MEASUREMENT OF WAVE PRESSURE ON PERFORATED CAISSON WALL UNDER OBLIQUE WAVE INCIDENCE

Sang-Ho Oh[1], Chang-Hwan Ji[1], Young Min Oh[1] and Hee Do Ahn[1]

Three dimensional experiments were carried out in a wave basin in order to examine the effects of wave obliquity on the wave pressure acting on perforated caisson walls. The magnitudes of pressures measured under oblique waves did not show decaying trend predicted by Goda's formula, for both the front and rear walls of the caisson. On the contrary, the wave force on a single caisson, estimated by integration of the vertical pressure profiles on the caisson front, showed slightly increasing trend on average with increase of the wave incidence angle. Meanwhile, the simultaneously measured wave force for the whole caissons is found to be apparently reduced with wave obliquity as a result of peak-delay force reduction in lateral direction along the caisson fronts.

Keywords: perforated caisson; wave pressure; wave obliquity; physical experiment

INTRODUCTION

High wave climate around nearshore region of Korea is commonly governed by typhoons in summer season while swell-related waves in winter season (See Figure 1). Breakwaters located in harbors or ports located in south or east coastal zone of Korea are thus required to be designed to resist to wave actions from those two coastal threats. At major trade ports, such as Jeju, Busan, Pohang, and Ulsan, typical design wave conditions corresponding to 50-year return period are H_s = 7~9 m and T_s = 15~17 s.

As the newly constructed breakwaters in these ports are located in relatively deep waters of h = 20~25 m, caisson breakwaters are mostly adopted to reduce costs for construction. In particular, porous structures have been very actively applied in the field to obtain good hydraulic performance in wave reflection and to reduce total wave loading on the structure. During the last decades, various shapes of porous structures have been suggested in order to take some advantage in winning turn-key contracts for construction of new breakwaters.

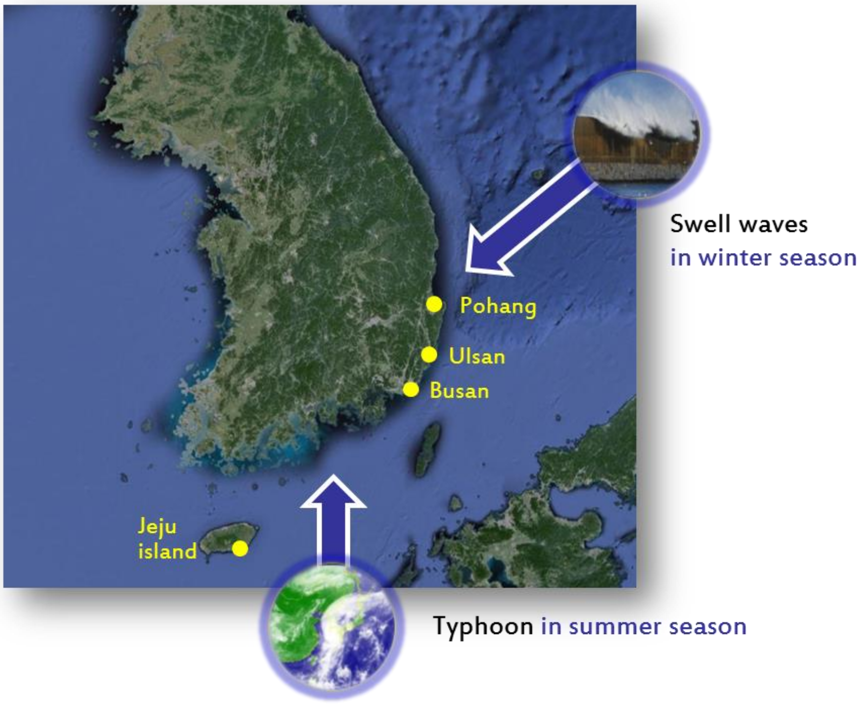

Figure 1. Major coastal threats around Korean sea waters in summer and winter seasons.

Meanwhile, most studies of wave loading on vertical walls are based on two-dimensional physical experiments because the normal incidence of waves to the coastal structures are implicitly considered as

---

[1] Coastal Development & Ocean Energy Research Division, Korea Institute of Ocean Science & Technology, 787 Haeanro, Ansan, 426-744, Republic of Korea

the most dangerous to invoke possible failure of the structures. Indeed, breakwaters are generally designed to be perpendicular to the principal wave direction, but they are often situated in an obliquely-incoming wave field.

Concerning this issue, several researchers have investigated influence of wave obliquity on the wave loading on solid vertical breakwaters (Franco et al., 1996; Allsop & Calabrese, 1998; Frigaard et al., 1998). They assessed the effects of wave obliquity and multi-directionality on the hydraulic response of non-perforated caisson walls. However, very little attention has been paid to such effects on the perforated vertical breakwaters so far. In order to examine this matter, experimental investigation was made in this study with different incidence wave angles between 0° and 45° to a series of perforated caisson arranged in a row. In the following, descriptions of the experimental setup and analysis results of the obtained experimental data are presented and the paper is concluded.

PHYSICAL EXPERIMENT

The experiment was conducted in a wave basin of 33m long, 30m wide, and 1m high. In this experiment, the width of the basin was reduced to 21 m for convenience of the experimental setup. Piston-type wave makers were used for generating waves in the basin, whose positions were changed depending on the wave incidence angle. The generated wave energy was absorbed on the gravel beach placed around the walls surrounding the wave basin.

A set of 15 caisson models were made of acrylic plate and installed in the wave basin as shown in Figure 2. The size of an individual caisson was 56 cm long, 44 cm high and 48 cm wide. The breakwater model was not a reproduction of a specific prototype structure, but the model scale was assumed to be 1:50 considering the typical geometry of a prototype caisson. On top of the caisson model, 8 cm high non-perforated crown was placed. The caisson model was put on an 8 cm-high rubble mound, which was protected by cubic concrete blocks and tetrapods to prevent possible scouring due to wave action. The water depth at the toe of the breakwater mound was 44 cm, in which condition the freeboard of the breakwater front wall was 16 cm. The porosity of the front wall, denoted as r in the following, was changed by 0.2 and 0.3. The vertical length of the perforated section was 50% of the caisson height, spanning from 17.6 to 39.6 cm above the mound.

Figure 2. Side and corner views of the perforated caisson installed in the wave basin.

Among the 15 caisson models, only five in the middle (model No. 6 to 10 in Figure 3) were used for the measurement of wave pressure. A total of 40 pressure sensors were attached on the front and rear walls of the five caisson models as shown in Figure 4. Small dots in the figure denote the locations where the pressure sensors were placed on the perforated front wall of the caisson model. With this arrangement of the pressure sensors, vertical pressure profiles on the front wall were measured at the caissons No. 7 and 9. Meanwhile, pressure distribution on the non-perforated rear wall was measured at the caisson No. 7. The number of pressure sensors were not the same for each caisson, but at least four sensors were placed at the same elevation (p_1~p_4 in Figure 4), by which it was possible to know the lateral pressure distribution from the caisson No. 6 to 10. In addition to the pressure measurement explained above, direct wave force acting on the caisson was also measured by installing load cells on the vertical walls of caisson model No. 9.

Test waves were prepared by using JONSWAP spectrum with $\gamma=2.0$. According to Suh et al. (2010), the most probable value of peak enhancement factor around Korean sea waters is $\gamma=2.14$. A total of 14 different sea conditions were generated for the experiment. The significant wave period, or $T_s=0.95T_p$, varied from 1.28 to 2.42 s, while the significant wave height H_s, computed from zeroth moment of the measured spectrum, was in the range of 3.8 to 19.5 cm. Wave steepness varied in the range between 0.02 and 0.05. The number of waves was five hundreds for every wave condition. Wave pressures were measured at the sampling rate of 800Hz.

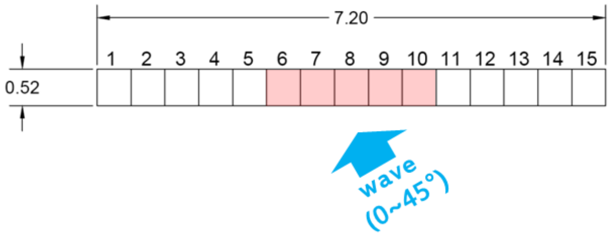

Figure 3. Schematic diagram showing the experimental setup (unit: m).

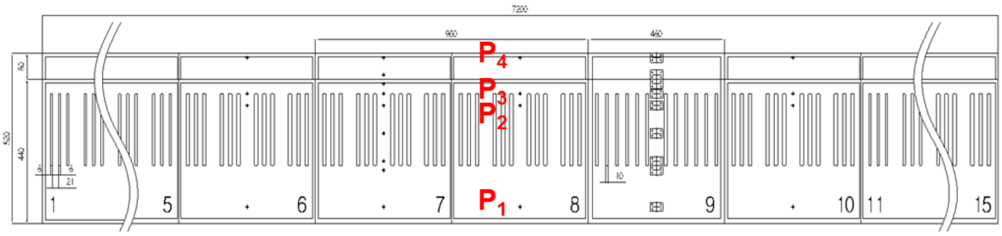

Figure 4. Instrumentation for the perforated caisson models.

EXPERIMENTAL RESULTS

Figure 5 shows three examples of the normalized pressure ($p/\rho gH_s$) distributions along the perforated front and non-perforated rear walls of the caisson, where the pressure is corresponding to the average of the two top pressure ($p_{1/250}$) at each measuring elevation. The figure corresponds to the case when $r=0.2$. It is clearly seen that the magnitudes of pressures measured under oblique waves ($\theta>0°$) are comparable to, or in some conditions slightly greater than, those values under zero wave incidence ($\theta=0°$), for both the front and rear walls of the caisson. This trend does not agree well with the Goda's formula (Goda, 2010), in which the magnitude of pressure under oblique waves of incident angle β will decrease with the factor of $0.5(1+\cos\beta)$. In Table 1, the values of this factor are listed for the incident wave angle from 0° to 90° at an interval of 15°. In the range of the present experiment, the value of this factor will decline from 1 to 0.85 when β is increasing from 0° to 45°.

Table 1. Values of $0.5(1+\cos\beta)$.

β (Deg.)	0	15	30	45	60	75	90
$0.5(1+\cos\beta)$	1.00	0.98	0.93	0.85	0.75	0.63	0.50

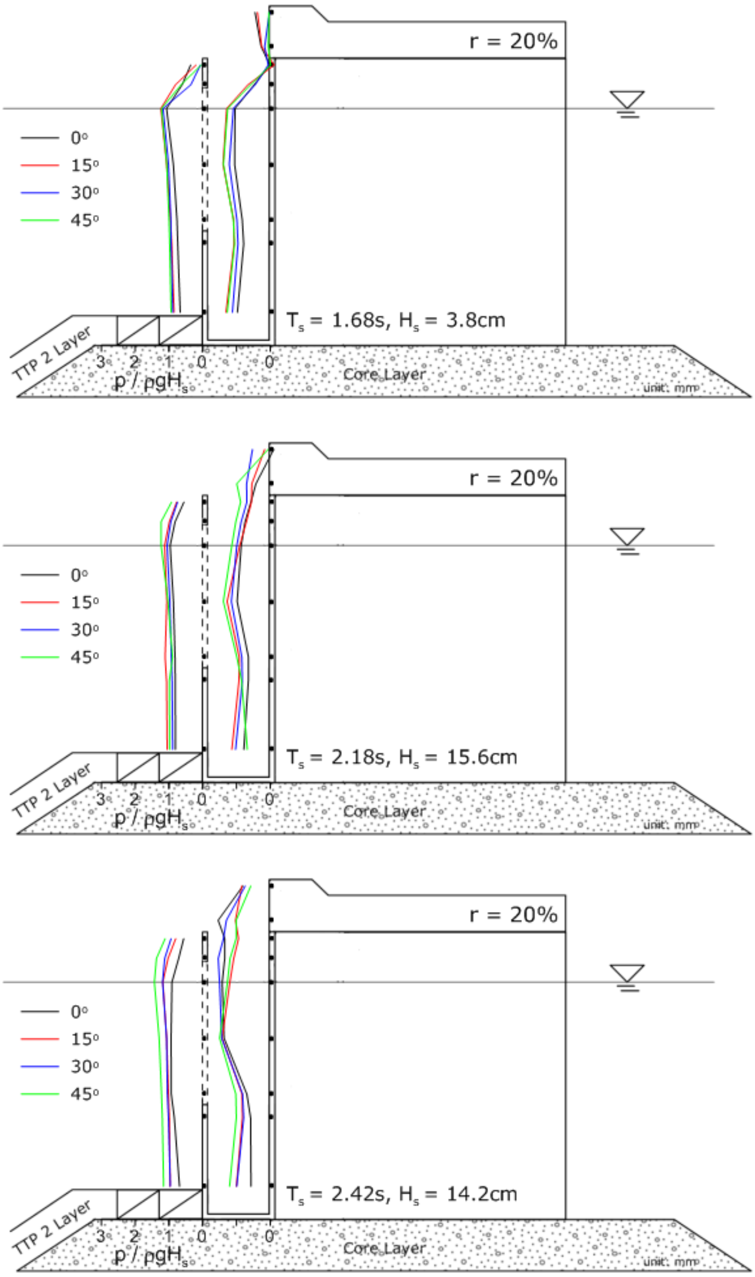

Figure 5. Comparison of the measured wave pressures at the front and rear walls according to different wave angle (when porosity = 0.2).

Similar results as in this study were reported by Franco et al. (1996), who showed that horizontal force on the solid caisson does not decay with increasing obliquity of the mean wave direction, originally assumed by Goda's formula. In contrast, relatively good agreement with Goda's formula for oblque waves under both breaking and non-breaking conditions was observed in the experiment of Frigaard et al. (1998). As there are only limited literatures that have investigated the effects of wave obliquity so far, further investigations seem to be necessary in order to obtain appropriate knowledge on which trend is more closely related to the real sea condition.

Meanwhile, Figure 6 presents another examples of the distribution of normalized pressure ($p/\rho g H_s$) when $r = 0.3$, for the same test wave conditions as in Figure 5. In general, the overall pattern in pressure distributions was very similar as in the case of $r = 0.2$ shown in the previous figure. It seems that porosity is less significant factor having influence on the change of wave pressure on the perforated caisson in terms of wave obliquity.

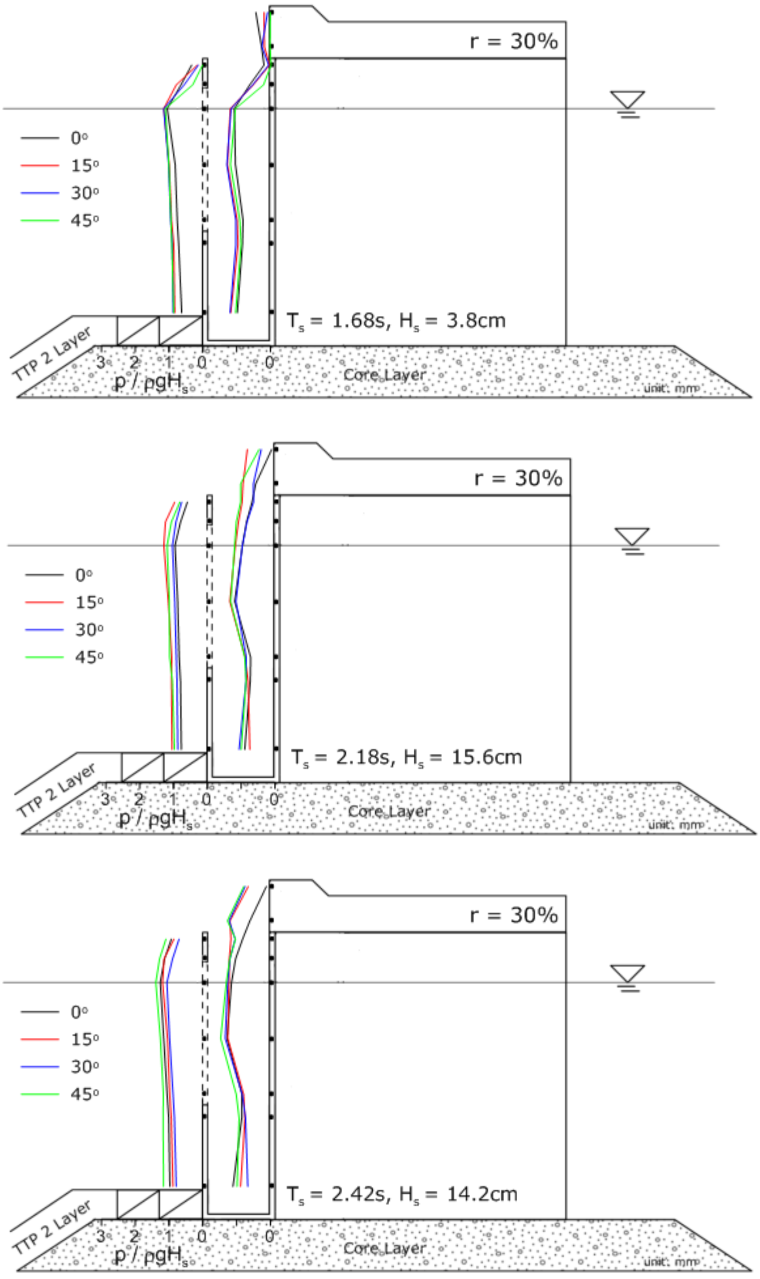

Figure 6. Comparison of the measured wave pressures at the front and rear walls according to different wave angle (when porosity = 0.3).

Figure 7 shows the normalized wave force ($F_p/\rho g H_s$) acting on the front wall of the model, based on calculation of F_p by integration of the measured pressures. Although there are pronounced scatter for the integrated wave force, the mean value showed slightly increasing trend with the incident wave angle. The tendency of higher wave loading under more oblique wave conditions was also confirmed from the results of direct measurement of wave loading by using the load cells. Similar trend as in this study was reported by Franco et al. (1996), who found general increase of the measured force on solid vertical wall with increasing wave obliquity.

As we placed at least four pressure sensors on each of the five caissons, as mentioned in the above, it was possible to examine the lateral distribution of wave pressure along the front walls of the five instrumented caissons (model No. 6 to 10 in Figure 3). One example of such results are provided in Figure 8, where the simultaneously measured pressures at four elevations (p_1 to p_4) of each caisson are shown for the four different wave angles from 0° to 45°. Note that the pressures shown in the figure were obtained at the same time instance when the wave force on the model No. 9 reached its maximum.

As shown in the figure, dissimilar spatial distributions of the wave pressures were obtained for different wave incidence angle. With increase of the wave angle, the simultaneously measured pressures more sharply decay along the caisson front. This feature appears because the maximum wave force tends to be delayed under obliquely incoming wave conditions. Then, the total wave force summed up for all the five caissons become smaller with increase of wave angle as a result of increase in phase delay of peak occurrence of wave loading on each of the five caissons. This implies that a single long caisson would have redundant stability against wave loading under oblique wave incidence. Further investigation is required to compare the present experimental results with the predictions for the peak delay reduction for solid wall (Battjes, 1982; Burcharth and Liu, 1998).

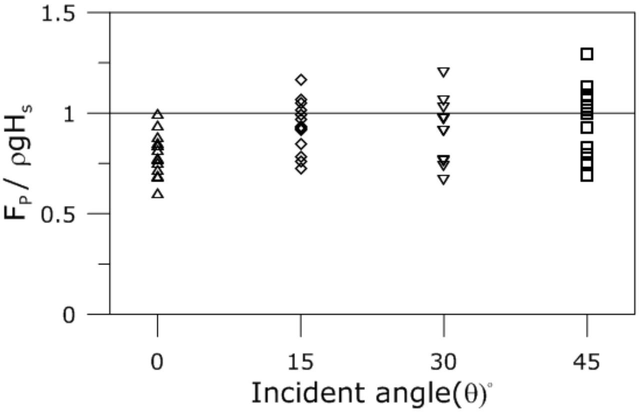

Figure 7. Integrated wave forces on the front wall based on the pressure measurement.

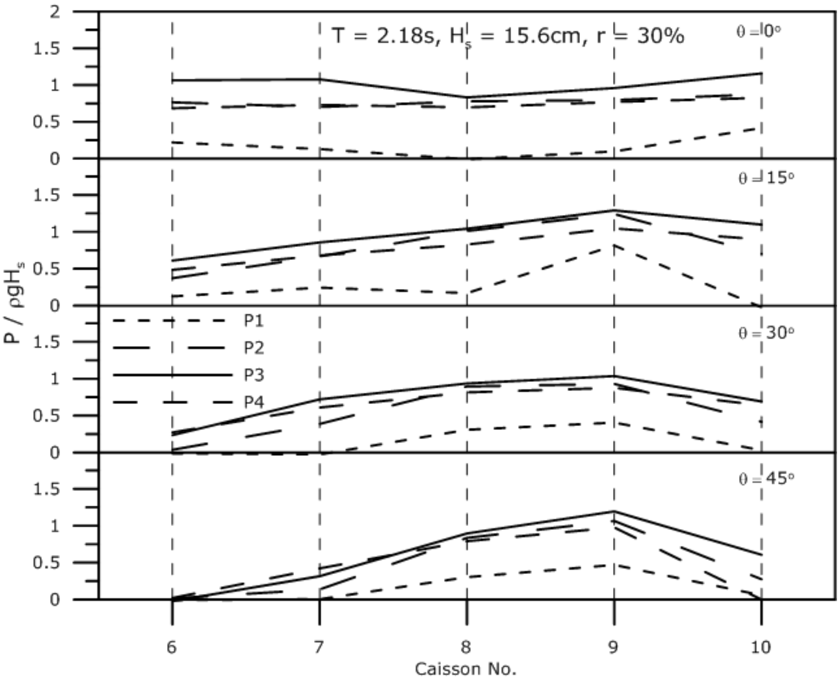

Figure 8. Distribution of wave pressures simultaneously measured along the five perforated caisson for the wave condition of Ts =2.18 s, Hs = 15.68 cm (porosity=0.3).

CONCLUSIONS

In this study, experimental investigation was made in order to understand the influence of wave obliquity on the wave loading on the vertical walls of the perforated caisson. By conducting physical experiments in a wave basin, some findings as follows were obtained.

- Wave pressure distributions on both the perforated front wall and the non-perforated rear wall showed insignificant difference with wave obliquity up to the incidence angle of 45°
- The influence of front wall porosity on the measured wave pressure was nearly negligible.
- With regard to the horizontal wave force acting on a single caisson, slightly increasing trend, on average, was found with increase of the incident wave angle.
- Due to the peak-delay effects for a long caisson, the magnitude of pressure in lateral direction decayed with oblique waves.

As this study is at an early stage of investigation, further detailed analysis and additional measurement are required in the future. This will include estimation of peak-delay reduction factor for the horizontal wave force under oblique waves and comparison with available formula predicting the reduction factor that were suggested for non-perforated caisson.

AKKNOWLEDGEMENTS

This research was a part of the project titled “Study on Method Improving Port Design Standard Considering Climate Change (PM57800)” funded by the Ministry of Oceans and Fisheries, Korea.

REFERENCES

Allsop, N.W.H. and Calabrese, M. 1998. Impact loadings on vertical walls in directional seas, *Proceedings of 26th International Conference on Coastal Engineering*, 2056-2068.

Battjes, J.A. 1982. Effects of short-crestedness on wave loads on long structures, *Applied Ocean Research*, 4, 165-172.

Burcharth, H.F. and Liu, Z. 1998. *Reduction of Wave Loads on Long Caissons Exposed to Short-crested Waves*, Department of Civil Engineering, Aalborg University, Denmark.

Franco, C., van der Meer J.W. and Franco, L. 1996. Multidirectional wave loads on vertical breakwaters, *Proceedings of 25th International Conference on Coastal Engineering*, 2008-2021.

Frigaard, P., Burcharth, H.F. and Kofoed, J.P. 1998. Wave impacts on caisson breakwaters situated in multidirectionally breaking seas, *Proceedings of 26th International Conference on Coastal Engineering*, 1959-1971.

Goda, Y. 2010. *Random Seas and Design of Maritime Structures*, 3rd Edition, World Scientific Publishing Co.

Suh, K.D., Kwon, H.-D. and Lee, D.-Y. 2010. Some statistical characteristics of large deepwater waves around the Korean Peninsula, *Coastal Engineering*, 57, 375-384.