EXPERIMENTAL INVESTIGATION OF HORIZONTAL WAVE FORCES ON THE PERFORATED CAISSON WITH SINGLE AND DOUBLE WAVE CHAMBERS

Chang-Hwan Ji[1], Sang-Ho Oh[1], Young Min Oh[1], Se-Chul Jang[1] and Dal Soo Lee[1, 2]

The horizontal wave force acting on vertical walls of perforated caisson breakwater was experimentally investigated in this study. The maximum horizontal wave force acting on single and double chamber caisson was measured respectively and compared each other. By analyzing the obtained experimental data, it was clarified that the total horizontal wave force for double chamber caisson was 9% smaller on average than that for single chamber caisson when the total chamber width was the same for both caissons. The reason for such reduction of horizontal wave force on the double chamber caisson is found from additional dissipation of wave energy at the porous middle wall of the structure, by which rather impulsive wave force on the rear wall could be slightly diminished compared to the single chamber caisson.

Keywords: perforated caisson; wave force; wave chamber, middle wall; physical experiment

INTRODUCTION

In Korea, newly constructed breakwaters in major ports are located in somewhat deep waters so that corresponding design wave height and period become greater than in the past. For this reason, vertical breakwaters are more popularly being adopted in such locations than the rubble mound structures. In particular, perforated wall caisson has been very widely applied to the field recently since it is known as favorable to reduce wave reflection and loadings acting on the breakwater.

Typically, perforated caisson breakwater has a single wave chamber, but some breakwaters are designed to have more than one chamber to meet specific request or requirement in the field. However, there are not so many researches that have investigated wave loading acting on a caisson having multiple chamber. Franco et al. (1998) conducted field and laboratory measurements of wave forces on a multi-chamber caisson and compared with Goda's formula. A comparison of one- and multi-chamber caisson in terms of the reflection properties and the wave loads was made by Bergmann and Oumeraci (2000) and Chen et al. (2002).

Although these previous studies have contributed to the knowledge of hydraulic characteristics of caisson with more than one chamber, it is still needed to improve our understanding of how waves interact with vertical walls of the caisson structure. In this context, we carried out physical experiments for measuring horizontal wave force acting on each of vertical walls consisting of the caisson. Based on this precise measurement, it was possible to analyze some detailed mechanism of wave action on the vertical walls with considering several wave phases. By comparing the obtained total wave loading on the double chamber caisson with that on the single chamber caisson, it was quantitatively clarified that the double chamber system is more favorable in reducing total wave loading on the caisson.

PHYSICAL EXPERIMENTS

Physical experiments were performed in a wave tank of 53m long, 1m wide and 1.25m high. A piston-type wave maker is installed at the upstream end of the wave tank. Wave energy absorption facilities are installed at the back of the wave maker and at the downstream end of the wave tank. In order to effectively estimate the hydraulic characteristics of the perforated caisson breakwater, the wave tank was partially separated into two channels as shown in Figure 1. The caisson breakwater model was installed in the wide channel of 0.6 m width.

The caisson model was 70 cm long, 53.5 cm high and 59 cm wide as shown in Figure 2. The shape and geometry of the single chamber caisson is similar as Takahashi and Shimosako (1994). It was made of acrylic plates and placed on a rubble mound. The horizontal length of the mound was 26 cm from both of the caisson end walls. On both sides of the caisson, two rows of cubic concrete blocks and tetrapods were placed to protect the mound against possible scouring due to wave action. The height of the crown measured from the tip of the front wall was 6 cm. The water depth in front of the breakwater was constant to be 55 cm. When the model is compared to the typical caisson breakwaters constructed in the field, it approximately corresponds to 1/40 of the prototype structure.

The porosity (ε) of the porous section of the front wall and the middle wall of the double chamber caisson was 0.3. A view of the front wall is shown in Figure 3. In the experiment, non-porous front wall was also used in order to validate the experimental data by comparing with Goda's formula.

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[1] Coastal Development & Ocean Energy Research Division, Korea Institute of Ocean Science & Technology, 787 Haeanro, Ansan, 426-744, Republic of Korea (Corresponding author: Sang-Ho Oh, e-mail: coast.oh@gmail.com)
[2] Research & Development Division, Hyein Engineering & Construction, 583 Yangcheonro, Seoul, 157-845, Republic of Korea

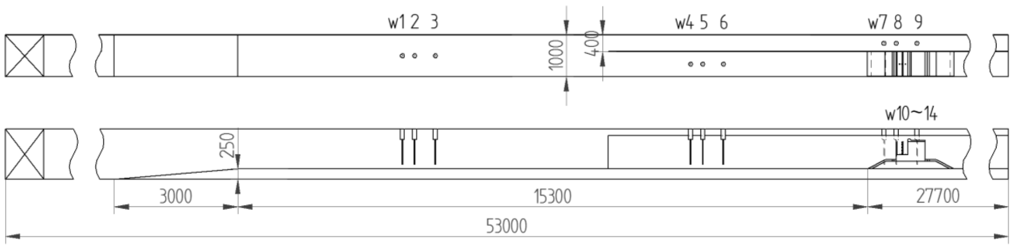

Figure 1. Schematic diagram of the experimental setup (unit: mm).

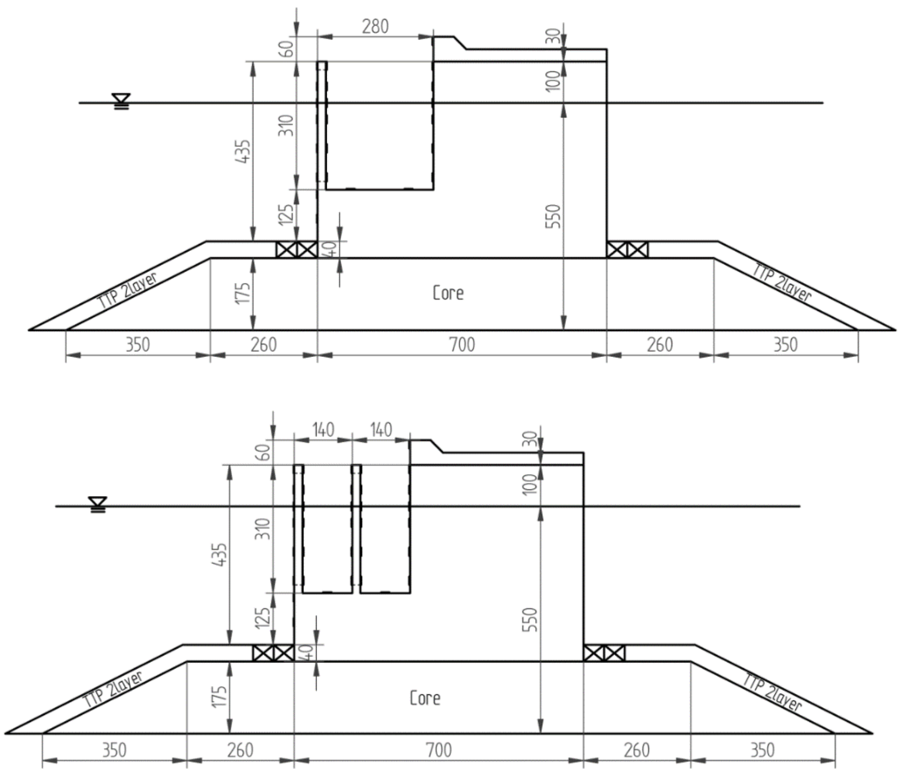

Figure 2. Side view of the caisson model with single and double chamber.

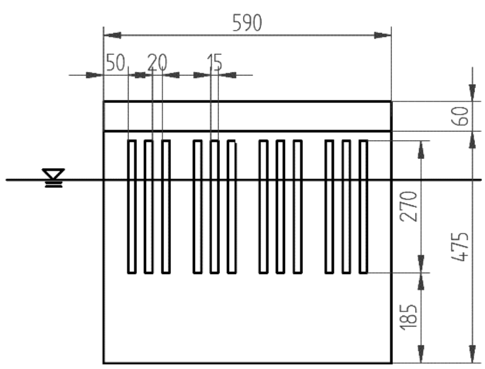

Figure 3. View of the front wall of the caisson model.

A total of 14 wave gauges were used in the experiment as shown in Figure 1. By using the force measuring system consist of load cells, the wave forces acting on the porous upper section and non-porous lower section of the front wall were separately measured. Similarly, the forces on the porous middle wall (in case of the double chamber caisson) and the solid rear wall were also measured individually. The caisson model was subjected to regular waves for 60 seconds whose wave period ranges from 0.77 to 2.70 s, while wave height from 2.8 to 24.8 cm.

WAVE FORCE ACCORDING TO WAVE PHASES

In case of perforated caisson, the peak value of horizontal wave force acting on the front and rear wall do not appear at the same time. Considering this, Takahashi and Shimosako (1994) proposed a pressure formula respectively for different phases of waves acting on the vertical walls. Figure 4 shows three different wave phases associated with positive horizontal force, which was defined by Takahashi and Shimosako (1994). In the figure, Crest I denotes the phase when the wave forces on the front walls (the porous upper and non-porous upper sections) reach their positive peak. Meanwhile, Crest IIa and IIb indicates the phases when the force on the wave chamber rear wall reaches an impulsive and pulsating quasi-static peak, respectively. At each of these different wave phases, Takahashi and Shimosako (1994) compared the measured wave force on vertical walls of the perforated caisson with the well-known Goda's formula (Goda, 2010). In this study, a similar comparison was made for the experimental data for the perforated caissons with single and double chamber.

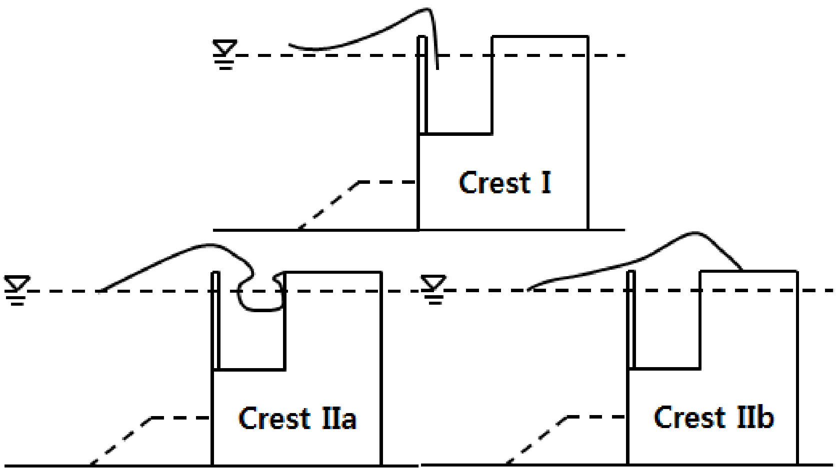

Figure 4. Three different phases during wave action on the perforated caisson defined by Takahashi and Shimosako (1994).

Figure 5 shows an exemplary time series of the measured force for the caisson with a single chamber. The test wave condition was T = 1.70 s and H = 16.5 cm. In the figure, F_S and F_L denote the wave force acting on the porous upper section and non-porous lower section of the front wall, respectively. Similarly, F_R indicates the force on the impermeable rear wall. The total force acting on the caisson is expressed as F_H. It is clearly shown in Figure 5 that the peak horizontal force appears simultaneously on the upper porous section and upper non-porous section of the front wall, which corresponds to the wave phase of Crest I defined by Takahashi and Shimosako (1994). Meanwhile, the force on the rear wall shows two peaks corresponding to impulsive wave action (Crest IIa) and pulsating loading (Crest IIb) on the wall. In this case, the maximum total force (F_H) occurs at the wave phase of Crest IIa.

Similar plot for the double chamber caisson with the same wave condition (T = 1.70 s and H = 16.5 cm) is shown in Figure 6. In this case, the force on the porous middle wall (F_M) is also shown in the figure. Overall variation of F_S and F_L are very close to that of single chamber caisson shown in Figure 5. On the other hand, the wave force on the rear wall (F_R) showed significant difference from the previous figure. The peak corresponding to Crest IIa, associated with the impulsive wave loading, is not clearly seen in Figure 6. In addition, the peak value at the phase of Crest IIb, corresponding to the time instant of maximum water level in the wave chamber, diminished compared to that shown in Figure 5. The time interval between Crest I and Crest IIb also slightly increased in case of double chamber caisson. Such a difference between the single and double chamber caissons is ascribed to the existence of the porous middle wall, by which further dissipation of wave energy is made. It is noteworthy that the maximum wave force on the middle wall itself is considerably smaller compared to the maximum value at the front or rear walls. The peak of total horizontal force also appears at the phase of Crest IIa as shown in the last panel of Figure 6, but its magnitude is slightly smaller compared to the corresponding value for the single chamber caisson shown in the previous figure.

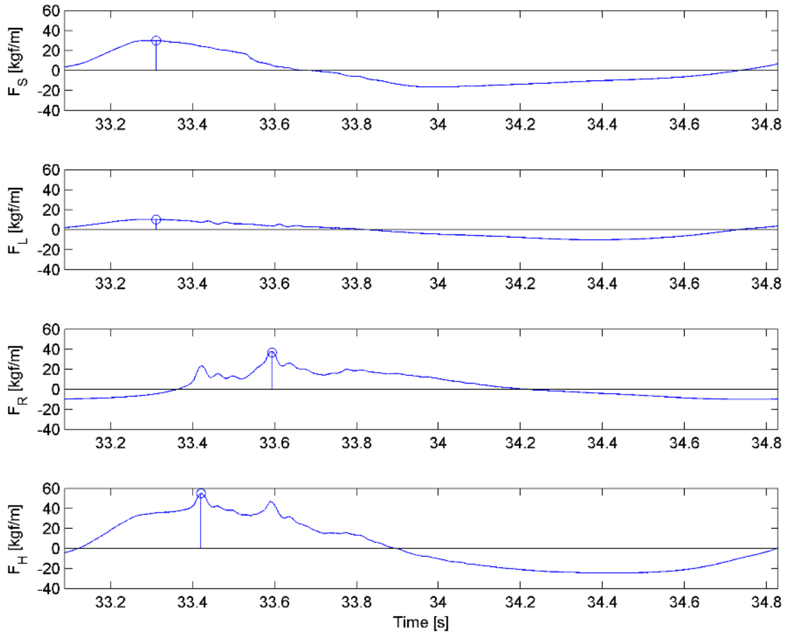

Figure 5. An example of time series of wave force on the single chamber caisson.

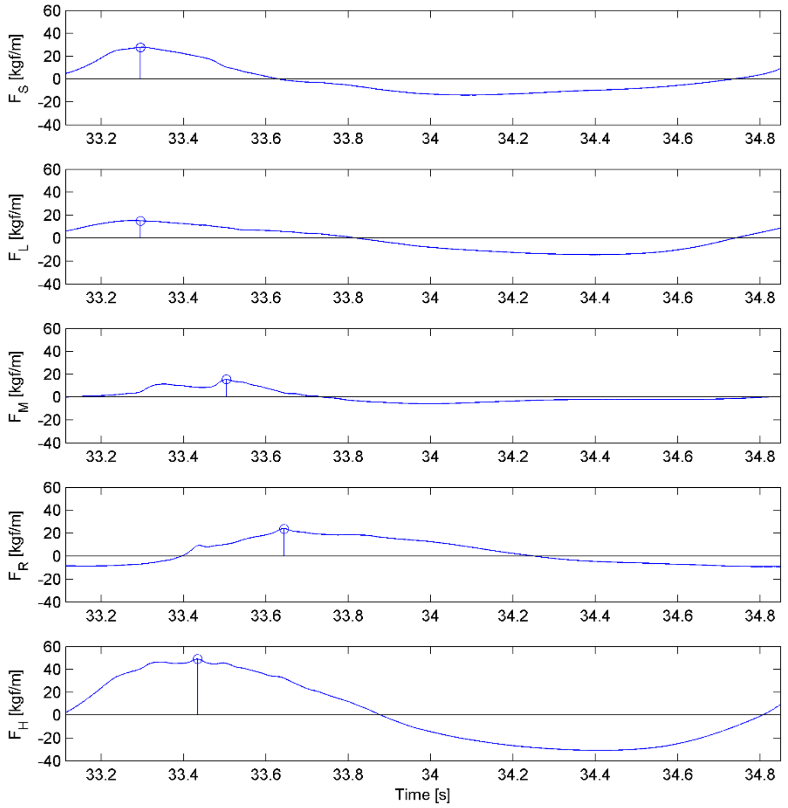

Figure 6. An example of time series of wave force on the double chamber caisson.

COMPARISON OF MAXIMUM WAVE FORCE

Wave force on the upper front wall (porous section)

Figure 7 shows the measured horizontal force on the perforated section of the front wall (F_S^{EXP}) normalized b the force calculated by Goda's formula (Goda, 2010) on the same section (F_S^{Goda}). In the figure, the experimental results for the single and double chamber caissons are compared. In calculation of F_S^{EXP}, the value of α_2 was set to be zero following the method presented in Takahashi et al. (1991). The parameter of F_S^{EXP}/F_S^{Goda} stands for the relative magnitude of the wave force acting on perforated caisson to the force on the solid caisson. Figure 7 shows that the values of F_S^{EXP}/F_S^{Goda} are smaller than unity for both caissons, which indicates that wave action on the upper section of the front wall is smaller in case of the perforated caisson compared to the non-perforated caisson, at the wave phase of Crest I. In addition, it is clearly seen in the figure that wave force is smaller in case of the single chamber caisson than the double chamber caisson

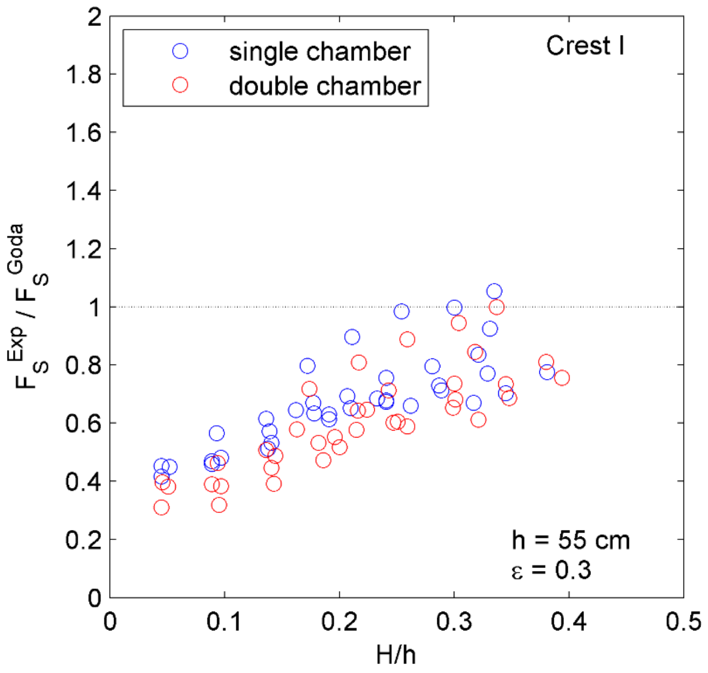

Figure 7. Normalized wave force on the porous upper section of the front wall.

Wave force on the lower front wall (non-porous section)

At the same wave phase of Crest I, similar results for the lower front wall is shown in Figure 8. As explained in the above, the wave force on this part of the front wall also reaches its maximum at Crest I. The values of F_L^{EXP}/F_L^{Goda} ranges around the value of unity as seen in the figure, which means that the measured wave force on this wall section is almost comparable to the estimate from Goda's formula. Also, the difference in the measured force between the single and double chamber caisson is nearly negligible in this case.

Wave force on the rear wall

In Figure 9, the values of F_R^{EXP}/F_R^{Goda} are shown for the single and double chamber caissons, where F_R^{EXP} denotes the measured force on the rear wall of the perforated caisson and F_R^{Goda} the corresponding value derived from Goda's formula. In this case, the results corresponding to the wave phase of Crest IIb are shown in the figure as the wave force on the rear wall tends to reach its maximum at this phase. The values of F_R^{EXP}/F_R^{Goda} are slightly less than unity on average. Also, they show slightly increasing trend with H/h, which is different from the results in Takahashi and Shimosako (1994). The reason of such a difference is not clear at the present, and further investigation is needed. Meanwhile, except some experimental data, the normalized wave forces acting on the double chamber caisson was smaller than those on the single chamber caisson, same as the result for the perforated section of the front wall presented in Figure 7.

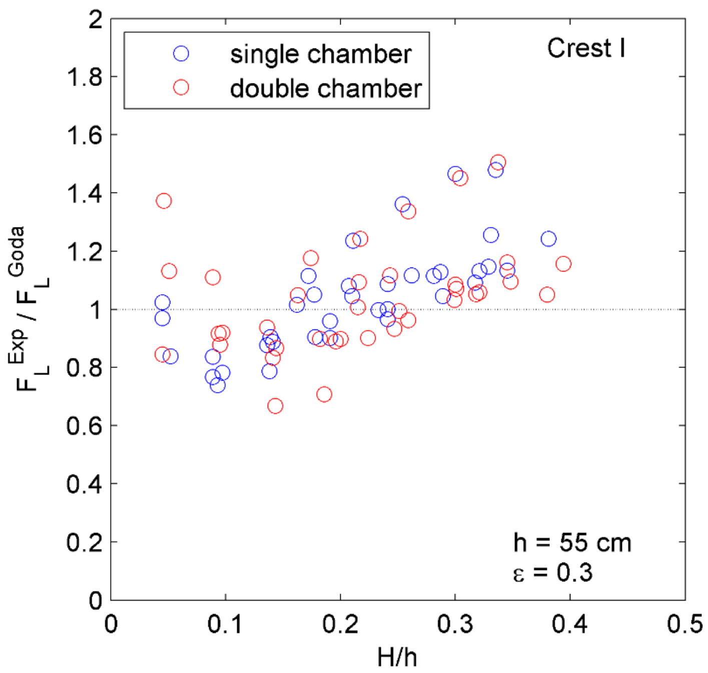

Figure 7. Normalized wave force on the non-porous lower section of the front wall

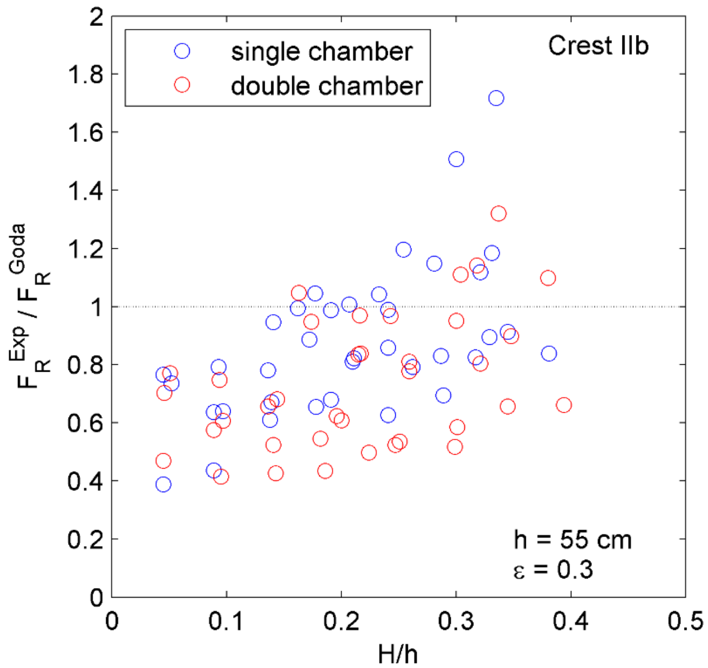

Figure 9. Normalized wave force on the impermeable rear wall.

Wave force on the middle wall (double chamber caisson)

In case of the double chamber caisson, it is possible to make similar analysis as above for the wave force on the middle wall. Figure 10 shows the normalized wave force on the middle wall (F_M^{EXP}/F_M^{Goda}), where F_M^{Goda} is the wave force on the middle wall section estimated from Goda's formula. This result is obtained for the wave phase at which the wave force on the middle wall reaches its maximum as shown in the fourth panel of Figure 6. It is clearly seen that the measured forces are substantially smaller (ranging from 20 to 40%) than the estimates of Goda's formula. This tendency is quite different from the results for the perforated upper section of the front wall or the rear wall, where the measured forces are almost comparable to the estimates from Goda's formula. The reason for such a comparatively smaller wave loading on the middle wall can be ascribed to its supplementary role in resisting wave action It is likely to receive rather mild wave action since it acts neither as the front wall by hitting strongly to undisturbed waves nor as the rear wall by resisting wave action as a final wall inside the caisson. In this context, the structural rigidity required for the middle wall might be less than that for the front wall.

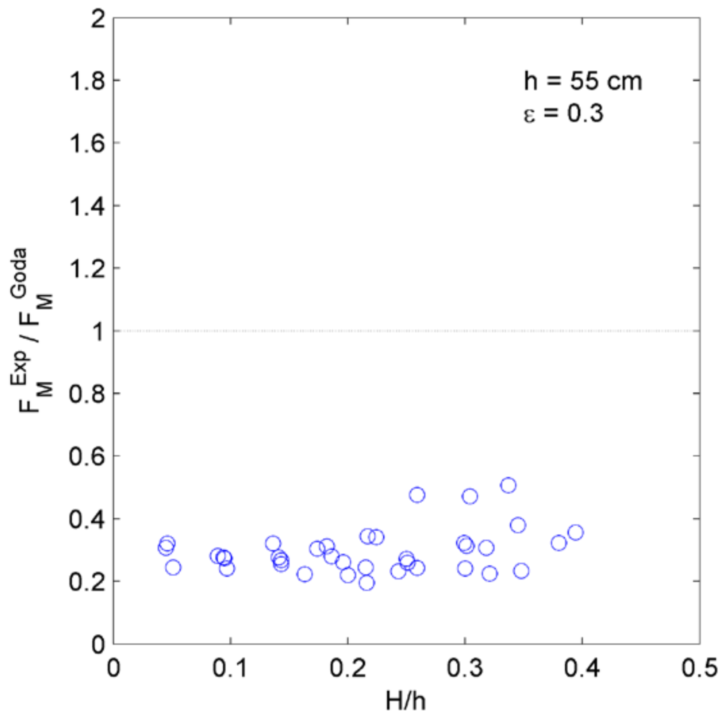

Figure 10. Normalized wave force on the perforated middle wall of the double chamber caisson.

Total horizontal wave force

Besides the individual wave force on each of the vertical walls, the total horizontal force acting on the caisson is an important quantity that is closely related to the overall stability of the structure. In this context, a comparison is made in Figure 11 between the single and double chamber caisson in terms of the total horizontal force. In the figure F_H^{SC} and F_H^{DC} respectively denote the maximum horizontal force on the single and double chamber caissons. As seen in the figure, the values of F_H^{DC}/F_H^{SC} are mostly less than unity, which indicate the maximum horizontal force on the double chamber caisson is smaller than that on the single chamber caisson generally. On average, the values of F_H^{DC} was 8.2% smaller than those of F_H^{SC}.

CONCLUSIONS

In this study, we measured the horizontal wave force acting on vertical walls consisting of the single or double chamber caisson by performing physical experiments in a wave flume. Based on the analysis method suggested by Takahashi and Shimosako (1994), the wave force acting on each of the vertical walls were analyzed separately with considering the specific wave phases that is closely related to the maximum force on the front, middle (in case of the double chamber caisson), or the rear walls of the caisson. Then, a series of comparison was made between the single and double chamber caisson in terms of the maximum horizontal force at the walls. It was found that the wave forces acting on the permeable front wall and the impermeable rear wall are slightly diminished in case of the double chamber caisson, as a result of supplementary dissipation of wave energy at the porous middle wall. Thanks to this additional energy dissipation at the middle wall, the time interval between the wave phases corresponding to the maxima of horizontal force on the front wall (Crest I) and the rear wall (Crest IIb) also slightly increased in case of the double chamber caisson. In the future, further investigation is required by performing experiments with caisson models having different geometry of rubble mound height, wave chamber width, and porosity of the front and middle walls, and so on.

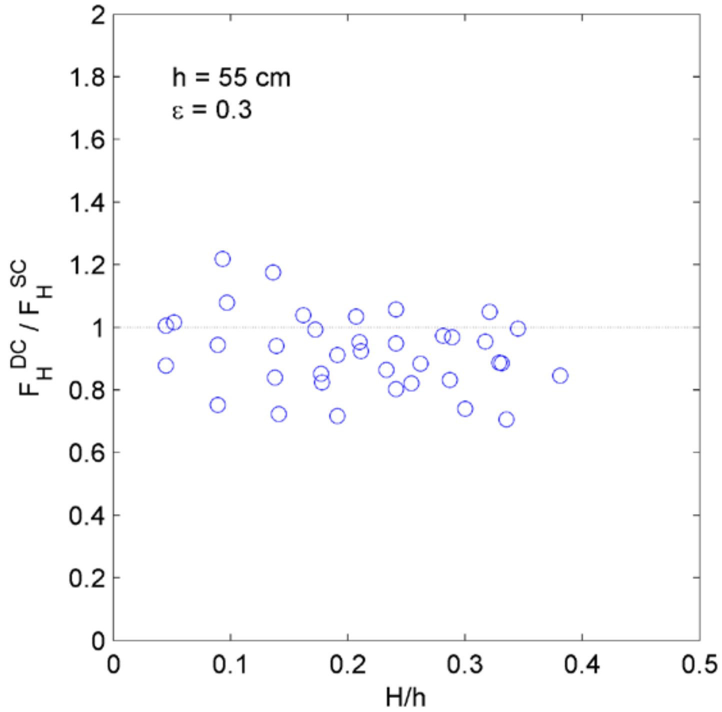

Figure 11. Comparison of the total wave force on the single and double chamber caisson.

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