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The influence of perforated plates on wave transmission and hydrodynamic performance of pontoon floating breakwater *

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Abstract: In this study, a perforated pontoon floating breakwater (FB) consisting of an impermeable plate and a perforated plate was designed to untangle the effect of a perforated plate on wave transmission and hydrodynamic performance of floating breakwater. A series of 2-D physical model experiments were conducted to measure the wave transmission coefficient, tension acting on the mooring line, and motion response of FB under a regular wave. The experimental results of the motion responses and mooring lines indicated that the new perforated plate was evidently effective. Furthermore, the study also discussed and analyzed the influence of the perforated plate on transmission coefficients. The experimental results showed that the new perforated plate did not lead to obvious improvement in the transmission performance

Key words: Floating breakwater, perforated plates, physical experiment, wave transmission coefficient, motion responses

Introduction

Over the last decade, the interest in floating breakwaters (FBs) has significantly increased due to efficient and inexpensive construction, mobility, and environmental friendliness. Previous studies have proposed several types of floating breakwaters.

The most common floating breakwater is the pontoon type. Many researchers have investigated the hydrodynamic performance of floating structures with single and double pontoons by experimental or theoretical methods[1-11].

Besides wave reflection, the dissipation for floating breakwater also plays an important role. Thus, a few dissipative structures, such as the fixed-type perforated wall caisson, were developed to enhance the performance of dissipating wave energy by forces, such as friction and turbulence. The front wall of caissons was often fully or partly perforated to reduce wave reflections, wave elevation, and the horizontal wave load on the caisson. The first perforated wall caisson breakwater was proposed by Jarlan[12]. This was followed by many experimental and theoretical studies that investigated the interaction between waves and perforated wall caissons[13-19]. Several experimental tests and theoretical results have proven the efficiency of a perforated wall caisson in terms of wave reflection and wave energy dissipation. As reported in most previous studies, a perforated wall is a useful and effective means to reduce wave elevation and dissipate wave energy through the porosity of a vertical wall. It should be noted that all experimental tests and theoretical results in the fore-mentioned studies with respect to perforated structures were aimed at fixed structures. Thus, although a perforated wall is effective and useful for a caisson, the impact of a perforated wall is uncertain for a floating breakwater. A pontoon type floating breakwater has a configuration similar to a caisson. Existing research has not confirmed the effectiveness of a perforated wall in terms of the transmission coefficient, mooring line tension, and motion response for a pontoon floating breakwater.

In practice, a few researchers have studied a porous structure. Stiassnie[20] proposed an analytical solution for the transmission coefficient of a floating

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porous box without mooring lines. Wang and Sun[21] conducted an experimental study of a porous floating breakwater. An experimental study by Shih[22] examined the performance characteristics of porous perpendicular pipe breakwaters. However, the porous structures in the fore-mentioned studies did not focus on pontoon structures.

In addition to wave transmission, the mooring force of floating breakwaters is also a main research concern for engineers. Mooring line tension is related to both wave attenuation and to FB safety. Several previous studies focused on the mooring force of floating breakwaters based on numerical and experimental methods. Lee and Cho[23] used a moored pontoon-type FB to conduct numerical investigation of incident wave interactions. The results indicated that the mean wave drift force significantly influenced mooring tensions. Particularly, the mooring tension on the seaward side rapidly changed due to the effect of the drift force. Therefore, mean wave drift force is an important factor in the analysis of a mooring system. Conversely, the effect of the drift force on the performance of the FB in regular waves appeared to be less important. Loukogeorgaki and Angelides[24] focused on stiffness of mooring lines and performance of FB in three dimensions. They concluded that a taut mooring line could increase the effectiveness of the FB for the entire range of examined frequencies.

Several scholars focused on increasing the hydrodynamic performance of a floating breakwater. However, a need for research addressing specific engineering demands continues to exist. Given that the pontoon breakwater is the most common floating breakwater type, it is necessary to improve the hydrodynamic performance of pontoon breakwaters in terms of the transmission coefficient, motion response, and mooring line tension. In this study, in order to clarify the effect of perforated plate structures for floating breakwaters, three FB models consisting of impermeable and perforated plates were investigated. With respect to a regular wave action, a series of 2-D experiments were conducted to assess the effectiveness of FB, motion responses, and mooring tension, and especially the function of a perforated plate. The relationship between the examined incident wave characteristics (wave period and wave height) and the FB was illustrated. Additionally, the performances of the three models and the perforated plate were thoroughly investigated and carefully discussed. The new perforated FB proposed in this study is expected to be important for marine structural design.

1. Physical model experiments

1.1 *Description of the experimental floating breakwaters*

FB generally dissipates the surface waves by the mechanisms including reflection, destruction of wave particle motion, and viscous damping. The pontoon is a typical floating breakwater type that mainly depends on wave reflection. In this study, an improved type of pontoon FB was designed to improve the efficiency of pontoon breakwaters and investigate the influence of perforated plates on wave transmission, motion response, and mooring force.

As shown in Fig. 1, the improved pontoon FB consisted of four stiffeners and eight plates. The plates in turn consisted of two vertical plates, three longitudinal plates, and three transverse plates. There were eight independent compartments formed by plates and stiffeners. Reinforced concrete was used in the plates and stiffeners. There were a few holes in the top horizontal plate and in the top parts of the longitudinal and transverse plates. In this manner, the porous plate allowed free seawater exchange and dissipated the wave energy. There are hollow rubbers positioned in the four compartments to provide sufficient buoyancy. The advantage of this arrangement was that it decreased the risk of failure over time for the hollow rubber as the other rubbers could provide buoyancy when a rubber was destroyed. Additionally, the destroyed rubber would fall between the stiffeners.

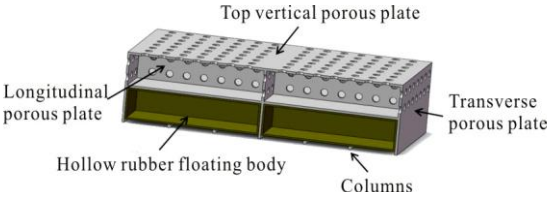

Fig. 1 (Color online) A 3-D diagram of the cross-section (the yellow part indicates the hollow rubber)

Three models with different plates were designed according to the Froude similarity theory to investigate the influence and the location of perforated plates (Figs. 2-4) Model 1 was completely composed of watertight plates. Based on Model 1, the top parts of the longitudinal and transverse plates of Model 2 were designed as perforated plates with watertight horizontal plates. A perforated plate also replaced the top horizontal plate in Model 3. Table 1 lists the main parameters of three models. As shown in the Table 1, the three models had the same structural size and buoyancy. Figures 2-4 show the different models listed in Table 1.

1.2 *Experimental facilities and instruments*

The experiments were performed in a 2-D wave flume of the Hydraulics Modeling Laboratory of Ocean University of China (OUC). The wave flume had a total width of 3.0 m, a depth of 1.5 m, and a length of 60 m. It was equipped with a piston-type

Table 1 Main parameters of the three models

	Length/ mm	Width/ mm	Height/ mm	Draught/ mm	Mass/ kg	Roll inertia/ $\text{kg}\cdot\text{m}^2$	Centre of gravity location above the bottom/mm
Model 1	760	500	200	100	28.6	0.669	71
Model 2	760	500	200	100	28.4	0.661	70
Model 3	760	500	200	100	28.0	0.647	69

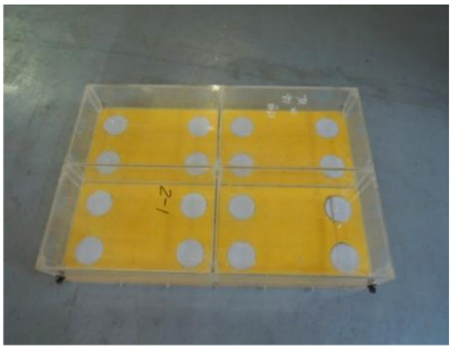

Fig. 2 (Color online) The pontoon breakwater (Model 1)

Fig. 3 (Color online) The perforated pontoon breakwater (Model 2)

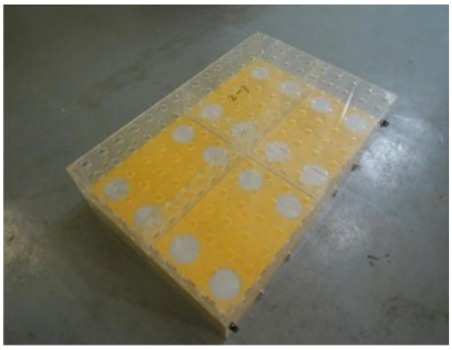

Fig. 4 (Color online) The perforated pontoon breakwater (Model 3)

wave generator at one end and a wave absorber at the other. The width of the wave flume was reduced to 0.8 m in the experiment such that it was concordant with the chosen scale.

The experimental equipment consisted of five resistance-type wave gages (WGs) that measure incident and transmitted wave heights. Table 2 lists the distances between the wave gages. Two load cells (LCs) were connected with mooring lines to measure the mooring line force.

Table 2 Distance between the wave gages

Wave gages	Distances/m
WG1, WG2	4.6
WG2, WG3	0.4
WG3, WG4	6.5
WG4, WG5	0.4

1.3 *Experimental model scale*

Froude similitude was considered as most appropriate for the model experiment involving a floating coastal structure. The scale was set as 1:20 in accordance with the dimensions of experimental facilities and the tested wave conditions.

1.4 *Experimental conditions*

In this study, a prototype water depth of 20 m was adopted for a regular wave. The target scale factor in the study was 1:20. Thus, the scale for wave height was 1:20, and the scale for a wave period was 1:4.47. Given engineering practice and the wave flume condition, the experimental wave periods (T) ranged from 0.9 s-1.4 s and the experimental wave heights (H) from 0.1 m-0.2 m. Table 3 list the details.

Table 3 Experimental test conditions

Incident wave height, H /m	Incident wave period, T /s
0.100	1.0
0.125	1.0
0.150	0.9, 1.0, 1.1, 1.2, 1.3 and 1.4
0.175	1.0
0.200	1.0, 1.1, 1.2, 1.3 and 1.4

As shown in Fig. 5, the FB models were moored by catenary lines made of stainless steel and having a length of 1.6 m with a line density of 0.63 kg/m. Two load cells were connected with mooring lines to measure the forces acting on the windward and leeward mooring lines. Two wave gages were placed at the front of the models to obtain the incident waves (WG2, WG3). Additionally, two similar wave gages installed at the back of the models were used to obtain the transmitted waves (WG4, WG5). The signals from the two wave gages positioned in the front of the models were processed to obtain the incident and reflected wave height. The amplitude of the incident

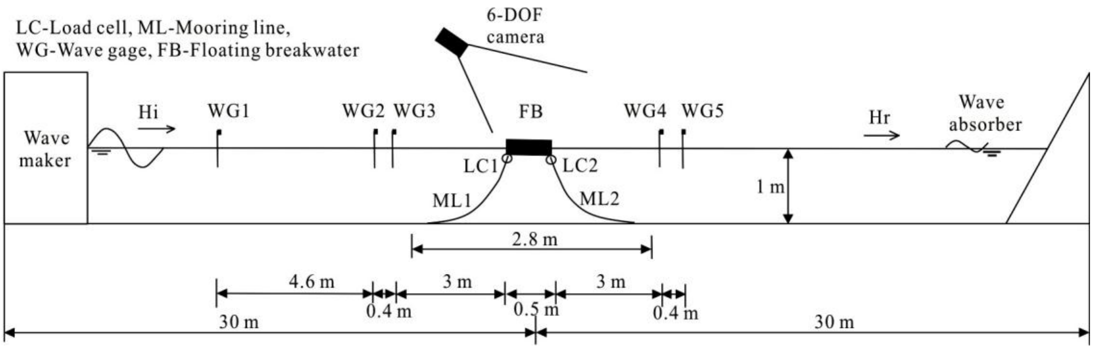

Fig. 5 Sketch of the experiment (floating)

wave (A_i) was separated from WG2, WG3 and the amplitude of the transmitted wave (A_t) was separated from WG4,WG5. The transmission coefficient (K_t) was defined as the ratio of the amplitudes of the transmitted waves (A_t) to the incident waves (A_i).

2. Results and discussions

The following section discusses the results of the present investigation with an emphasis on the effect of a perforated plate on the hydrodynamic performance of the FB.

2.1 *Wave transmission coefficients of FBs under regular waves*

Figure 6 shows the experimental wave transmission coefficients (K_t) of the three models when the wave period was 1.0 s (H/L, where H is the wave height, L is the wave length). Figures 7, 8 show the transmission coefficients for wave heights of 0.15 m and 0.20 m.

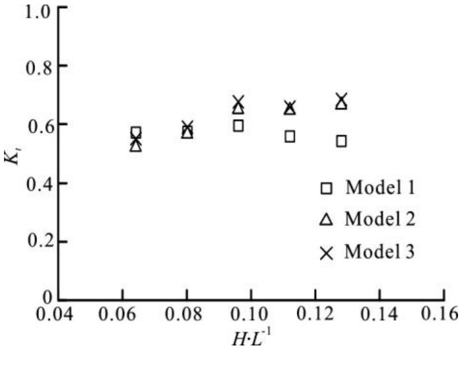

Fig. 6 Transmission coefficients of the three models ($T = 1.0$ s)

As observed in Fig. 6, the experimental results indicate that the wave height does not have a significant influence on the wave transmission. The experimental results show that the wave period is a key factor influencing the wave transmission coefficient.

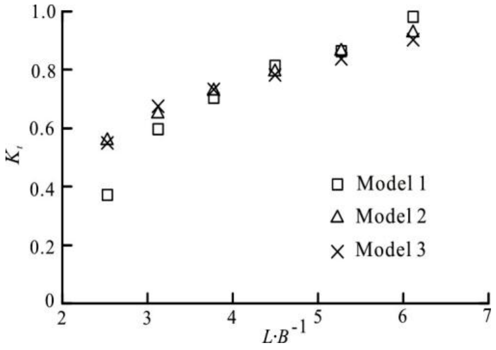

Fig. 7 Transmission coefficients of the three models ($H =$ 0.15

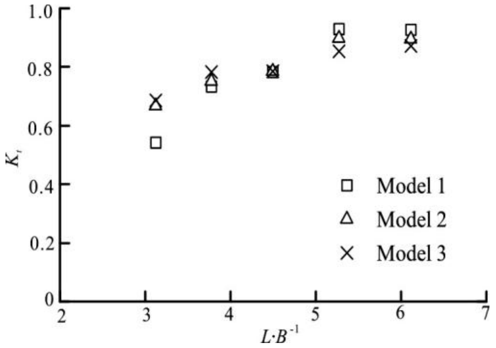

Fig. 8 Transmission coefficients of the three models ($H =$ 0.20

Given the same structural dimension and draught, the three models indicated similar performances with respect to the transmission coefficient. The reflection performances of model 3 and model 2 were slightly different from that of model 1 due to the perforated plate. As shown in Figs. 7, 8, the K_t of Model 3 slightly exceeded that of Model 2 as the relative wave length (L/B, where B is the floating breakwater width) was less than 4.5. However, when the relative wave length (L/B) exceeded 4.5, the K_t of Model 3 was slightly less than that of Model 2. The top horizontal porous plate dissipated waves instead of allowing wave transmission with an increase in the wave period. This implied that the perforated plate played an effective role in a few wave periods. To summarize, in conjunction with the increase in the wave period, perforated plates had some effects on the wave energy dissipation.

The original intention of the perforated plate design involved increasing the wave dissipation by turbulence and friction. However, the lack of the filler in the pontoon was insufficient to adequately improve the performance of wave dissipation by increasing the friction coefficient. Hence, given an insufficient friction coefficient and lower wave reflection than Model 1, more wave energy transmits through the floating breakwater with respect to Models 2, 3. Based on the current design and structural arrangement, except for a certain wave period, the perforated box type model did not display a better hydrodynamic performance than that of the traditional box type with respect to the transmission coefficient. This phenomenon is different from that observed in fixed perforated wall caissons.

2.2 *Effect of the perforated plate on motion responses of the FB under regular waves*

The above figures show the motion responses of the three floating breakwater models (ζ_2 is the sway motion, ζ_3 is the heave motion, ζ_4 is the roll motion). Figures 9-11 show the measured motion responses versus wave steepness. The motion response of the FB is proportional to wave steepness. The experimental results of motion responses indicated that the influence of the perforated plate on the motion responses for the three models was different. A comparison of the three models suggested that the perforated plate did not have a significant influence on the sway motion response. However, the heave and roll motion response was evidently influenced by the perforated plate. The heave motion of Model 3 was 30% lower than that of Model 1 and was slightly smaller than that of Model 2. Additionally, the roll motion of Model 3 was 50% lower than that of Model 1 and approximately 20% lower than that of Model 2. A certain amount of water flooding and model sinking existed under the wave action due to the perforated plates This portion of water increased the mass and inertia of the floating breakwater. Therefore, Models 3, 2 showed gentle movements. The heave motion and roll motion of Model 3 were the smallest. Figures 12-17 show the relationship between the motion responses and relative wave lengths (L/B) given H values of 0.15 m and 0.20 m, respectively. The data in Figs. 12, 13 and 15, 16 indi-

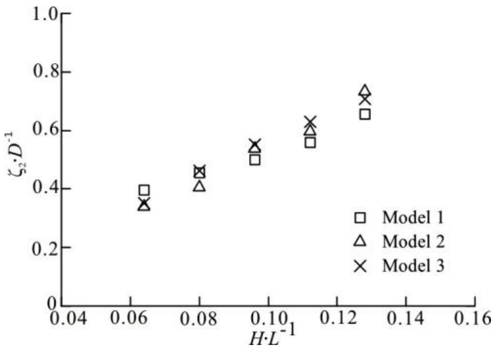

Fig. 9 Sway motion of the three models ($T = 1.0$ s)

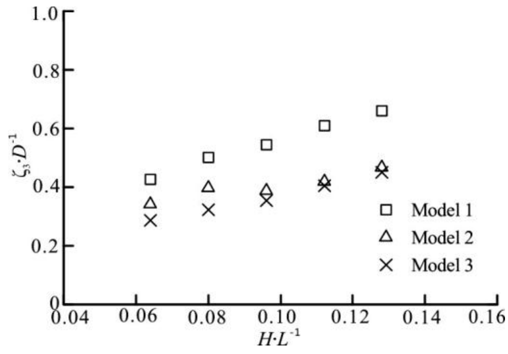

Fig. 10 Heave motion of the three models ($T = 1.0$ s)

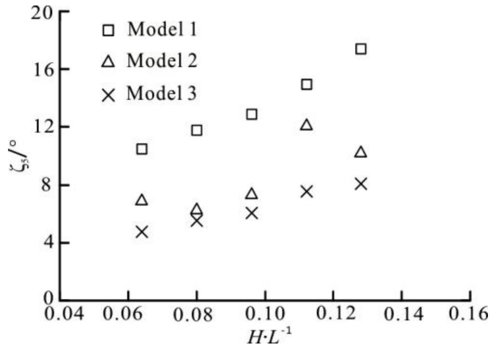

Fig. 11 Roll motion of the three models ($T = 1.0$ s)

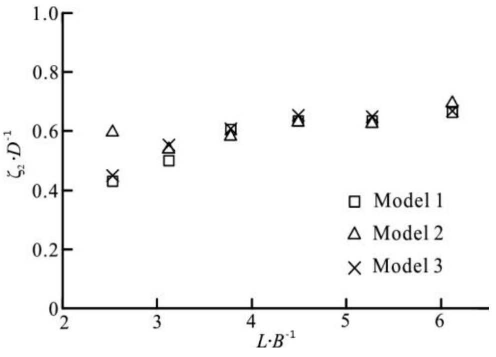

Fig. 12 Sway motion of the three models ($H = 0.15$ m)

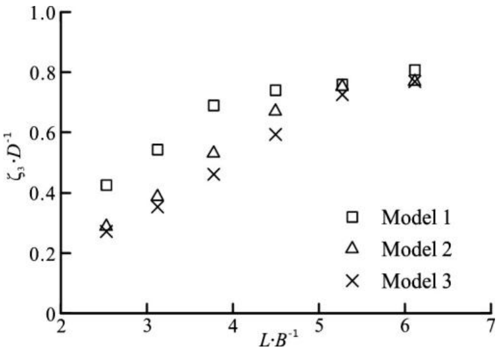

Fig. 13 Heave motion of the three models ($H = 0.15$ m)

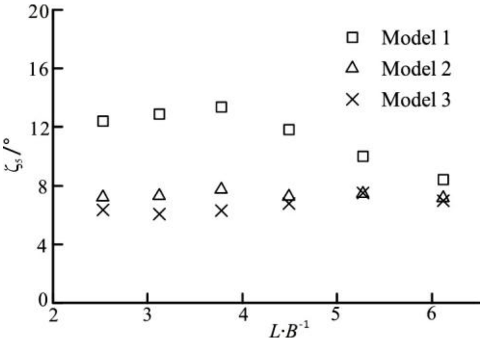

Fig. 14 Roll motion of the three models ($H = 0.15$ m)

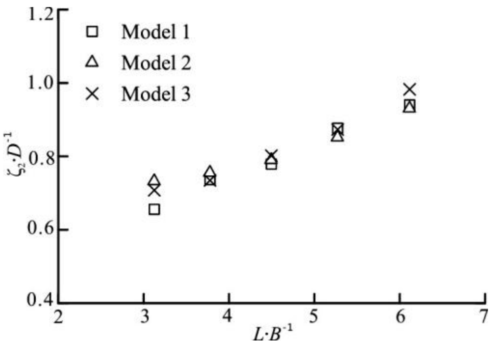

Fig. 15 Sway motion of the three models ($H = 0.20$ m)

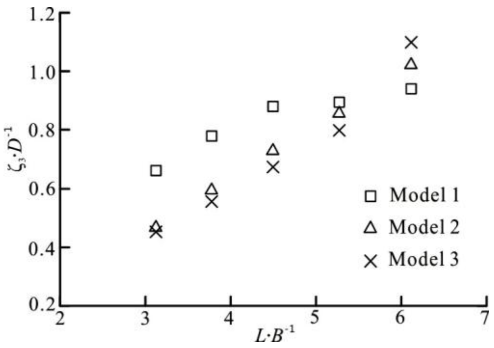

Fig. 16 Heave motion of the three models ($H = 0.20$ m)

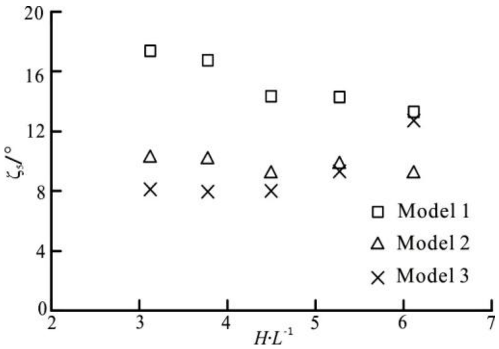

Fig. 17 Roll motion of floating Models 1, 2 and 3 ($H =$ 0.20 r

cate similar experimental results. Similarly, the perforated plate did not have a significant effect on the sway motion response for the three models. Models 2, 3 indicated better hydrodynamic performances in terms of reducing the motion response with the same dimension as that of the pontoon type. In summary, the reasons can be attributed to the larger inertia and mass of Models 2, 3 due to water in the top space of the model through the porous plate. The experimental data did not indicate that the perforated plate increased model damping.

2.3 *Effect of the perforated plate on tensions of mooring lines under regular waves*

The tension of the mooring line is an important factor in designing the FB system. Under wave action, the maximum force acting on the windward mooring line was defined as F_w. Similarly, the maximum force acting on the leeward mooring line was defined as F_1.

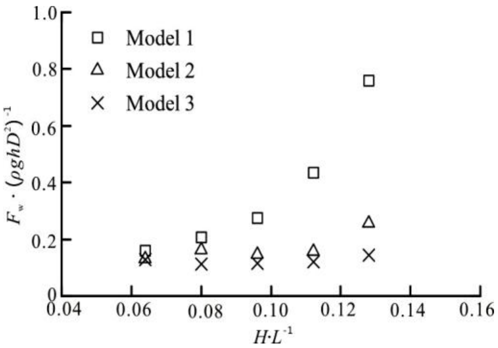

Fig. 18 Forces acting on the windward mooring lines of the three models ($T = 1.0$ s)

The mooring forces of FB on the windward ($F_w / \rho g h D^2$, where ρ is the density of water, g is the acceleration of gravity, h is the water depth of wave flume, D is the draft of model) and leeward $(F_1/\rho ghD^2)$ mooring lines at $T=1.0\text{ s}$, are shown in Figs. 18, 19. A comparison of the experimental data of mooring tension in the seaward and leeward mooring lines indicated that Models 2, 3 showed a better performance in terms of mooring line tension. Given the increase in wave steepness, it was evident that the design of the perforated plate in the seaward direction was valid and beneficial in reducing the mooring line tension. When the wave height was 0.15 m or 0.20 m, Figs. 21-23 show the changes in the relationships between mooring forces (in the windward and leeward sides) and relative wave length (L/B). In a manner similar to the aforementioned results, Figs. 20-23 indicated that it was beneficial for a box-type floating breakwater to decrease the mooring line tension. This was because the smaller motion responses with respect to the heave and roll motions for Models 2, 3 resulted in better performance in terms of the mooring line tension.

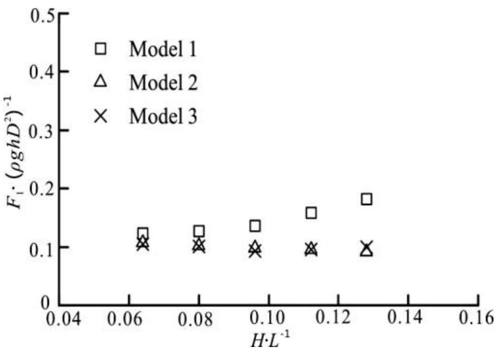

Fig. 19 Forces acting on the leeward mooring lines of the three models $(T=1.0\text{ s})$

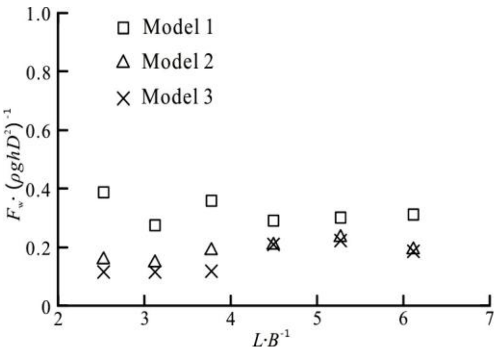

Fig. 20 Forces acting on the windward mooring lines of the three models $(H=0.15\text{ m})$

Model 1 was composed of watertight plates and mainly attenuated surface waves through reflection. Hence, the mooring lines of Model 1 suffered from a larger force. Thus, the Models 2, 3 suffered the smaller wave fore for the perforated pate design. Additionally, another reason was that some of the fluid flowed into the top space of the pontoon through the perforated plates for Models 2, 3. In summary, the perforated plate was a useful and effective method to reduce the tension of the mooring line.

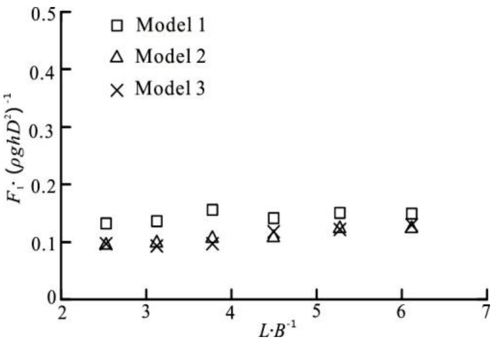

Fig. 21 Forces acting on the leeward mooring lines of the three models $(H=0.15\text{ m})$

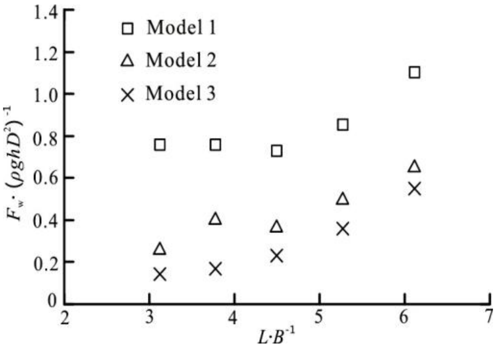

Fig. 22 Forces acting on the windward mooring lines of the three models $(H=0.20\text{ m})$

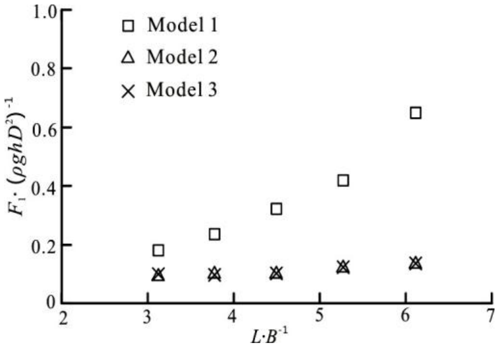

Fig. 23 Forces acting on the leeward mooring lines of the three models $(H=0.20\text{ m})$

3. Conclusions

In this study, an experiment involving three FB models was performed to investigate the features of a perforated plate and to achieve better hydrodynamic performance with respect to mooring line tension under regular wave action. A comparison of the experimental results indicated the following conclusions:

(1) As widely known, improving the effectiveness of FBs is an international issue. It was proposed that the combination of wave reflection and wave dissipation is an effective method. The results indicated that the perforated plates did not have a significant effect on the wave energy dissipation given an increase in the wave period, that is, the porous plates were influenced by the wave length. The experimental results indicated that the perforated plate played an effective role in a certain wave period. The experimental results in the present study indicated that the perforated plate did not have a significant influence on the transmission coefficient. Hence, the structural dimensions and arrangements should be further optimized to improve the hydrodynamic performance.

(2) A comparison of the three models indicated that the design of the perforated plate for seaward mooring lines is a useful and effective choice to decrease the motion response. The water flowing into the FB increased the inertia and mass. Given the same structural dimensions, the mass and inertia were also key parameters for the floating breakwater in terms of the hydrodynamic performance. Hence, the perforated plate was effective in reducing the motion response along the same dimensions for pontoon type. The characteristics of the perforated plate that involved decreasing the motion responses is useful in engineering to reduce the cost of mooring lines.

(3) A distinct result included the variation of the mooring force with the three different models due to the influence of fluid flowing into the porous plate. Therefore, the increased draft of the FB resulted in a decrease in the mooring line tension. Thus, Model 3 had the smallest mooring forces.

To summarize, a perforated plate design is a meaningful and smart method despite its inability to improve the transmission coefficient. The perforated plate design reduced the motion responses and decreased the mooring line tension that constituted a large portion of the total floating breakwater system cost. This study provides useful insights in terms of the future applications of FB. However, a perforated plate may not be optimal for all wave periods. Hence, further research examining ways to increase the performance of wave dissipation is required.

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