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Experimental study on the method of estimating the vertical design wave force acting on a submerged dual horizontal plate

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ABSTRACT: *A steel-type breakwater that uses a submerged dual horizontal porous plate was originally proposed by Kweon et al. (2005), and its hydrodynamic characteristics and design methodology were investigated in a series of subsequent researches. In particular, Kweon et al. (2011) proposed a method of estimating the vertical uplift force that acts on the horizontal plate, applicable to the design of the pile uplift drag force. However, the difference between the method proposed by Kweon et al. (2011), and the wave force measured at a different time without a phase difference, have not yet been clearly analyzed. In this study, such difference according to the method of estimating the wave force was analyzed, by measuring the wave pressure acting on a breakwater model. The hydraulic model test was conducted in a two-dimensional wave flume of 60.0 m length, 1.5 m height and 1.0 m width. The steepness range of the selected waves is 0.01~0.03, with regular and random signals. 20 pressure gauges were used for the measurement. The analysis results showed that the wave force estimate in the method of Kweon et al. (2011) was smaller than the wave force calculated from the maximum pressure at individual points, under a random wave action. Meanwhile, the method of Goda (1974) that was applied to the horizontal plate produced a smaller wave force, than the method of Kweon et al. (2011). The method of Kweon (2011) was already verified in the real sea test of Kweon et al. (2012), where the safety factor of the pile uplift force was found to be greater than 2.0. Based on these results, it was concluded that the method of estimating the wave force by Kweon et al. (2011) can be satisfactorily used for estimating the uplift force of a pile.*

KEY WORDS: Dual horizontal porous plates; Steel-type breakwater; Wave force; Phase difference; Safety factor; Uplift force.

INTRODUCTION

Many ways to reduce coastal beach erosion have been introduced, including the typical method of constructing a conventional submerged breakwater. However, the conventional breakwater has the disadvantage of rapidly changing its neighboring wave field, due to excessive wave reflection or wave energy dissipation. To overcome such disadvantage, smooth wave energy control may be required. In this respect, many studies have been conducted on a horizontal plate with a relatively larger transmitted wave energy ratio (Tuck, 1975; Isaacson et al., 1998; Cho and Kim, 1998; Cho, 2002; Kee et al., 2006; Cho and Kim, 2013). Meanwhile, the hydrodynamic performance of a perforated horizontal porous plate was investigated by a series of analytical and numerical investigations (Liu, et al., 2007; Liu et al., 2008; Liu et al., 2013).

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It is considered possible for the submerged horizontal dual plate to control the transmitted wave height, thanks to the correlation between the incident wave length and the plate width. Kweon et al. (2005) proposed a permeable breakwater that uses a horizontal dual plate with a submerged depth as the wave energy dissipation plate, and named the structure a "steel-type breakwater" (STB). A series of related researches (Kweon et al., 2008; Kwon et al., 2011; Lee et al., 2011; Kweon et al., 2012) that followed verified the stability and functionality of the detached steel-type breakwater, using a horizontal porous dual plate with a submerged water depth as the dissipation material, through structural design methodology, and experimental verification in a real sea.

In particular, Kweon et al. (2011) proposed a method of estimating the vertical uplift force that acts on the horizontal plate, applicable to the design of the pile uplift drag force. Then, Kweon et al. (2012) confirmed the validity of the load estimation methodology suggested by Kweon et al. (2011), by measuring and analyzing the displacement of a steel-type breakwater that was installed in a real sea. However, the difference between the method proposed by Kweon et al. (2011), which estimates the wave force based on the maximum pressure at an individual point, under the action of a regular wave that corresponds to the significant design wave, and the wave force measured at a different time without a phase difference, have not yet been clearly compared. This research intends to verify a reasonable method of estimating the external design force that acts on the horizontal plate, by conducting a hydraulic model test.

Meanwhile, Goda (1974) proposed a wave pressure equation that acts on an unfolded caisson breakwater, based on the results of a number of hydraulic model tests and site observations. After its validity was proven from worldwide use, Goda's equation was accepted as the standard means of estimating the wave pressure that acts on the vertical breakwater walls, replacing Hiroi's equation (Hiroi, 1919). Goda's equation is based on quasi-static approaches to the wide ranges of wave pressure and force measurement data, and basically presents the maximum wave pressure at each point area that acts on a vertical breakwater wall, rather than the simultaneous pressure. Therefore, there are many cases in which the wave pressures acting on a vertical wall at a particular moment and a particular point area are much smaller, than those measured with Goda's pressure equation. In normal structural design, such as a caisson breakwater, the total wave force obtained by integration of Goda's pressure formula over the entire height of the vertical wall is conventionally considered as the external design force. In addition, Goda (1974) recommended use of the equation H_{max} = 1.8 $H_{1/3}$, when estimating the maximum pressure exerted by random wave. This study compares Goda's method with other methods of estimating the vertical wave pressure that acts on the horizontal area, and provides some detailed discussions on the results.

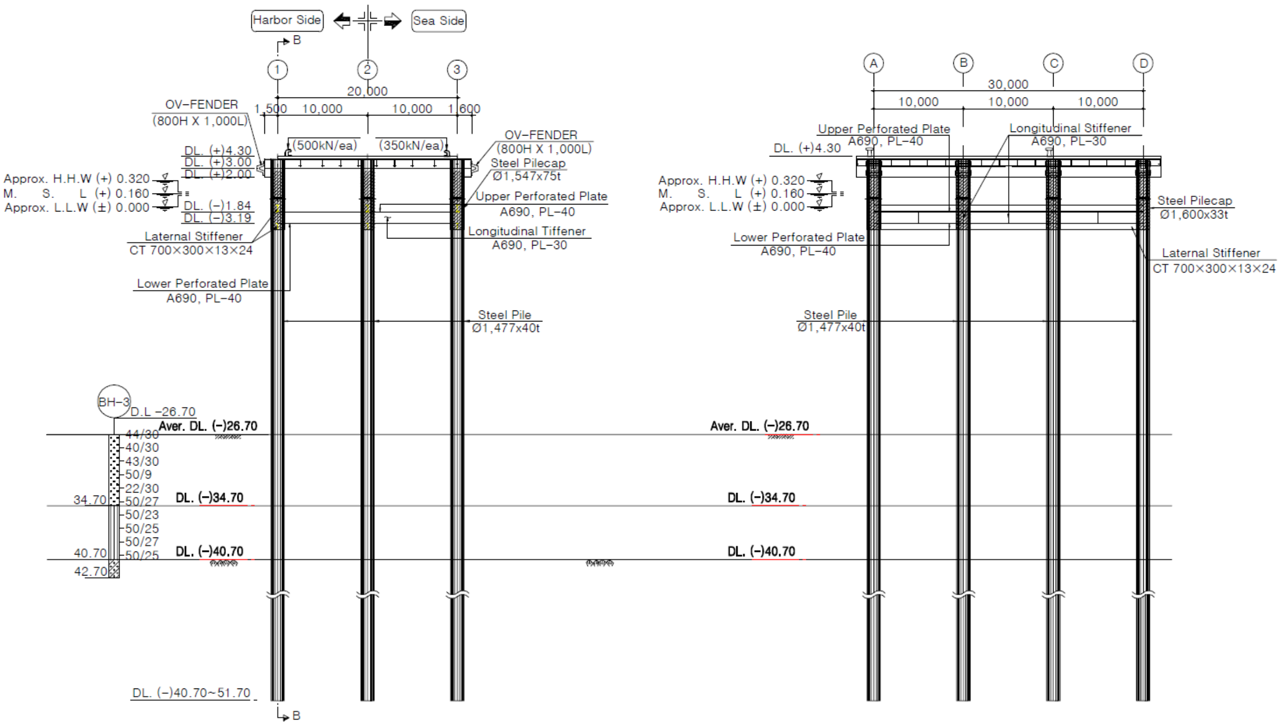
EXPERIMENTAL SETUP AND DATA ACQUISITION SYSTEM

A 1/25-scale model section was installed in a one-directional flume to measure the wave pressure, the wave pressures of the waves that passed the middle part of the wave maker were measured by point area. The experimental section was divided into three sections, by assembling the measurement subjects, i.e. the upper and lower plates, in the middle, to be independent of each other; and the wave pressures were simultaneously measured and monitored.

Design and manufacture of the model

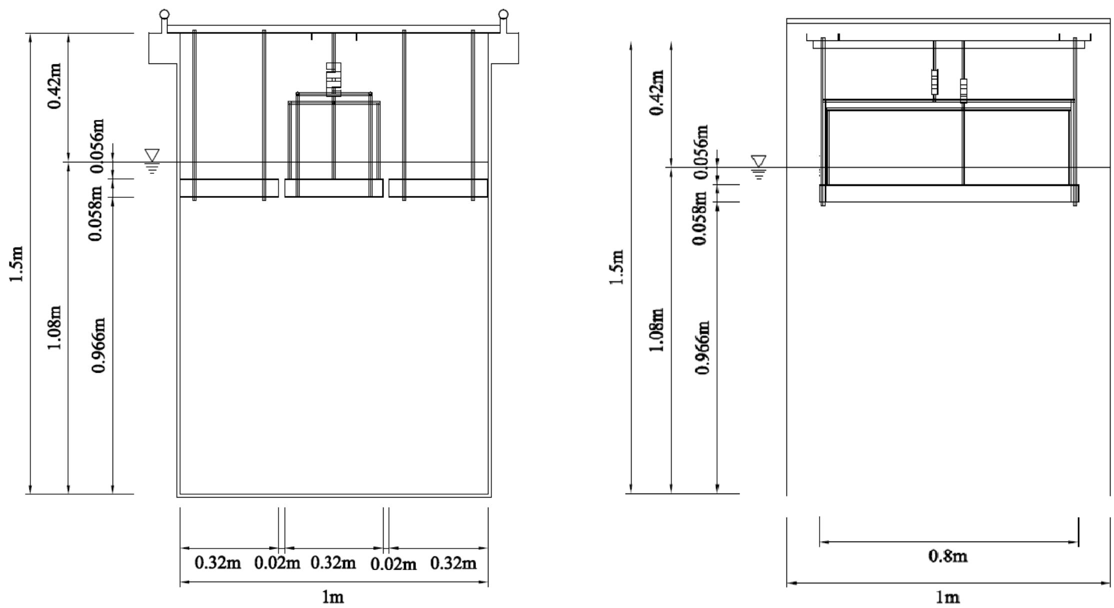
The test model was manufactured according to the design of D breakwater, composed of vertical piles and horizontal porous plates (see Fig. 1). The experimental setup of the model breakwater is presented in Fig. 2. The model scale was determined to be 1/25, considering the dimension of the wave flume and the wave maker capacity. The horizontal porous plate was made of steel, and divided into three sections in the transverse direction, as shown in Fig. 2(a). The gap between each of the three sections in the transverse direction was set to be 2 *cm*. The wave load and pressures were measured only at the middle plates among the three. The other two plates on both sides were used as dummy structures.

The model breakwater was connected by a support pole to the horizontal bar attached to the upper part of the wave flume, as shown in Fig. 2. The upper and lower porous plates were connected to the two load cells independently, through the support system. The support system for the upper and lower plates did not contact each other. In particular, the vertical pole holding the lower plate was designed to not touch the upper plate. In this manner, the wave load acting on the upper and lower plates could be measured independently. The middle plate was 0.8 *m* long, 0.32 *m* wide and its thickness was 2 *mm*. The diameter porous hole in the plates was 0.01 *m*. The total porosity of each plate was approximately 7%.



(a) Side view. (b) Front view.

Fig. 1 General design of the breakwater, composed of vertical piles and dual horizontal plates.



(a) Front view. (b) Side view.

Fig. 2 Experimental setup for the physical experiment.

Experimental equipment and measurement system

The hydraulic model test was conducted in a two-dimensional wave flume of 60.0 *m* length, 1.5 *m* height and 1.0 *m* width. The wave flume produces waves with a piston-type wave paddle that is operated by a hydraulic pump. Wave absorbers were placed at the back of the wave paddle, as well as the other end of the flume. The stroke of the wave paddle was precisely controlled, using a DC motor and a screw. The model breakwater was installed at 22.5 *m* from the wave paddle. Fig. 3 shows a schematic of the wave flume, and the arrangement of the experimental model.

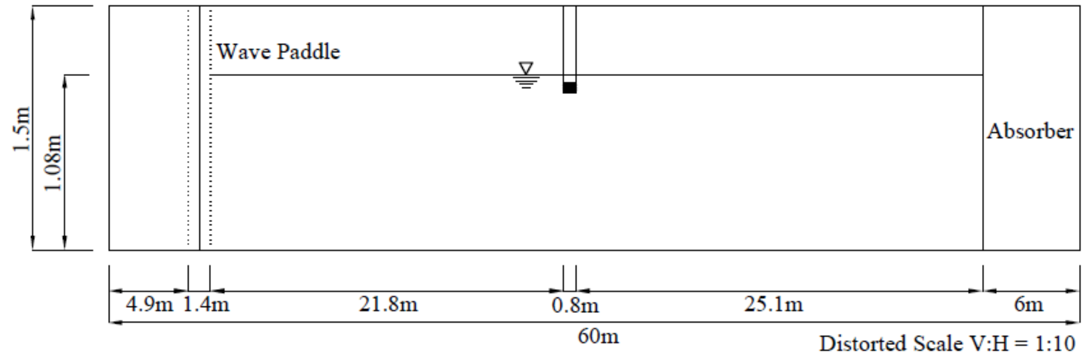
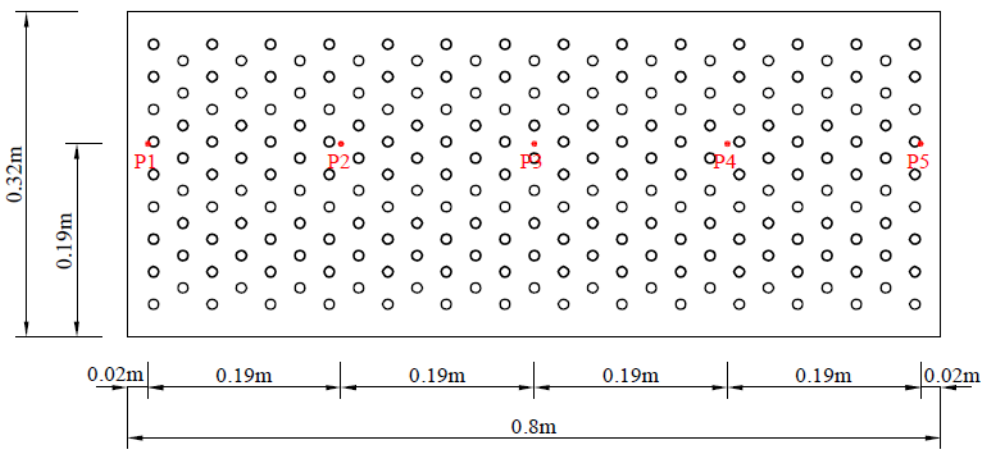
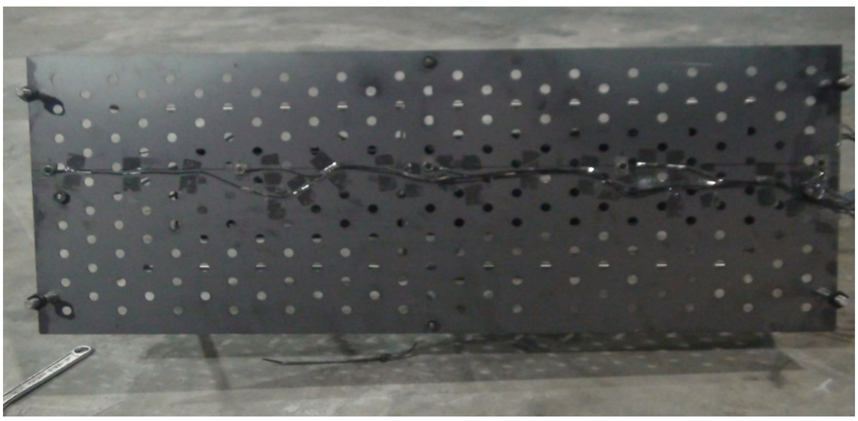


Fig. 3 Schematic of the wave flume and arrangement of the model.

Adhesion-type pressure gauges manufactured by SSK Co. Japan were used in the experiment. The capacity of these pressure gauges was 10 *g/cm*^{2}. Five pressure gauges were attached to the upper and lower surfaces of two horizontal plates, respectively, at even intervals, as shown in Fig. 4. They were aligned in the wave propergating direction, the first gauge being placed 2 *cm* from one edge of the plate, and the rest at 19 *cm* intervals each other. The pressure gauges were fixed to the plate using a high-quality double-sided adhesive tape. Fig. 5 shows the total layout of the 20 pressure gauges that were used for the measurement. The measured values of the pressure gauges attached to the upper side of the horizontal plate (p01-05 and p11-15) were designated as positive (+) sign, while those to the lower side (p06-10 and p16-20) as negative (-) sign.



(a) Positions of the five pressure gauges.



(b) Photograph of the five pressure gauges.

Fig. 4 Placement of the pressure gauges on the horizontal plate.

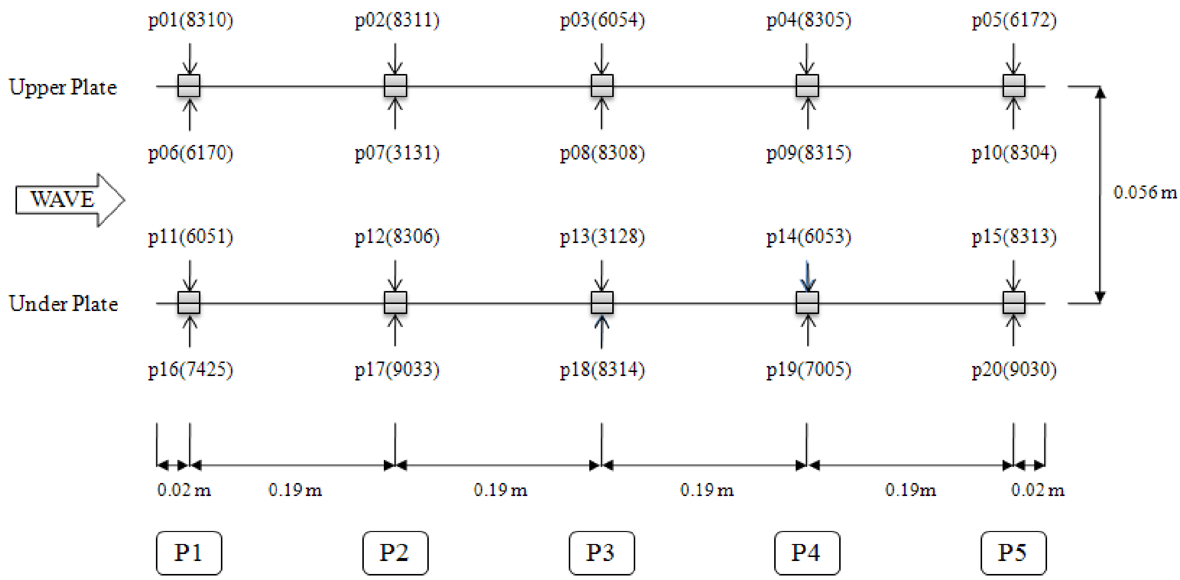
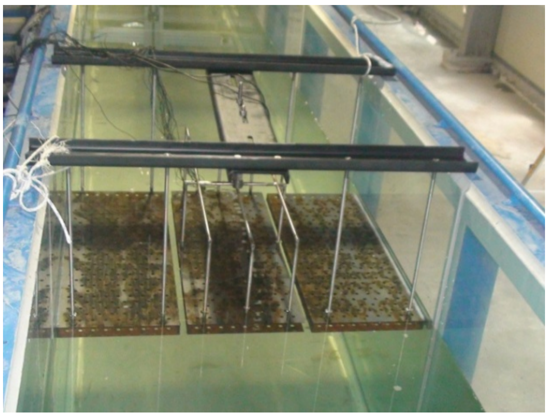


Fig. 5 Arrangement of the 20 pressure gauges on the upper and lower plates.

In order to verify and enhance the accuracy of the wave pressure measurement, the wave forces acting on the horizontal plates were simultaneously measured by load cells connected to the support system. Fig. 6 shows photographs of the supporting bars holding horizontal plates and the load cells, which were connected to the support system at the upper part of the wave flume. Meanwhile, the measurement data obtained from the pressure gauges and load cells were collected using a data acquisition system, transferred to a notebook PC through a USB cable, and saved on hard disc. The wave pressure signals were monitored in real time during the experiment, using data acquisition software.

(a) Top angle.



(b) Bottom angle.

Fig. 6 Framework for the measurement of wave pressure and force.

Test wave

The incident waves for the experiment were selected so that the wave steepness (s) would be 0.01, 0.02 and 0.03, considering the design wave period. In general, the wind wave has engineering significances when the wave steepness is within the range of 0.02~0.04. However, the case of wave steepness of 0.04 was not conducted, because it went over the limit of the wave maker stroke capacity. As the experiment was conducted to compare the pressure estimation method proposed by Kweon et al. (2011) with other methods, both regular and random waves were used in the experiment, as shown in Table 1. The maximum wave height was set to be 0.350 m. The wave heights of regular waves were selected, so as to correspond to the significant wave heights of random waves.

Table 1 Experimental wave conditions.

Condition		Water depth	Wave period	Wave height	Wave-length	Shoaling coefficient	Equivalent deep water wave height	Deep water wave-length	Wave steepness
		h (m)	T (s)	$H_{1/3}$ (m)	L (m)	K_s	H_0' (m)	L_0 (m)	$s(H_0'/L_0)$
Regular wave	Case 1_reg	1.08	2.72	0.108	7.98	0.94	0.115	11.54	0.01
	Case 2_reg	1.08	2.72	0.217	7.98	0.94	0.231	11.54	0.02
	Case 3_reg	1.08	2.72	0.350	7.98	0.94	0.373	11.54	0.03
	Case 4_reg	1.08	2.78	0.114	8.19	0.94	0.121	12.06	0.01
	Case 5_reg	1.08	2.78	0.227	8.19	0.94	0.241	12.06	0.02
	Case 6_reg	1.08	2.78	0.350	8.19	0.94	0.371	12.06	0.03
Random wave	Case 1_ran	1.08	2.72	0.108	7.98	0.94	0.115	11.54	0.01
	Case 2_ran	1.08	2.72	0.217	7.98	0.94	0.231	11.54	0.02
	Case 4_ran	1.08	2.78	0.114	8.19	0.94	0.121	12.06	0.01
	Case 5_ran	1.08	2.78	0.227	8.19	0.94	0.241	12.06	0.02

ANALYSIS METHODS AND RESULTS

The methods with regular waves and random waves were analyzed, and compared with the wave force estimation method proposed by Kweon et al. (2011), using the maximum wave pressure at the point areas produced by the regular wave that co-rresponded to the significant wave. The incident waves for the experiment were selected so that the wave steepness (s) would be 0.01, 0.02 and 0.03, considering the design wave period.

Analysis methods

To calculate the total wave force acting on the horizontal plate, three different methods were used, considering differences in wave pressure distribution along the plate. In the first method, the maximum wave forces were calculated from the instantaneous pressure distributions obtained at exactly the same time. In the second method, the total wave forces were calculated based on the wave pressure distributions with consistent wave phases, but at different times. In the third method, the total wave forces were estimated from the maximum pressure distributions, irrespective of the influence of the wave phases, as well as acting time. For all the three methods, the difference in wave pressure between the upper and lower sides of the horizontal plate was calculated, and used for estimating the net wave force acting on the plate. The analysis methods according to the aforementioned three types of wave distributions are referred to as methods A, B and C, respectively. The mathematical equations corresponding to the three methods are presented in the following:

$$F^*_{1st} = \max\left\{ \begin{array}{l} \sum[(p_{01}^t - p_{06}^t)\Delta w, (p_{02}^t - p_{07}^t)\Delta w, (p_{03}^t - p_{08}^t)\Delta w, (p_{04}^t - p_{09}^t)\Delta w, \\ (p_{06}^t - p_{10}^t)\Delta w, (p_{11}^t - p_{16}^t)\Delta w, (p_{12}^t - p_{17}^t)\Delta w, (p_{13}^t - p_{18}^t)\Delta w, \\ (p_{14}^t - p_{19}^t)\Delta w, (p_{15}^t - p_{20}^t)\Delta w] \end{array} \right\}_{t=tstart}^{t=tfinal} \tag{1}$$

$$\begin{aligned} F^*_{2nd} = \sum[&\max(p_{01} - p_{06})^{t_{01}}\Delta w, \max(p_{02} - p_{07})^{t_{02}}\Delta w, \max(p_{03} - p_{08})^{t_{03}}\Delta w, \max(p_{04} - p_{09})^{t_{04}}\Delta w, \\ &\max(p_{06} - p_{10})^{t_{05}}\Delta w, \max(p_{11} - p_{16})^{t_{11}}\Delta w, \max(p_{12} - p_{17})^{t_{12}}\Delta w, \max(p_{13} - p_{18})^{t_{13}}\Delta w, \\ &\max(p_{14} - p_{19})^{t_{14}}\Delta w, \max(p_{15} - p_{20})^{t_{15}}\Delta w] \end{aligned} \tag{2}$$

$$F^*_{3rd(+)} = \sum[\max(p_{01})^{t_{01}}\Delta w, \max(p_{02})^{t_{02}}\Delta w, \max(p_{03})^{t_{03}}\Delta w, \max(p_{04})^{t_{04}}\Delta w, \max(p_{05})^{t_{05}}\Delta w, \max(p_{11})^{t_{11}}\Delta w, \max(p_{12})^{t_{12}}\Delta w, \max(p_{13})^{t_{13}}\Delta w, \max(p_{14})^{t_{14}}\Delta w, \max(p_{15})^{t_{15}}\Delta w] \tag{3}$$

$$F^*_{3rd(-)} = \sum[\max(p_{06})^{t_{01}}\Delta w, \max(p_{07})^{t_{02}}\Delta w, \max(p_{08})^{t_{03}}\Delta w, \max(p_{09})^{t_{04}}\Delta w, \max(p_{10})^{t_{05}}\Delta w, \max(p_{16})^{t_{11}}\Delta w, \max(p_{17})^{t_{12}}\Delta w, \max(p_{18})^{t_{13}}\Delta w, \max(p_{19})^{t_{14}}\Delta w, \max(p_{20})^{t_{15}}\Delta w] \tag{4}$$

where, F^* refers to the wave force per unit length (*m*) in the transverse direction for the length of horizontal plate (L = 0.8 *m*); $\sum[\,]$ the summation of all the quantities in []; max ( ) the maximum of the variables in ( ); p_i the wave pressure measured from the gauge numbered as i, as shown in Fig. 5; and t_i the time instant corresponding to the pressure gauge p_i. The quantity Δw refers to the length in charge of each pressure gauge, being 0.115 *m* for the pressure gauges at both ends, and 0.19 *m* for the remainder of the gauges in the middle.

By the first analysis method (F^*_{1st}), the total wave force was calculated, based on the wave pressure distribution at a certain particular time (t_0). Meanwhile, the second method according to Equation (2) corresponds to the pressure formula of Goda (1974) that is applied to the horizontal plate. That is, the equation produces the maximum wave force, from the difference in vertical pressures between the upper and lower plates, measured at different times. This can be understood as the same concept as the maximum wave pressure of Goda (1974), which is based on the difference in horizontal pressures between the front and back of the vertical wall, measured at different times.

Results of the wave pressure analysis

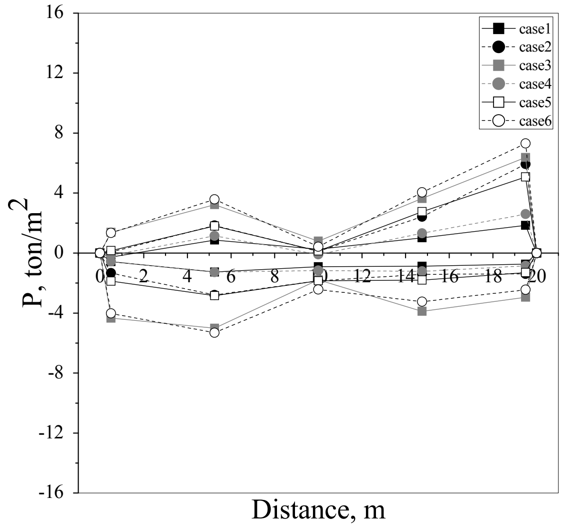
The wave pressures measured in the experiment were converted to values corresponding to the real sea. Fig. 7 shows wave pressure distributions along the horizontal plate, where positive (+) value represents downward pressure, whereas negative (-) depicts uplift force. The figure shows that the magnitudes of the wave pressure were different, according to the measurement point. In addition, pressures of the random waves were generally larger than those of the regular waves having similar wave height. The magnitude of wave pressures were larger sequentially, with the order of analysis method A, B and C. When method A was used in the analysis, the maximum pressure was measured at the most downstream pressure gauge. The difference in pressure magnitude between the regular and random wave was relatively small by this method. This implies that the differences in pressure distribution between the regular and random waves were insignificant, if the wave pressures on the upper and lower sides of the horizontal plate were taken into account together. In contrast, the apparent pressure difference between the results of regular and random waves was shown, when method C was applied in the analysis, as clearly seen in Figs. 7(e) and (f). This indicates that significant difference in pressure distribution might be obtained between the regular and random waves, if only the wave pressures acting on either one of the upper or lower side of the horizontal plate are considered. One noteworthy thing in Fig. 7 is that the pressure magnitude in Fig. 7(d), corresponding to the random wave result by Goda's method (1974), is rather smaller than that in Fig. 7(e), corresponding to the regular wave result by the method presented in Kweon et al. (2011).

Safety factor of the pile uplift force

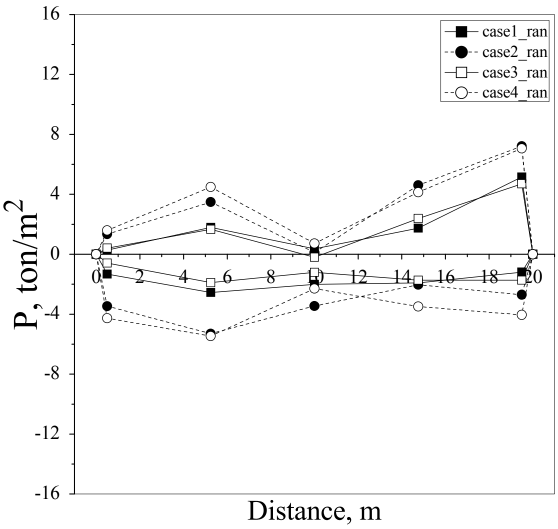
The external design force that was applied on the pile against the uplift or pullout force can be estimated as follows:

$$F_V = \alpha_s R_f \tag{5}$$

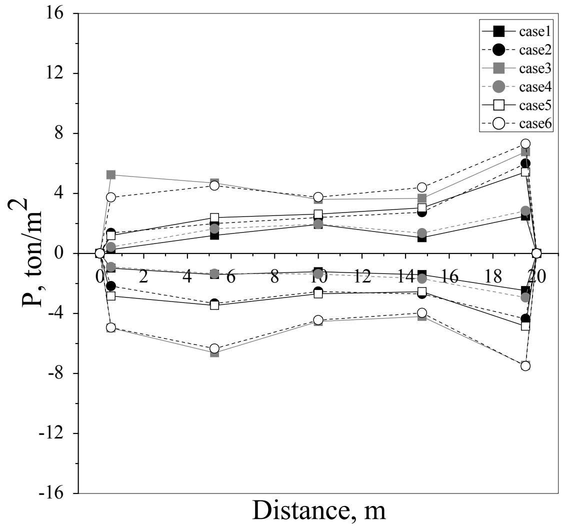
where, F_V is the design uplift force; α_s the safety factor against pile pullout (> 1.0); and R_f the uplift resistance of the pile. With respect to the design of a steel-type offshore breakwater, Kweon et al. (2012) proposed a safety factor of 2.0 against the uplift force acting on piles. Since the method C mentioned above corresponded to the concept of wave force estimation by Kweon et al. (2012), the safety factor for the pile uplift force by method C can be assumed to be 2.0.



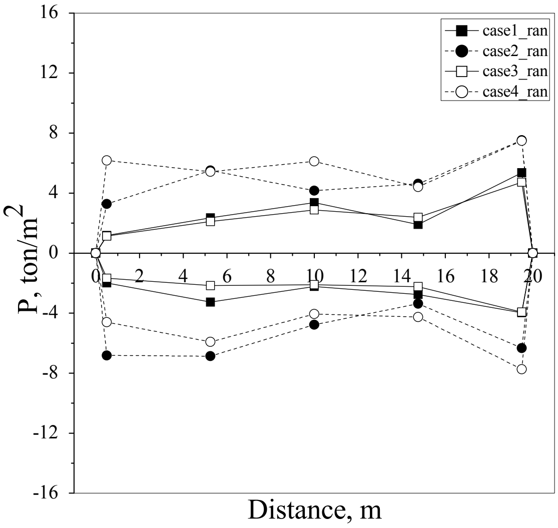
(a) Results of method A for regular test waves.



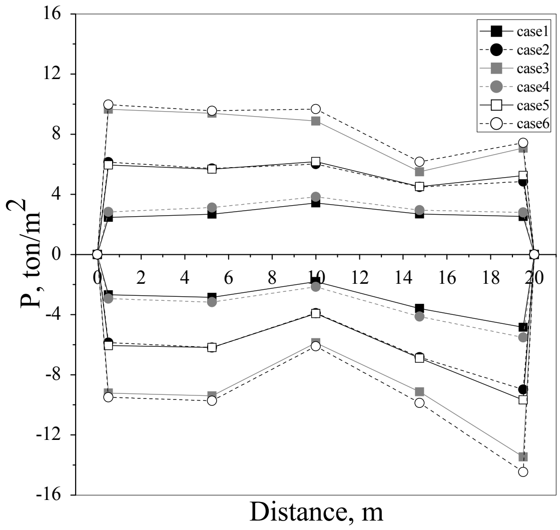
(b) Results of method A for random test waves.



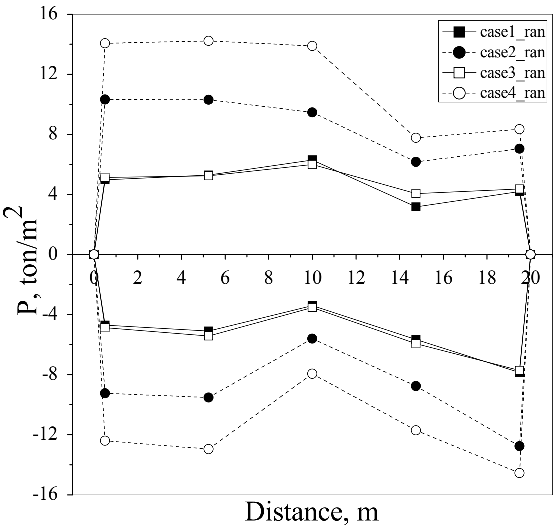
(c) Results of method B for regular test waves.



(d) Results of method B for random test waves.



(e) Results of method C for regular test waves.



(f) Results of method C for random test waves.

Fig. 7 Wave pressure distribution along the porous plate.

In order to calculate and compare the safety factors by the other two methods, the unit wave force acting upward on the horizontal plate was obtained by integrating the pressure distributions along the plate shown in Fig. 7. Then, the integrated wave forces by the two methods were divided by the corresponding value for the regular wave case, calculated by method C. Finally, the divided values were multiplied by two, for easy comparison. Tables 2 and 3 show the thus obtained safety factors for the regular and random wave cases, respectively. The safety factors shown in the two tables can be interpreted as relative factors, compared to the proposed value of 2.0, by the method shown in Kweon et al. (2011).

Table 2 Comparison of the uplift forces and safety factors (regular wave case).

	Method A		Method B		Method C	
Test condition	Unit force	S.F.	Unit force	S.F.	Unit force	S.F.
	tf/m	α_s	tf/m	α_s	tf/m	α_s
Case 1	-18.0	0.61	-28.2	0.96	-58.9	2.00
Case 2	-36.0	0.60	-57.9	0.97	-119.2	2.00
Case 3	-69.8	0.80	-105.6	1.20	-175.5	2.00
Case 4	-21.0	0.63	-30.9	0.92	-67.1	2.00
Case 5	-39.2	0.64	-61.5	1.01	-122.1	2.00
Case 6	-69.1	0.75	-102.8	1.11	-185.0	2.00

Table 3 Comparison of the uplift forces and safety factors (random wave case).

	Method A		Method B		Method C	
Test condition	Unit force	S.F.	Unit force	S.F.	Unit force	S.F.
	tf/m	α_s	tf/m	α_s	tf/m	α_s
Case 1	-37.3	1.27	-54.8	1.86	-100.2	3.40
Case 2	-67.4	1.13	-105.7	1.77	-171.2	2.87
Case 3	-29.1	0.87	-45.6	1.36	-103.8	3.09
Case 4	-75.3	1.23	-100.0	1.64	-226.0	3.70

As shown in Table 3, safety factors by method C for the random wave case were only larger than those corresponding to Kweon et al. (2011). In the other four cases, the estimated factors were smaller than 2.0. The average safety factor according to method A for the random wave case was approximately 1.0, almost half of the results by Kweon et al. (2011). In particular, the safety factors estimated by method B, corresponding to Goda's formula, were comparable, but still smaller than 2.0. Although the design uplift force can be satisfactorily estimated by using Goda's formula, the method proposed by Kweon et al. (2011) might be more convenient to use, as it is based on the pressure distribution obtained from regular wave action.

Fig. 8 shows the values of safety factor for the wave load acting on unit length, calculated by the above methods, respectively. As shown in the figure, the safety factor due to method C for the random wave case was 3.0, which is greater than the method of Kweon et al. (2011). Meanwhile, the value was smaller for all the other four methods. In particular, it was only 1.0 on average, when estimated by the method A for random waves, where wave loadings are acting at the same time. The method B for random waves, corresponding to the case applying Goda's method to the horizontal plate, also yields a smaller safety factor than 2.0.

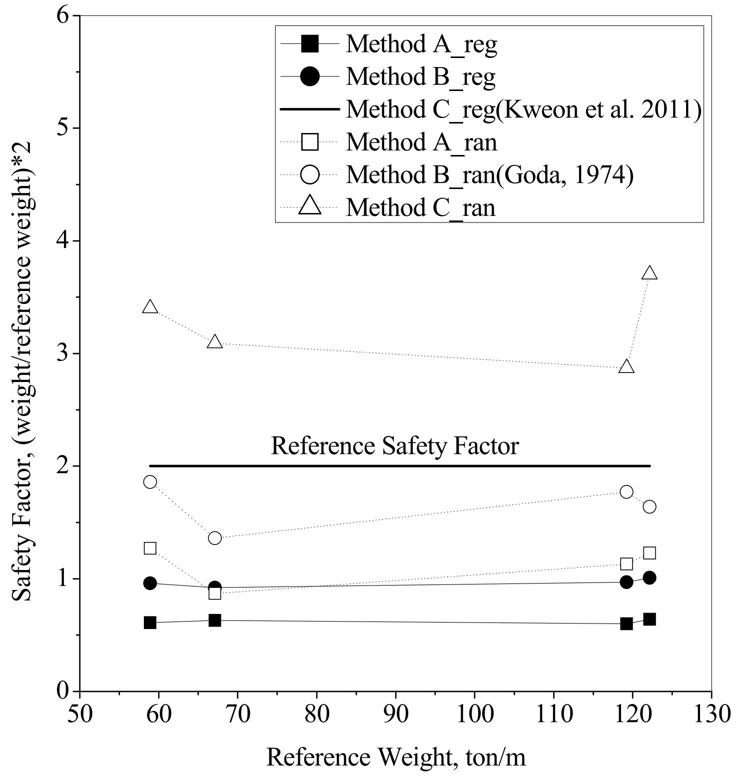


Fig. 8 Estimation of the safety factor of the uplift load acting on the pile.

CONCLUSION

The steel-type offshore breakwater that is supported by vertical piles and dual horizontal plates should be designed safely against the uplift force acting on the plates. Kweon et al. (2011) proposed a method for estimating the design uplift force, based on the regular wave corresponding to the design significant wave. This method was verified by real sea experiment, as reported in Kweon et al. (2012), which demonstrated that the safety factor of 2.0 could be satisfactorily used, by restricting the possible pile displacement within some allowable limit. However, this method has not been clearly compared with the conventional design methods, particularly with the well-known pressure equation proposed by Goda (1974). In order to further investigate this imperfection, a hydraulic model test was conducted in this study, by measuring the wave pressures acting on the horizontal plates. By estimating the wave forces using three different analysis methods, and comparing the relative safety factors for the pile uplift force, according to the use of the different methods, the following conclusions were obtained.

(1) The safety factor of the pile uplift force estimated from the randomly varying wave pressure acting at the same time was estimated to be approximately 1.0, on average.

(2) The safety factor of the pile uplift force estimated by Goda's pressure estimation method was smaller than 2.0, on average. Use of Goda's method might underestimate the uplift force, as the corresponding safety factor is found to be smaller than that estimated from the real sea experiment of Kweon et al. (2012). This study applied Goda's concept for the vertical barrier to the horizontal one.

(3) The safety factor estimated by method C for random waves was approximately 3.0 on average, so that this method might overestimate the pile uplift force.

(4) The methodology of estimating wave force based on the maximum upward pressure of the regular wave corresponding to the significant design wave, suggested by Kweon et al. (2011), seems to be used as a reasonable design method, for estimating the pile uplift force acting on the steel-type offshore breakwater. This method has the advantage of using the regular wave, in estimating the design uplift force.

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