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Wave Reflection from Partially Perforated Wall Caisson Breakwater

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1 Introduction

In order to reduce wave reflection from a breakwater, a perforated wall caisson is often used. A conventional perforated wall caisson breakwater for which the water depth inside the wave chamber is the same as that on the rubble mound berm has less weight than a vertical solid caisson with the same width and moreover the weight is concentrated on the rear side of the caisson. Therefore sometimes difficulties are met in the design of a perforated wall caisson so as to satisfy the design criteria against sliding and overturning of the caisson or the sliding failure of the sub-bottom soil. In order to solve these problems in part, a partially perforated wall caisson as shown in Fig. 1 is often used, which provides an additional weight to the front side of the caisson.

Recently Park et al. (1993) reported a laboratory experiment for wave reflection from a partially perforated wall caisson mounted on a rubble mound foundation. On the other hand, Suh and Park (1995) developed an analytical model that can predict the wave reflection from a perforated wall caisson mounted on a rubble mound foundation when waves are obliquely incident to the breakwater at an arbitrary angle. In the present study, the Park et al.'s (1993) experimental results are compared with the Suh and Park's (1995) model results. The Suh and Park's model, originally developed for a fully perforated wall caisson, is used for a partially perforated wall caisson by assuming that the lower part of the front face of the caisson (which is non-perforated and vertical) is not vertical but has a very steep slope. Also the inertial resistance term at the perforated wall is modified by using the blockage coefficient proposed by Kakuno and Liu (1993).

2 Summary of Laboratory Experiment

The experiment of Park et al. (1993) was carried out in a wave flume of 53.15 m length, 1 m width, and 1.25 m height. Fig. 1 shows an example of the breakwater model with a wave chamber of 20 cm width. The perforated wall of the caisson 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 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 ($2 \times 3 + 10 \times 2 \times 3$).

It is well known that the wave reflection from a perforated wall caisson breakwater depends on the width of the wave chamber relative to the wave length. Since the wave reflection of a perforated

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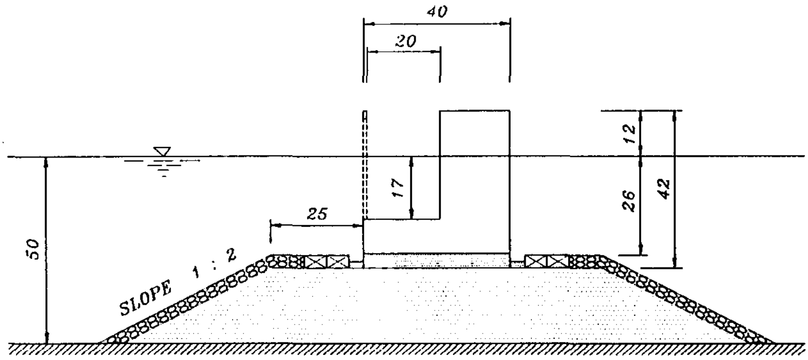

Figure 1: Illustration of the breakwater model.

wall caisson is related to the resonance inside the wave chamber, for a partially perforated wall caisson breakwater it may be reasonable to take the wave length inside the wave chamber.

Fig. 2 shows the variation of the measured reflection coefficients with respect to B/L_c in which B = wave chamber width and L_c = wave length inside the wave chamber. The reflection coefficient shows its minimum at B/L_c around 0.2, which is 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 term at the perforated wall. In front of a perforated wall caisson breakwater, a partial standing wave is formed due to the wave reflection from the breakwater. If there is no perforated wall, the node occurs at a distance of $L_c/4$ from the back wall of the wave chamber, and hence the largest energy loss may be gained at this point because there is no inertial resistance. But, in reality, there exists the inertial resistance, and the location of the node will move onshore, and consequently 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. In Fig. 2, it is also observed that the reflection coefficient decreases as the wave steepness increases as in other coastal structures.

3 Summary of Analytical Model

Based on the extended refraction-diffraction equation proposed by Massel (1993), Suh and Park (1995) developed an analytical model to calculate the reflection coefficient of a conventional fully perforated wall caisson 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 and dividing the model domain into three regions (Region 1: $x < -b$, Region 2: $-b \leq x \leq 0$, and Region 3: $0 < x \leq B$), Suh and Park (1995) showed that the function $\tilde{\varphi}(x)$ [see Suh and Park (1995) for its definition] on the rubble mound ($-b \leq x \leq 0$) satisfies the following ordinary differential equation:

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

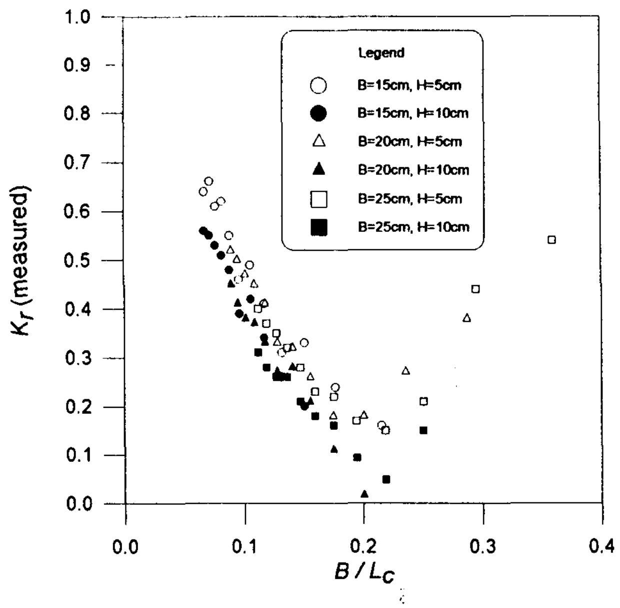

Figure 2: Variation of the measured reflection coefficients with respect to B/L_c.

with the boundary conditions as follows:

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

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

The depth-dependent functions $D(x)$ and $E(x)$ in (1) can be found in Suh and Park (1995).

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

$$\gamma = \frac{8\alpha}{9\pi}H_w\omega\frac{W}{\sqrt{W^2(R+1)^2 + C^2}}\frac{5 + \cosh 2k_3h_3}{2k_3h_3 + \sinh 2k_3h_3} \tag{4}$$

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

$$\alpha = \left(\frac{1}{r\cos\theta_3 C_c}\right)^2 - 1 \tag{5}$$

is the energy loss coefficient at the perforated wall, which is a modification of the head loss coefficient for the plate orifice formula. 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, and C_c is the empirical discharge coefficient at the perforated wall. In the present study $C_c = 0.55$ was used. Rearranging of (4) gives a quartic polynomial of γ, which can be solved by the eigenvalue method.

The differential equation (1) with the boundary conditions (2) and (3) can be solved using the finite-difference method. Using the forward-differencing for $d\tilde{\varphi}(-b)/dx$, backward-differencing for

$d\tilde{\varphi}(0)/dx$, and central-differencing for the derivatives in (1), the boundary value problem (1) to (3) is approximated by a system of linear equations, $\mathbf{AY} = \mathbf{B}$. After solving this matrix equation, the reflection coefficient K_r is calculated by

$$K_r = \mathrm{Re}\{\tilde{\varphi}(-b) - 1\} \tag{6}$$

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

In the calculation of the dissipation coefficient at the porous wall γ in (4), 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

$$i\tilde{\varphi}(0)k_3 \cos\theta_3 = \frac{d\tilde{\varphi}(0)}{dx} \tag{7}$$

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 $K_t = \mathrm{Re}\{\tilde{\varphi}(0)\}$, from which H_w is calculated as K_t times the incident wave height on the flat bottom.

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 wall caisson breakwater. However, for a partially perforated wall caisson used in the experiment (see Fig. 1), 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 wall 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. In order to examine the effect of the fore slope of the caisson, 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. 3 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. 2 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

$$C' = \frac{b}{2}\left(\frac{A}{a} - 1\right) + \frac{2A}{\pi}\left[1 - \log\left(\frac{4a}{A}\right) + \frac{1}{3}\left(\frac{a}{A}\right) + \frac{281}{180}\left(\frac{a}{A}\right)^4\right] \tag{8}$$

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

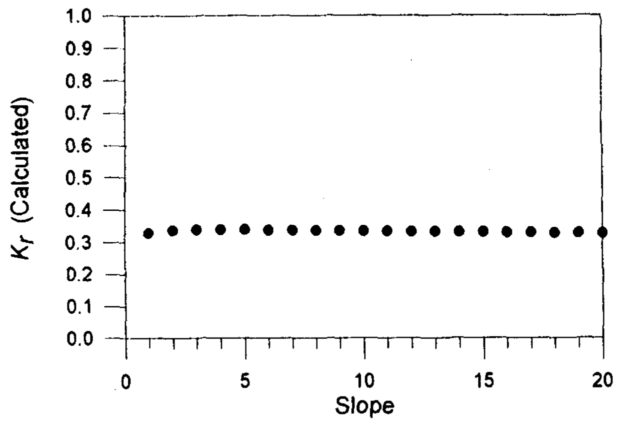

Figure 3: Reflection coefficients calculated for different fore slopes of the caisson.

$$\ell = 2C' \tag{9}$$

For the vertical slit wall used in the present experiment, $b = 1$ 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. 4 (a) shows the comparison between measured and calculated reflection coefficients when the jet length, ℓ, is assumed to be equal to the wall thickness, b, and Fig. 4 (b) shows a similar plot when the jet length, ℓ, is calculated by (8) and (9) so that $\ell = 5.84b$. In this figure and Fig. 5, the open and solid symbols denote the incident wave height 5 cm and 10 cm, respectively. In Fig. 4 (a), 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. When $\ell = 5.84b$ (see Fig. 4 (b)), the data of the wave height 5 cm show somewhat better agreement than that of $\ell = b$ in Fig. 4 (a), but the data of the wave height 10 cm still exhibit a significant overprediction of the model except some points of larger reflection coefficients.

Fig. 5 (a) and (b) 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. 2 in which the measured reflection coefficients are plotted against B/L_c, it is found that the effect of inertial resistance is important so that the calcualted results using $\ell = 5.84b$ give better agreement with the measured results than those using $\ell = b$ in point of B/L_c of the minimum reflection. Comparison between Fig. 2 and Fig. 5 (b) 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.

The preceding analyses show that the model overpredicts the reflection coefficients for the larger

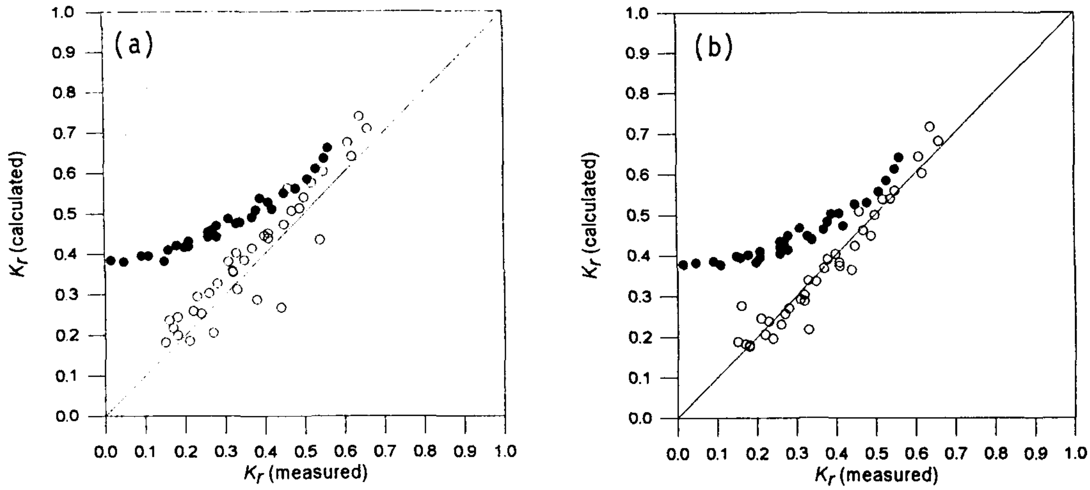

Figure 4: Comparison of the reflection coefficients between model results and experimental data; (a) $\ell = b$, (b) $\ell = 5.84b$.

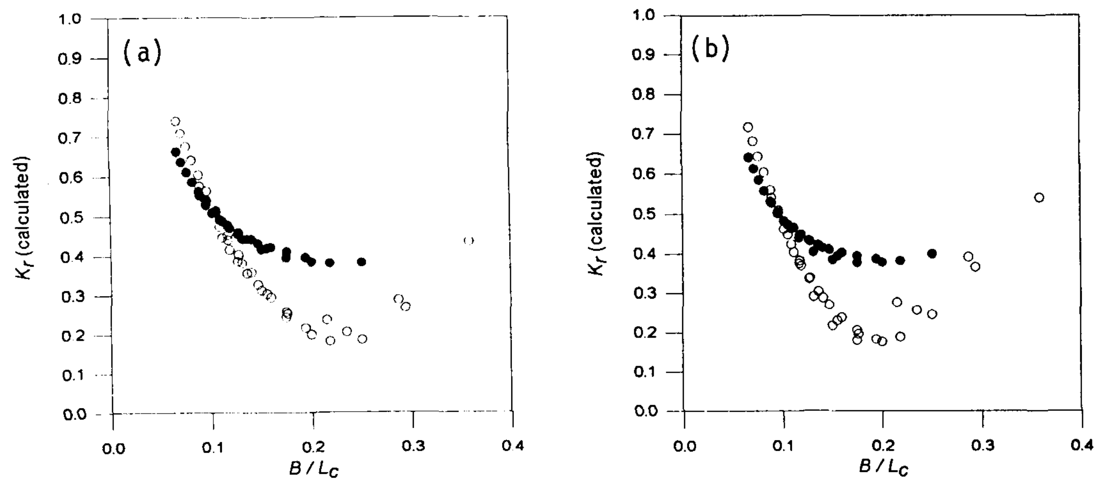

Figure 5: Variation of the calculated reflection coefficients with respect to B/L_c; (a) $\ell = b$, (b) $\ell = 5.84b$.

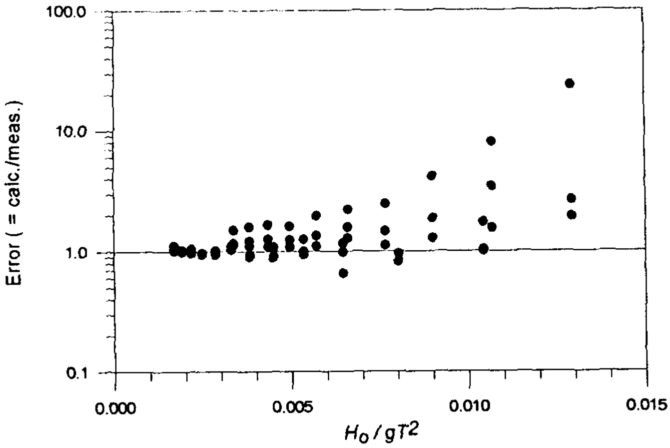

Figure 6: Error (=calculation/measurement) of the model in terms of wave steepness.

wave height (H = 10 cm). The present model is based on the linear wave theory and it utilizes the linearized expression for the perforated wall dissipation coefficient γ as in (4). 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. 6 in terms of H_o/gT^2 in which H_o is the deepwater wave height and T is the wave period. It is observed that the model tends to overestimate the reflection coefficient as the wave steepness increases. It seems that for steeper waves addtional energy dissipation other than that through the perforated wall occurs in the experiment so that a reflection coefficient smaller than the theoretical value is observed.

5 Conclusions

The analytical model of Suh and Park (1995), originally developed for a conventional fully perforated wall caisson breakwater, was applied to the partially perforated wall 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. 3) 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 wall caisson breakwater. It was shown that the inertial resistance term at the perforated wall is important so that the reflection shows its minimum at a value of B/L_c smaller than 0.25 when this term is included. 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.

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