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Wave Reflection from Partialy Perforated Caisson Breakwater
部分 有孔 케이슨 防波堤로부터의 波의 反射

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Abstract□The Suh and Park's analytical model, originally developed to calculate wave reflection from a conventional fully perforated caisson breakwater, is applied to a partially perforated caisson breakwater by approximating the vertical wall of the lower part of the front face of the caisson as a very steep sloping wall. ɹlso, in the model, the inertial resistance term at the perforated wall is modified by using the blockage coefficient proposed by Kakuno and Liu. The model is compared against the hydraulic experimental data reported by Park *et al.* in 1993. Both the experimental data and the analytical model results show that the influence of inertial resistance is important so that wave reflection becomes minimum when B/L_c is approximately 0.2 (in which B = wave chamber width, and L_c = wave length inside the wave chamber), which is somewhat smaller than the theoretical value $B/L_c = 0.25$ obtained by assuming that the influence of inertial resistance is negligible. It is also shown that the analytical model based on a linear wave theory tends to overpredict the reflection coefficient as the wave nonlinearity increases, thus the model is preferably to be used for ordinary waves of small steepness.

要 旨 : 기존의 全有孔 케이슨 방파제로부터의 파 반사를 계산하기 위하여 개발된 Suh and Park의 이론 모형을, 케이슨 전면 하부의 연직벽을 경사가 매우 급한 경사벽으로 가정함으로써, 부분 유공 케이슨 방파제에 적용하였다. 또한, 이 모형에서, Kakuno and Liu가 제안한 遮斷係數를 이용하여 有孔壁에서의 慣性抵抗項을 수정하였다. 이 모형을 1993년도에 보고된 Park et al.의 수리실험 자료와 비교해 본 결과, 실험 자료 및 이론 모형 결과에서 모두 관성저항의 영향이 중요하여 B/L_c가 약 0.2일 때 반사율이 최소가 됨을 보이는데 (여기서 B = 遊水室의 幅, L_c = 유수실 내에서의 파장), 이 값은 관성저항의 영향을 무시했을 때 얻어지는 값 0.25보다 약간 작은 값이다. 또한 線形波 이론에 근거한 이 모형은 파의 非線形性이 증가함에 따라 반사율을 크게 계산하는 경향이 있음을 보이며, 따라서 이 모형은 波形傾斜가 작은 通常波에 적용하는 것이 바람직함을 알 수 있었다.

1. INTRODUCTION

Since Jarlan (1961) introduced the concept of a perforated caisson breakwater, numerous theoretical or experimental studies have been performed to investigate its hydraulic and hydrodynamic characteristics. A perforated caisson breakwater has a number of desirable features that have encouraged its use within harbors. It reduces not only wave reflection but also wave transmission due to overtopping. It also reduces wave force, especially impulsive wave pressure acting on the caisson [see Takahashi and Shimosako (1994) and Takahashi *et al.* (1994)]. A conventional perforated caisson breakwater for which the water depth inside the wave chamber is the same as that on the mound berm as shown in Fig. 1(a) consists of a front wave chamber and a back solid caisson so that the weight of the caisson is less than that of a vertical solid caisson with the same width, and moreover the weight is concentrated on the rear side of the caisson. Therefore

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sometimes difficulties are met in the design of a perforated caisson so as to satisfy the design criteria against sliding and overturning within limited dimensions of the caisson. In addition, in the case where the bearing capacity of sea bottom is not large enough, the excessive weight on the rear side of the caisson gives an adverse effect. In order to solve these problems in part, a partially perforated caisson as shown in Fig. 1(b) is often used, which provides an additional weight to the front side of the caisson. In this case, however, other hydraulic characteristics of the caisson such as wave reflection and overtopping may become deteriorated compared with a conventional fully perforated caisson.

In order to examine the reflection characteristics of a perforated caisson breakwater, hydraulic model tests have been used [Jarlan (1961), Marks and Jarlan (1968), Terret *et al.* (1968), Tanimoto *et al.* (1976), Bennett *et al.* (1992), and Park *et al.* (1993) among others]. Efforts towards developing analytical models for predicting the reflection coefficient have also been made. Based upon linearized shallow water wave theory, Kondo (1979) developed an analytical model for calculating reflection coefficient of a perforated caisson having one or two wave chambers. Using the method of matched asymptotic expansions, Kakuno *et al.* (1992) developed an analytical model for predicting wave reflection from a single-chamber perforated caisson. A similar model and comparisons with large-scale laboratory data were given by Bennett *et al.* (1992). On the other hand, Fugazza and Natale (1992) proposed a closed-form solution for wave reflection from a multi-chamber perforated caisson. The aforementioned analytical approaches deal with the case in which the waves are normally incident to the perforated caisson lying on a flat sea bottom. Recently, based on the extended refraction-diffraction equation proposed by Massel (1993), Suh and Park (1995) developed an analytical model that can predict the wave reflection from a single-chamber perforated caisson mounted on a rubble mound foundation when waves are obliquely incident to the breakwater at an arbitrary angle.

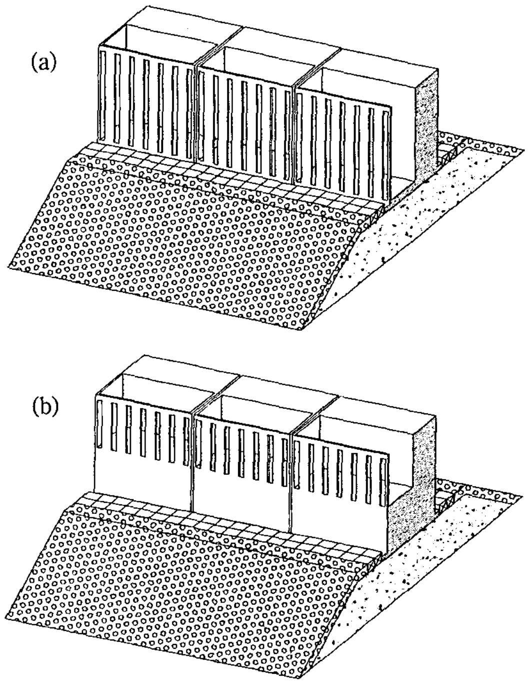

Fig. 1. Bird's-eye views of a conventional perforated caisson breakwater (a) and a partially perforated caisson breakwater (b).

Recently Park *et al.* (1993) reported a laboratory experiment of wave reflection from a partially perforated caisson mounted on a rubble mound foundation. In the present paper, the experimental data of Park *et al.* are compared with the Suh and Park's (1995) analytical model results. The Suh and Park's model, originally developed for a fully perforated caisson breakwater, is used for a partially perforated caisson breakwater by assuming that the lower part of the front face of the caisson (which is vertical in reality) is not vertical but has a very steep slope. Also, in the model, the inertial resistance term at the perforated wall is modified by using the blockage coefficient proposed by Kakuno and Liu (1993). In the following section, the Suh and Park's (1995) analytical model is summarized. The next section provides a brief summary of the Park *et al.*'s (1993) laboratory experiment and the experimental results are re-investigated considering the influence of inertial resistance at the perforated wall. The model is then compared against the experimental data, and major conclusions follow.

2. ANALYTICAL MODEL

Based on the extended refraction-diffraction equation proposed by Massel (1993), Suh and Park (1995) recently developed an analytical model to calculate the reflection coefficient of a conventional perforated caisson [see Fig. 1(a)] mounted on a rubble mound when waves are obliquely incident to the breakwater at an arbitrary angle. The x-axis and y-axis are taken to be normal and parallel, respectively, to the breakwater crest line, and the water depth is assumed to be constant in the y-direction. Taking $x=0$ at the perforated wall, $x=-b$ at the toe of the rubble mound, and $x=B$ at the back wall of the wave chamber, Suh and Park (1995) showed that the function $\tilde{\phi}(x)$ [see Suh and Park (1995) for its definition] on the rubble mound ($-b \leq x \leq 0$) satisfies the following ordinary differential equation:

$$\frac{d^2\tilde{\phi}}{dx^2}+D(x)\frac{d\tilde{\phi}}{dx}+E(x)\tilde{\phi}=0 \tag{1}$$

with the boundary conditions as follows:

$$\frac{d\tilde{\phi}(-b)}{dx}=i[2-\tilde{\phi}(-b)]k_1\cos\theta_1 \tag{2}$$

$$\tilde{\phi}(0)=\left[\frac{1}{\beta_3}\frac{\exp(-\beta_3 B)+\exp(\beta_3 B)}{\exp(-\beta_3 B)-\exp(\beta_3 B)}-\ell-\frac{i\gamma}{\omega}\right]\frac{d\tilde{\phi}(0)}{dx} \tag{3}$$

The subscripts 1 and 3 denote the area of flat sea bottom ($x \leq -b$) and inside of the wave chamber ($0 \leq x \leq B$), respectively, and θ is the wave incident angle. In (1) the depth-dependent functions $D(x)$ and $E(x)$ are given by

$$D(x)=\frac{G(kh)}{h}\frac{dh}{dx} \tag{4}$$

$$E(x)=k^2+\frac{(kh)^2}{ph^2}\left[R_1\left(\frac{dh}{dx}\right)^2+R_2\frac{d^2h/dx^2}{\lambda}\right]-\chi^2 \tag{5}$$

in which k is the wave number which is related to the water depth h, wave angular frequency ω, and gravity g by the dispersion relationship $\omega^2=gk(\tanh kh)$; $\lambda=\omega^2/g$; $\chi=k_1\sin\theta_1$ $(=k_3\sin\theta_3)$; and

$$p=\frac{1}{2}\left(1+\frac{2kh}{\sinh 2kh}\right) \tag{6}$$

$$G(kh)=\frac{kh}{\tau+kh(1-\tau^2)}\left[1-3\tau^2+\frac{2\tau}{\tau+kh(1-\tau^2)}\right] \tag{7}$$

in which $\tau=\tanh(kh)$. R_1 and R_2 are given by

$$R_1=\frac{1}{\cosh^2(kh)}(W_1I_1+W_2I_2+W_3I_3+W_4I_4+W_5I_5+W_6) \tag{8}$$

and

$$R_2=\frac{1}{\cosh^2(kh)}(U_1I_1+U_2I_2+U_3I_3) \tag{9}$$

The expressions for W_n, U_n and I_n are given in the paper of Suh and Park (1995). As can be seen in (5), the model equation includes the terms proportional to the square of bottom slope and to the bottom curvature which were neglected in the mild-slope equation so that it can be applied over a bed having substantial variations of water depth.

In (2) and (3), $i=\sqrt{-1}$; $\beta_3=ik_3\cos\theta_3$; $\ell=$ length of the jet flowing through the pergorated wall; and $\gamma=$ linearized dissipation coefficient at the perforated wall, given by Fugazza and Natale (1992) as

$$\gamma=\frac{8\alpha}{9\pi}H_w\,\omega\frac{W}{\sqrt{W^2(R+1)^2+C^2}}\frac{5+\cosh 2k_3h_3}{2k_3h_3+\sinh 2k_3h_3} \tag{10}$$

in which $H_w=$ incident wave height at the perforated wall; $W=\tan(k_3B)$; $R=\gamma k_3/\omega$; $C=1-PW$; $P=\ell k_3$; $r=$ porosity of the wall; and

$$\alpha=\left(\frac{1}{r\cos\theta_3 C_c}\right)^2-1 \tag{11}$$

is the energy loss coefficient at the perforated wall, which is a modification of the head loss coefficient for the plate orifice formula [see Mei (1983) p. 257].

In the preceding equation, $r\cos\theta_3$ denotes the effective ratio of the opening of the porous wall taking into account the oblique incidence of the waves to the wall. For normal incidence, this reduces to r as in Fugazza and Natale (1992). C_c is the empirical discharge coefficient at the perforated wall. Hattori (1972) concluded that the discharge coefficient ranged from 0.4 to 0.75 and Fugazza and Natale (1992) showed that the use of $C_c = 0.55$ provided good agreement with experimental data for perforated breakwaters. Rearranging of (10) gives a quartic polynomial of γ, which can be solved by the eigenvalue method [see Press *et al.* (1992) p. 368].

The differential equation (1) with the boundary conditions (2) and (3) can be solved using the finite-difference method. Using the forward-differencing for $d\tilde{\phi}(-b)/dx$, backward-differencing for $d\tilde{\phi}(0)/dx$, and central-differencing for the derivatives in (1), the boundary value problem (1) to (3) is approximated by a system of linear equations, $\mathbf{AY} = \mathbf{B}$, where $\mathbf{A}$ is a tridiagonal band type matrix, $\mathbf{Y}$ is a column vector, and $\mathbf{B}$ is also a column vector. After solving this matrix equation, the reflection coefficient K_r is calculated by

$$K_r = \mathrm{Re}\ \{\tilde{\phi}(-b) - 1\} \tag{12}$$

in which the symbol Re represents the real part of a complex value.

In the calculation of the dissipation coefficient, γ, in (10), the incident wave height at the porous wall, H_w, is a priori unknown. In the case where the caisson does not exist and the water depth is constant as h_3 for $x \geq 0$, Massel (1993) has shown that the transmitting boundary condition at $x = 0$ is given by

$$i\tilde{\phi}(0)k_3\cos\theta_3 = \frac{d\tilde{\phi}(0)}{dx} \tag{13}$$

The governing equation (1) and the upwave boundary condition (2) do not change. After solving this problem, the transmission coefficient K_t is given by $K_t = \mathrm{Re}\{\tilde{\phi}(0)\}$, from which H_w is calculated as K_t times the incident wave height on the flat bottom.

3. LABORATORY EXPERIMENT

3.1 Experimental Apparatus

Experiments were carried out in the wave flume in the Coastal Engineering Division at the Korea Ocean Research and Development Institute. The flume is 53.15 m long, 1 m wide, and 1.25 m high. It is equipped with a piston-type wavemaker at one end and a wave absorbing beach at the other end. The wave generation and data acquisition are controlled by an IBM 386 PC. Water surface displacement was measured with resistance-type wave gauges.

3.2 Breakwater Model

A composite breakwater with a partialy perforated caisson was used in the experiment. Fig. 2 shows an example of the breakwater model with a wave chamber of 20 cm width. The mound was constructed with crushed stones of 0.12 to 0.24 cm^3 class and it was covered by 3 cm thick armor stones of 5.6 cm^3 class as shown in Fig. 2. Two rows of concrete blocks of 3 cm thickness were put at the front and back of the caisson. The total height of the mound was 24 cm with 1:2 fore and back slopes, and the berm width of the mound was taken as 25 cm. The model caisson was made of transparent acrylic plates of 10 mm thickness. Park *et al.* (1993) used three different types of perforated walls; vertical slits, horizontal slits, and circular holes. They found that the difference of the reflection coefficients of different types of perforated walls is small. In this study, only the data of the vertical slit wall are used, which contained vertical slits of 2 cm width and 27 cm height with 4 cm separation between each slit so that the opening ratio was 0.33. The breakwater was installed at a

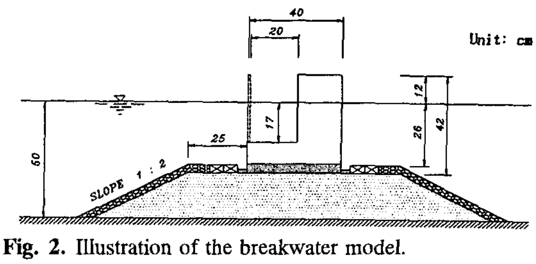

Fig. 2. Illustration of the breakwater model.

distance of about 30 m from the wavemaker.

3.3 Test Conditions

The water depths on the flat bottom and inside the wave chamber were 50 and 17 cm, respectively, throughout the experiment. The crest elevation of the caisson was 12 cm above the still water level, which did not permit wave overtopping for all the tests made in the experiment. Regular waves were generated. The wave period was changed from 0.7 to 1.8 s at the intervals of 0.1 s, and two different wave heights of 5 and 10 cm were used for each wave period, except 0.7 and 0.8 s wave periods for which only 5 cm wave height was used. Three different wave chamber widths of 15, 20, and 25 cm were used. This resulted in a total of 66 cases ($2\times3+10\times2\times3$). The test conditions and the measured reflection coefficients are presented in Table 1.

Table 1. Test conditions and measured reflection coefficients for experiment of Park *et al.* (1993).

T	H	Measured reflection coefficient		
(s)	(cm)	B = 15 cm	B = 20 cm	B = 25 cm
0.7	5	0.16	0.38	0.54
0.8	5	0.24	0.27	0.44
0.9	5	0.33	0.18	0.21
	10	0.20	0.016	0.15
1.0	5	0.31	0.18	0.15
	10	0.26	0.11	0.048
1.1	5	0.41	0.26	0.17
	10	0.34	0.21	0.093
1.2	5	0.49	0.32	0.22
	10	0.42	0.28	0.16
1.3	5	0.46	0.33	0.23
	10	0.39	0.27	0.18
1.4	5	0.55	0.41	0.28
	10	0.48	0.33	0.21
1.5	5	0.62	0.45	0.32
	10	0.51	0.37	0.26
1.6	5	0.61	0.47	0.35
	10	0.53	0.38	0.26
1.7	5	0.66	0.50	0.37
	10	0.55	0.41	0.28
1.8	5	0.64	0.52	0.40
	10	0.56	0.45	0.31

3.4 Data Acquisition and Analysis

Wave measurements were made at the middle between the wavemaker and the breakwater by three wave gauges separated by 20 and 35 cm one another along the flume . Data were collected at the sampling rate of 20 Hz for each of the three gauges. The first part of the wave record contains only the incident waves until they are contaminated by the waves reflected from the breakwater. After a while, the wave record shows a more complicated shape due to the waves re-reflected from the wave paddle. A part of the wave record which contains both incident and reflected waves but not the re-reflected waves was taken and analyzed by the method proposed by Park *et al.* (1992) to separate the incident and reflected waves.

3.5 Experimental Results

It is well known that the wave reflection from a perforated caisson breakwater depends on the width of the wave chamber relative to the wave length. For a fully perforated caisson lying on a flat sea bottom, Fugazza and Natale (1992) showed analytically that the resonance inside the wave chamber is important so that the reflection is at its minimum when $B/L=0.25$ in which B = wave chamber width, and L = incident wave length. Fugazza and Natale also provided some experimental data supporting this fact. For a fully perforated caisson lying on a flat sea bottom, the wave length does not change as the wave propagates into the wave chamber as far as the inertial resistance at the perforated wall is assumed to be negligible. For a partially perforated caisson mounted on a rubble mound examined in this study, however, the wave length changes as the wave propagates from the flat bottom to the wave chamber. Since the wave reflection of a perforated caisson is related to the resonance inside the wave chamber, it may be reasonable to take the wave length inside the wave chamber.

Fig. 3 shows the variation of the measured reflection coefficients with respect to B/L_c in which L_c = wave length inside the wave chamber. The reflection coefficient shows its minimum at B/L_c around 0.2, which is

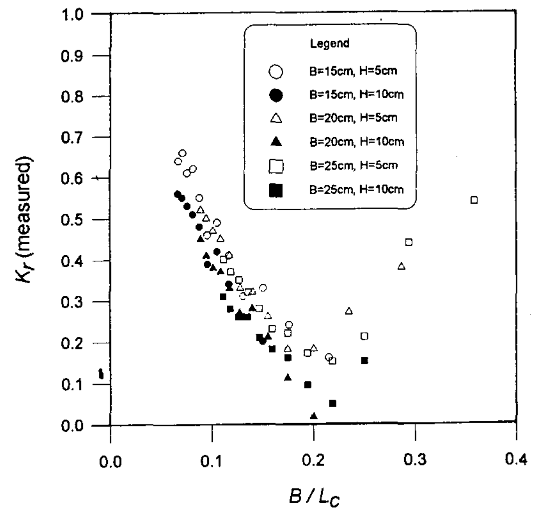

Fig. 3. Variation of the measured reflection coefficients with respect to B/L_c.

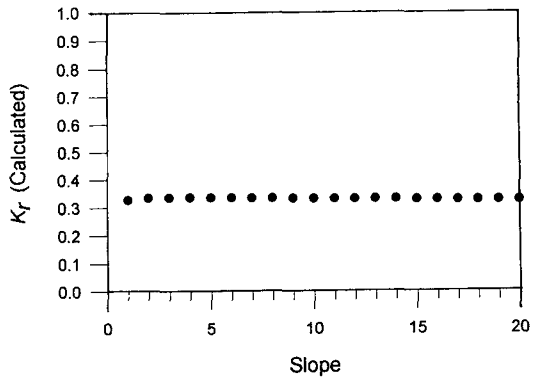

Fig. 4. Reflection coefficients calculated for different fore slopes of the caisson.

somewhat smaller than the theoretical value of 0.25 obtained by Fugazza and Natale (1992). In the analysis of Fugazza and Natale, they neglected the inertial resistance at the perforated wall. In front of a perforated caisson breakwater, a partial standing wave is formed due to the wave reflection from the breakwater. If there was no perforated wall, the node would occur at a distance of $L_c/4$ from the back wall of the wave chamber, and hence the largest energy loss may occur at this point because there is no inertial resistance. But, in reality, there exists the inertial resistance at the perforated wall, which decreases the wave length of the wave, thus slowing it. Consequently the location of the node will move onshore, and the point where the maximum energy loss is gained becomes smaller than $L_c/4$. Thus the minimum reflection occurs at a value of B/L_c smaller than 0.25. This point will be discussed later when the analytical model results are presented. Also, in Fig. 3, it is observed that the reflection coefficient decreases as the wave steepness increases as in other coastal structures.

4. COMPARISON OF MODEL WITH EXPERIMENTAL DATA

The analytical model described in the previous section assumes that the water depth inside the wave chamber is the same as that on the mound berm as in a conventional fully perforated caisson breakwater shown in Fig. 1(a). However, for a partially perforated caisson used in the experiment (see Fig. 2), these water depths are different each other, having depth discontinuity at the location of the perforated wall. In order to apply the model to the case of a partially perforated caisson, we assume that the front face of the lower part of the caisson (below the wave chamber) is not vertical but has a very steep slope. As mentioned previously, the model equation (1) which includes the terms proportional to the square of bottom slope and to the bottom curvature can be applied over a bed having substantial variations of water depth. In order to examine the effect of the fore slope of the caisson (which is infinity in reality), the reflection coefficient was calculated by changing the slope from 1 to 20 for the test of wave period 1.3 s, wave height 5 cm, and wave chamber width 20 cm, in which the measured reflection coefficient was 0.33. The distance from the toe of the mound ($x = -b$) to the perforated wall caisson ($x = 0$) was devided by 999 equally spaced intervals in the calculation. Fig. 4 shows the calculated reflection coefficients for different fore slopes of the caisson. The calculated reflection coefficients are almost constant with respect to the change of the slope. Therefore, in the following calculations the slope was fixed at 4.0.

In (3), the length of the jet flowing through the perforated wall, ℓ, represents the inertial resistance at the perforated wall. Both Fugazza and Natale (1992) and Suh and Park (1995) assumed that the importance of the local inertial term is feeble, and thus they took the jet length, ℓ, to be equal to the thickness of the perforated wall, b. As discussed previously, however, the experimental data in Fig. 3 shows that the influence of the inertial resistance term is important. Kakuno and Liu (1993) proposed a blockage coefficient of a perforated wall with vertical slits to be

$$C' = \frac{b}{2}\left(\frac{A}{a}-1\right) + \frac{2A}{\pi}\left[1-\log\left(\frac{4a}{A}\right)+\frac{1}{3}\left(\frac{a}{A}\right) + \frac{281}{180}\left(\frac{a}{A}\right)^4\right] \qquad (14)$$

in which a = half-width of opening of the vertical slit wall, and A = half distance between centers of two adjacent columns of the vertical slit wall. Comparison of the models of Kakuno and Liu (1993) and Suh and Park (1995) shows that

$$\ell = 2C' \qquad (15)$$

For the vertical slit wall used in the experiment of Park *et al.* (1993), $b = 1$ cm, $a = 1$ cm, and $A = 3$ cm so that the jet length, ℓ, is calculated as 5.84 cm by the preceding equations, which is almost six times the thickness of the wall.

Fig. 5 shows the comparison between measured and calculated reflection coefficients when the jet length, ℓ, is assumed to be equal to the wall thickness, b. In this figure and Figs. 6 to 8, the open and solid symbols denote the incident wave height 5 cm and 10 cm, respectively. The data of the smaller wave height show reasonable agreement between measurement and calculation, even though the model slightly overpredicts the reflection coefficient and scattering of several data points is observed. For the data of the larger wave height, the model significantly overpredicts the reflection coefficient, especially when the reflection coefficients are small.

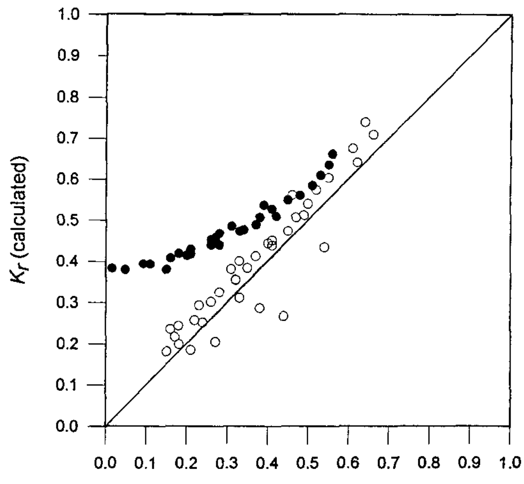

Fig. 5. Comparison of the reflection coefficients between model results and experimental data when $\ell = \mathbf{b}$ is used; ○ = wave height of 5 cm, ● = wave height of 10 cm.

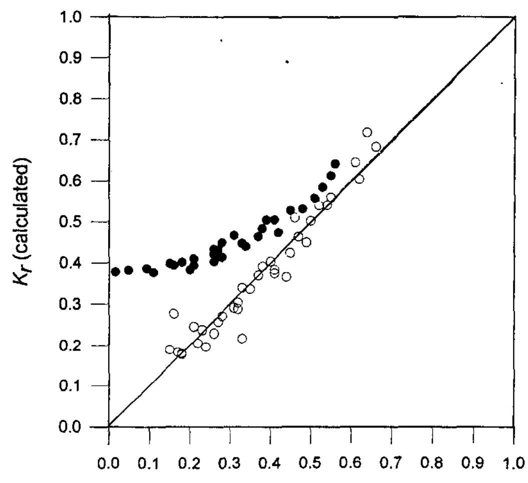

Fig. 6. Comparison of the reflection coefficients between model results and experimental data when $\ell = 5.84\mathbf{b}$ is used; ○ = wave height of 5 cm, ● = wave height of 10 cm.

Fig. 6 shows a plot similar to Fig. 5 when the jet length, ℓ, is calculated by (14) and (15) so that $\ell = 5.84b$. The data of the wave height 5 cm show somewhat better agreement than that of $\ell = b$ in Fig. 5, but the data of the wave height 10 cm still exhibit a significant overprediction of the model except some points of larger

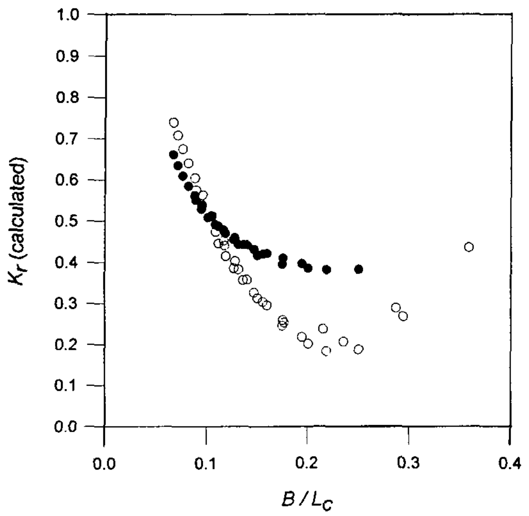

Fig. 7. Variation of the calculated reflection coefficients with respect to B/L_c when $\ell = b$ is used; ○ = wave height of 5 cm, ● = wave height of 10 cm.

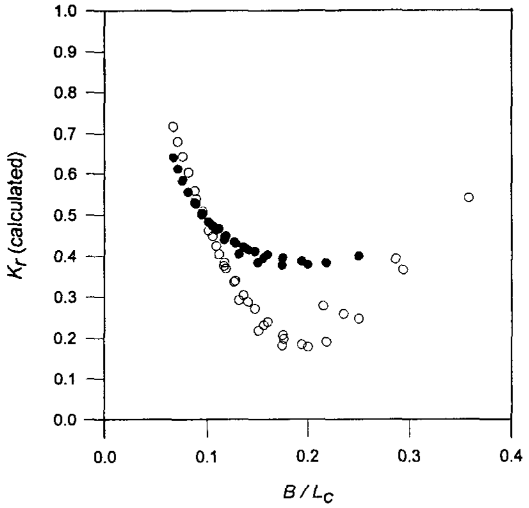

Fig. 8. Variation of the calculated reflection coefficients with respect to B/L_c when $\ell = 5.84b$ is used; ○ = wave height of 5 cm, ● = wave height of 10 cm.

reflection coefficients.

Figs. 7 and 8 show the plots of the calculated reflection coefficients versus B/L_c for the cases of $\ell = b$ and $\ell = 5.84b$, respectively. For the case of $\ell = b$, the reflection coefficient shows its minimum at B/L_c around 0.25. For the case of $\ell = 5.84b$, however, it becomes minimum at B/L_c around 0.2. Comparing these figures with Fig. 3 in which the measured reflection coefficients are plotted against B/L_c, it is found that the influence of inertial resistance is important so that the results calcualted using $\ell = 5.84b$ give better agreement with the measurement than those using $\ell = b$ in view of B/L_c giving the minimum reflection. Comparison between Fig. 3 and Fig. 8 shows that for the smaller wave height ($H = 5$ cm) the calculated and measured results show very similar trend but for the larger wave height ($H = 10$ cm) the calculated reflection coefficients are much larger than the measured ones especially when the reflection coefficients are small. In the measurement the reflection coefficients for larger wave height are consistently smaller than those for smaller wave height, but in the calculation the reverse is true for the reflection coefficients smaller than about 0.5.

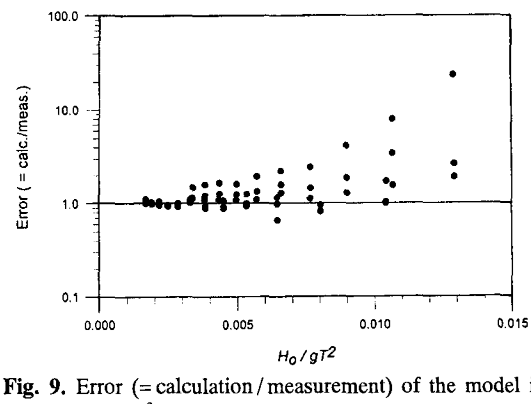

Fig. 9. Error (= calculation / measurement) of the model in terms of wave steepness.

The preceding analyses show that the model overpredicts the reflection coefficients for the larger wave height ($H = 10$ cm). The present model is based on a linear wave theory and it utilizes the linearized expression for the perforated wall dissipation coefficient γ as in (10). Therefore, the model may not be applicable for highly nonlinear waves. In order to examine the effect of nonlinearity, the errors (= calculation/measurement) of the model were plotted in Fig. 9 in terms of H_o/gT^2 in which H_o = deepwater wave height and T = wave period. It is observed that the model tends to overestimate the reflection coefficient as the wave steepness increases. A similar trend is observed for other experimental data [see Fig. 5 in the paper of Suh and Park (1995) for example]. In Fig. 9, it seems that the model gives reasonably accurate results for the value of H_o/gT^2 up to about 0.003. At this value the deepwater wave height, H_o, for $T=6$, 8, and 10 s is approximately 1, 2, and 3 m, respectively. Considering that wave reflection from a breakwater is of more interest for ordinary waves than the severe storm waves (because during the severe wave condition most ships seek refuge into harbors), the present model may provide useful information about wave reflection in the design of perforated caisson breakwaters.

Considering the discrepancy between the measured and calculated reflection coefficients for steeper waves, it seems that addtional energy dissipation other than those considered in the theoretical model occurs in the experiment for steeper waves. One possible mechanism for additional energy dissipation may be due to the difference of water levels between the front and back of the perforated wall. In the theoretical model, it is assumed that the water level is continuous at the location of the perforated wall. But in the experiment it is observed that this is not true. When the wave advances toward the wave chamber, water is piled up at the front of the perforated wall because its forward movement is partially blocked by the wall. Thus the water level in front of the wall becomes higher than that inside the wave chamber. When the wave retreats, the reverse occurs. This difference of water levels, therefore, produces waterfall-like phenomenon, which may give additional energy dissipation other than that due to inertial resistance and flow separation at the perforated wall. That phenomenon becomes more significant as the wave steepness increases.

5. CONCLUSIONS

The experimental results of Park *et al.* (1993) show that the wave reflection is at its minimum when the relative width B/L_c of the wave chamber is about 0.2, which is somewhat smaller than the theoretical value $B/L_c=0.25$ obtained by assuming that the influence of inertial resistance at the perforated wall is negligible. The analytical model results also show that the effect of inertial resistance is important so that the calculated reflection coefficient becomes minimum at B/L_c around 0.2 as in the measurement when the enhanced influence of inertial resistance is included (i.e. $\ell=5.84b$ calculated by (14) and (15) is used), while it becomes minimum at B/L_c around 0.25 when the jet length, ℓ, is assumed to be just equal to the wall thickness, b.

The analytical model of Suh and Park (1995), originally developed for a conventional fully perforated caisson breakwater, was applied to the partially perforated caisson breakwater by assuming that the front face of the lower part of the caisson (below the wave chamber) is not vertical but has a very steep slope. The numerical test made by changing this slope (see Fig. 4) and the comparison of the model with the experimental data showed that such an assumption was reasonable so that the Suh and Park's model could be applied to a partially perforated caisson breakwater. It was also shown that the theoretical model based on a linear wave theory tends to overpredict the reflection coefficient as the wave nonlinearity increases. Therefore the model is preferably to be used for ordinary waves of small steepness.

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