some working conditions and experimental results are presented in table 1, where \( Q_n \) is the net flow rate through the buoy cross section, \( H' \) is the inside wave height, \( H \) is the incident wave height. A higher \( K \) indicates a better motion response of inside water body and a stronger water oscillation.

| Group | \( H \) (m) | \( T \) (s) | \( H' \) (m) | \( Q_n \) \((10^{-4} \text{m}^3 \text{s}^{-1})\) |
|-------|--------|------|--------|------------------|
| 1     | 0.06   | 1.0  | 0.5125 | -0.0010          |
| 2     | 0.08   | 1.0  | 0.5556 | -0.0090          |
| 3     | 0.10   | 1.0  | 0.6428 | 0.0042           |
| 4     | 0.12   | 1.0  | 0.6704 | -0.0029          |
| 5     | 0.14   | 1.0  | 0.8321 | -0.0090          |
| 6     | 0.06   | 2.0  | 0.6313 | -0.0003          |
| 7     | 0.08   | 2.0  | 0.6328 | 0.0020           |
| 8     | 0.10   | 2.0  | 0.7200 | 0.0012           |
In order to illustrate the inside wave surface variation, the relative amplitude of wave height in the buoy is defined as

\[ K = \frac{H'}{H} \]

(1)

Taking \( T = 1 \) s, 2 s and 3 s as examples, Figure 3 shows the \( K \) relationship with \( H \) for different \( T \). It was found that \( K \) increased with increasing \( H \) and \( T \) respectively. A possible explanation is that the incident wave energy increases with increasing \( H \), and the energy wave entering the buoy increased, \( H' \) increased higher than \( H \). As a result, \( K \) increased. A small \( T \) resulted into a strong water viscosity and wave energy dissipation, \( H' \) decreased, and \( K \) decreased consequently.

4.2 flow rate history in buoy

Figure 4 shows the flow rate history in the buoy for \( H = 0.1 \) m and \( T = 2.5 \) s. Assume the upward flow rate is positive and the downward flow rate is negative. It was observed that the flow rate \( Q \) changed periodically, and the variation period is similar to \( T \). The flow rate curve appeared as irregular wave with long crest and short trough. For a whole period, the upward flow duration is longer, but its peak is smaller. In comparison, the downward flow duration is shorter, but its peak is higher.
4.3 Net flow rate variation

In order to examine the water exchange efficiency, a net flow rate of $Q_n$ through the buoy cross section is defined as follows,

$$Q_n = \frac{\int_0^T Q(t) \, dt}{T}$$

Figure 5 shows the $Q_n$ relationship with $T$ for different $H$. It was found that when $T$ is less than 2 s, $Q_n$ is small, even close to zero. When the water turbulence is violent for small $T$, its turbulence energy dissipation is strong, and the lower water exchange efficiency occurs. When $T$ is higher than 2 s, $Q_n$ and water exchange efficiency increased significantly. For a high $T$ and $H$, the net flow is positive. A possible reason is a great deal of incident wave water crossed the buoy top directly and fell into the leeside water of buoy, the overtopping water proportion into the buoy decreases. The upper region of buoy produced an upward suction, which is consistent with the conclusion of the relevant literature [10]. For a small $H$ and a high $T$, a great deal of incident wave water fell into the buoy directly, and $Q_n$ is negative.

![Figure 5](image.png)

**Figure 5** $Q_n$ Relationship with $T$ for different $H$

5. Conclusion

A series of experiments of the hollow buoy is conducted for regular waves, the wave heights and flow rate inside the buoy are measured, and the vertical exchange performance of water body is discussed. It was found that,

1) With the increase of the incident wave height and period, the relative response amplitude in the buoy increases.

2) The flow rate inside the buoy changed periodically, and the variation period is similar to incident wave period. The flow rate curve appeared as irregular wave with long crest and short trough.

3) When incident wave period is less than 2 s, the net flow rate is small, even close to zero. When incident wave period is higher than 2 s, the net flow rate and water exchange efficiency increased significantly. For a high incident wave period and height, the net flow rate is positive. In comparison, the net flow rate is negative for a small incident wave height and a high wave period.

The limitation of our investigation should be pointed out that the wave flume and the hollow buoy parameters are determined considering the laboratory scale. The water exchange behavior in complex sea environment still needs further study.

References

[1] Folley M, Whittaker T J T. Analysis of the nearshore wave energy resource[J]. Renewable Energy, 2009, 34: 1709-1715

[2] Al-Habaibeh A, Su D, McCague J, Knight A. An innovative approach for energy generation from waves[J]. Energy Conversion and Management, 2010, 51: 1664-1668
[3] Chen W X, Gao F, Meng X D, Fu J X. Design of the wave energy converter array to achieve constructive effects[J]. Ocean Engineering, 2016, 124: 13-20

[4] Viet N V, Xie X D, Liew K M, Banthia N, Wang Q. Energy harvesting from ocean waves by a floating energy harvester[J]. Energy, 2016, 112: 1219-1226

[5] Sierra J P, Martín C, Mösso C, Mestres M, Jebbad R. Wave energy potential along the Atlantic coast of Morocco[J]. Renewable Energy, 2016, 96: 20-32

[6] Robert J, Diaz. Overview of Hypoxia around the World[J]. Journal of Environmental Quality, 2001, 30: 275-281

[7] Stommel H, Arons A B, Blanchard D. An oceanographical curiosity: the perpetual salt fountain[J]. Deep-Sea Research, 1956, 3: 152-153

[8] Maruyama S, Yabuki T, Sato T, Tsubaki K, Komiya A, Watanabe M, Kawamura H, Tsukamoto K. Artificial Upwelling of Deep Seawater Using the Perpetual Salt Fountain for Cultivation of Ocean Desert[J]. Deep-Sea Research Part1, 2011, 58: 567-574

[9] Margheritini L, Lennart C. An Innovative Way of Utilizing Wave Energy to Counteract Eutrophication and Hypoxia[C]. European Wave and Tidal Energy Conference, 2011

[10] Antonini A, Lamberti A, Archetti R. An Innovative Way of Utilizing Wave Energy to Counteract Eutrophication and Hypoxia[J]. Coastal Engineering, 2015, 104: 54-68