Development of a New Type of Reef Breakwater, Theoretical and Experimental Study

Shohachi KAKUNO*[1], Masao ENDOH*[2], Yiming ZHONG*[3], Takaaki SHIGEMATSU*[1], and Kazuki ODA*[1], Member of ASCE

Abstract

The concept of a horizontal perforated plate placed in water, with a method for implementing the concept in a real sea as a new type of reef breakwater, is proposed in the present paper. The feasibility and superiority of the proposed breakwater in hydraulic characteristics in comparison with conventional reef breakwaters has been shown by theoretical and experimental study.

1. Introduction

Wave height reduction with reef breakwaters is caused by energy dissipation from waves breaking over the crests of the breakwaters. Mass transport caused by the wave breaking, however, may generate offshore flow at the gaps between two adjacent breakwaters and, hence scouring at the bottoms of the gaps. Also, the massive structural body of the breakwater may interfere with existing currents on the beach. As an alternative breakwater, an impermeable plate placed horizontally in the water does not interfere with currents. However, strong wave forces may be exerted on the plate, causing problems. If perforations are made in the horizontal plate, much wave energy dissipation at the perforations due to flow separation and reduced wave forces may be anticipated. The perforations could also encourage vertical flow with vertical oxygen transport. The region under the perforated plate could become good shelter for aquatic creatures.

The objective of this study is to propose the concept of a horizontal perforated plate placed in water, with a method for implementing the concept in a real sea as a new type of reef breakwater, and to investigate the hydraulic characteristics of the breakwater theoretically and experimentally.

---

*1: Dept. Civil Engrg., Osaka City Univ., Sugimoto, Sumiyoshi-Ku, Osaka 558-8585, Japan

*2: Toyo Suiken Co. Ltd., Tokyo, Japan

*3: Shusei Consultant Co. Ltd., Osaka, Japan

2. Theoretical Study

2-1. A boundary-value analysis

A theoretical study to search for an optimum opening ratio for the plate was performed as a boundary-value problem for small amplitude waves (Kakuno & Zhong 1993). A plate having slits as perforations was considered. To analyze the problem, the whole region was divided into five regions, as shown in **Fig.1**. In each region except that which holds the plate, a velocity potential which satisfies the boundary conditions at the sea surface and/or the sea bottom was assumed, with unknown coefficients. Evanescent waves which may occur near the plate were neglected. The waves over and under the plate were assumed to have the same wave number because of the continuity of flow through the slits. In the region which holds the slitted plate, a velocity potential for flow through a slitted plate that has been obtained theoretically is assumed (Kakuno & Liu 1993). The unknown coefficients included in each velocity potential can be determined after matching the potentials at the boundaries.

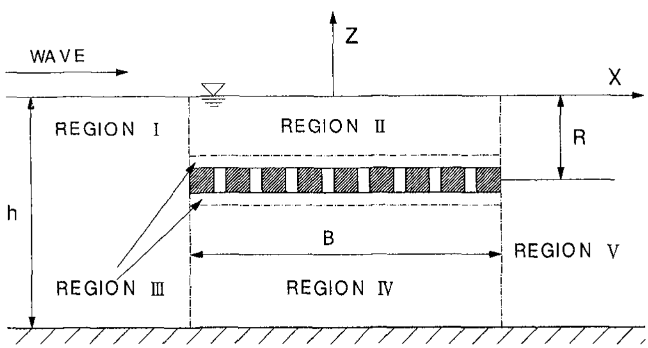

Fig.1 A boundary-value problem

2-2. An Energy Dissipation Model

The effect of the energy dissipation due to flow separation at slits can be included by introducing a complex wave number in the regions over and under the plate. The imaginary part of that wave number can be determined by equating the energy flux difference between plate ends evaluated linearly using the imaginary part to that evaluated using quadratic resistance at the slits. The same value, f=1.5, was assigned as for vertical slits (Kakuno & Liu 1993), where f is the value of the energy dissipation coefficient included in the quadratic resistance.

2-3. Preliminary experiments to verify the theory

To verify the theory, preliminary experiments to measure the reflection and transmission coefficients were performed using a horizontal slitted plate placed in water of constant depth, h=0.3m, in a wave tank 20m long, 0.5m wide, and 0.6m high. The thickness, the width in the direction of wave propagation, the opening ratio, and the submerged depth of the plate were b=6mm, B=60m, r=0.089, and R=6cm, respectively.

Fig. 2 (a) and **(b)** show comparisons of the theoretical transmission and reflection coefficients, γ_T and γ_R, with laboratory data as a function of *B/L*, where *L* is the wave length, under the conditions of the wave steepness *H/L*=0.01 and 0.02, where *H* is the wave height. The agreement between the theoretical results, in which the effect of the energy dissipation is taken into consideration, and the laboratory data is good overall; hence the validity of the theory has been shown.

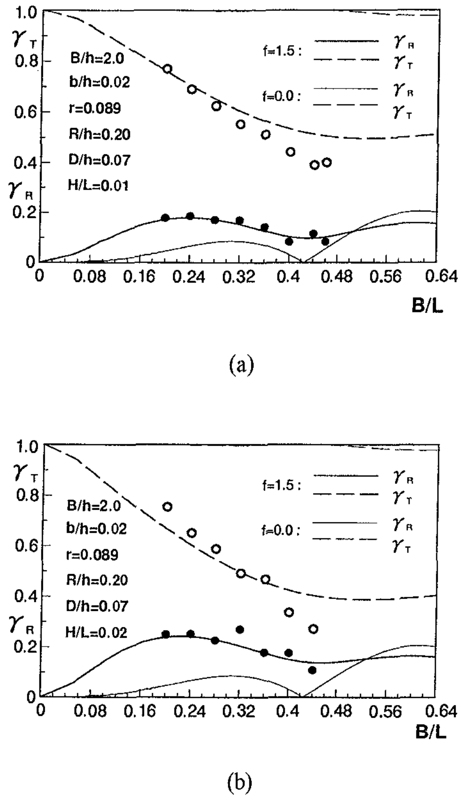

Fig.2 Comparison of transmission coefficients between theory and experiment

2-4. Comparison with impermeable horizontal plate

To examine the difference between the perforated horizontal plate and the solid horizontal plate, laboratory data for an impermeable plate (Aoyama et al. 1988) were compared with calculated results for the perforated plate under the same conditions (**Fig.3**). As shown in the figure, the characteristics of the two types of plate are remarkably different. Lower transmission and reflection may be attained by the perforated plate over a wide range of *B/L*, indicating more effective energy dissipation by the perforated plate.

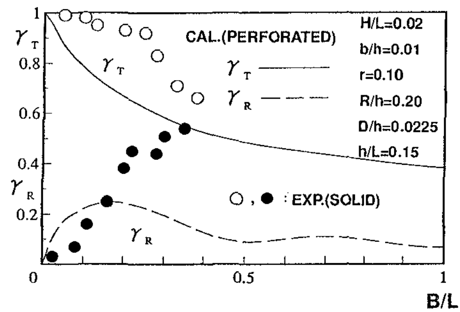

Fig.3 Comparison of transmission and reflection coefficients with those of an impermeable horizontal plate

2-5. Optimum opening ratio

Fig.4 shows calculated results for the perforated plate for a varied opening ratio. As shown in the figure, a smaller ratio leads to less transmission and greater reflection. An opening ratio of r=0.1 may be concluded to be the optimum which minimizes transmission and reflection.

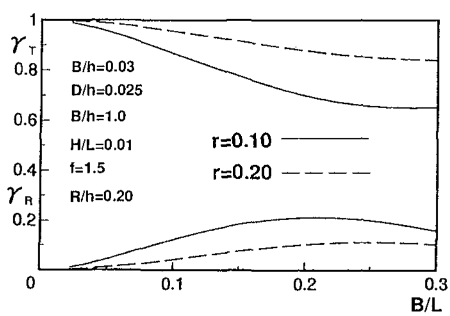

Fig.4 Transmission and reflection coefficients as a function of opening ratio

3. Proposal of a New Type of Reef Breakwater

To implement the concept of the horizontal perforated plate in the sea, concrete units, whose schematic diagram is shown in **Fig.5**, were conceived. Each unit is principally composed of a horizontal perforated upper slab which plays a principal role in wave energy dissipation, and columns to support the slab from the bottom. The dimensions and weight of a typical unit in the sea are 3m×3m×3m and Wa=16tf, respectively. The opening ratio of a unit will be about r=0.1, which was determined to be the optimum in the theoretical study. The units will be placed in a single layer on a rubble mound with a crest depth of 0m - 2m in the sea, as shown in **Fig.6**.

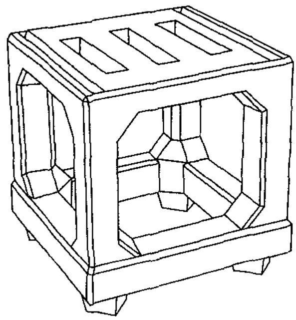

Fig.5 A concrete unit to make up a new type of reef breakwater

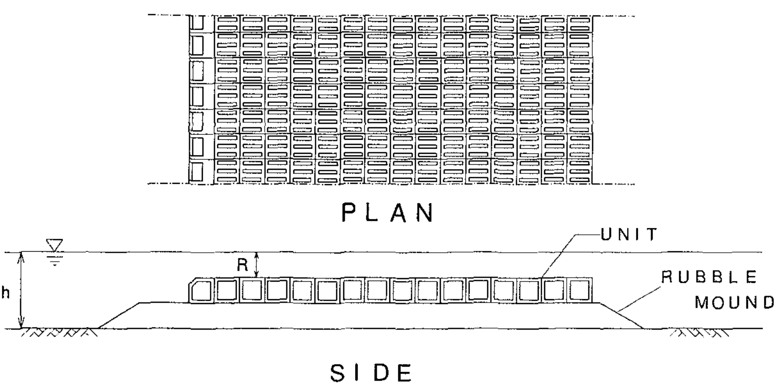

Fig.6 A new type of reef breakwater

4. Experimental Studies

A series of experimental studies was performed using 1/20 scale models of the units in a wave tank 50 m long, 1 m wide, and 1.50 m high, to measure the transmission and reflection coefficients. Experiments to measure water level rise and wave height attenuation over the breakwater, and to examine the stability of the units, were also performed using the same wave tank. The waves were regular in all experiments. The model units were placed on a 15 cm-thick rubble mound on a horizontal floor in the wave tank. The breakwater width tested was primarily B=2.4m, 16 rows of units, but in the experiments to measure the transmission and reflection coefficients, breakwaters with widths B=1.2m, 8 rows of units, and 0.6m, 4 rows of units, were also tested. The water depths (crest water depth) tested were h=30cm (R=0cm), 35cm (5cm), 40cm (10cm), and 45cm (15cm). **Fig.7** shows a picture of waves over the crest of the breakwater model (B=2.4m, R=0cm, T=3s, H=15.5cm).

The experiments to examine the stability of the units were performed by using breakwater models which were placed on a horizontal floor raiscd from the wave tank floor. The berm widths tested were 30cm and 75cm, with the length from the rubble mound end to the offshore edge of the units, L_M, 55cm and 100cm, respectively. Four wave periods within the range from 1.5s to 3.15s were used, and the wave heights were increased till instability was observed, keeping the period constant. Because instability was observed in the row at the very offshore side edge only, modifications were made for the row. One of the modifications was made by using units made of high density material, and the other was made by modifying the cross section of the units. **Fig.8** shows a unit with the modified cross section, and **Fig.6** shows a breakwater with the units at the offshore edge. It was found that the units with the modified cross section were most stable. This is because that the larger opening in the upper slab may reduce wave forces exerted on a unit. The degree of stability was determined on the basis of the criteria shown in **Table 1**.

Table 1 A criterion used to judge stability

STABILITY	CRITERION
STABLE	STATIONARY OR ROCKING≦5mm
UNSTABLE	ROCKING>5mm OR FLOATING

5. Results

5-1. Comparison of transmission coefficient with that of a conventional reef breakwater

Fig.9 (a) and **(b)** show examples of comparisons of experimental data for the transmission coefficients of the present breakwater with those of a conventional reef breakwater (Uda et al. 1988) as a function of B/L_0, where L_0 is the deep water wave length, with relative crest depth, R/H_0', as a parameter, where H_0' is the wave height in deep water if the wave is not refracted. In transmission wave records, the effect of bi-frequency components was found to be small, and hence these were not included in the figures. As shown in the figures, the transmission coefficients of the present breakwater are much smaller than those of conventional breakwaters, implying effective energy dissipation over the breakwater. The difference between the two types of breakwaters becomes large when relative crest depth, R/H_0' , becomes large, which implies that, at deeper crest depths, effective energy dissipation caused by separation can still be expected in the present breakwater, while breaking waves of large scale may not occur in conventional reef breakwater. A flat water surface with no waves nor any disturbances was observed under the condition R/H_0' =0 and B/L_0>0.75, shown in **Fig.9 (b)**. The slits were aligned with the direction of wave incidence in all experiments. But the same results were obtained in an experiment in which the slits were changed to be perpendicular to the wave incidence,.

Fig.7 Waves over the crest of the breakwater model

The transmission and reflection coefficients were obtained from transmitted and reflected wave heights behind and in front of the model by using Goda's method (Goda et al. 1976). The period and the wave height were varied from 1s to 3s, and from 0.01m to 0.16m, with the wave steepness H/L=0.01-0.05.

The water level rise and the wave height attenuation over the breakwater were measured at 13 points over the crest, including the offshore edge and lee edge. Water level fluctuations were recorded for 60s with sampling period 0.04s, from the time that the first wave arrived at the wave gauge at the offshore side. The water level records were then averaged for the duration, excluding the first 20s and the last several waves, to obtain averaged water level rise from the still water surface. The wave heights over the breakwater were determined by using the zero-up crossing method.

Fig.8 A concrete unit with modified cross section for the offshore side edge

The reflection coefficients were confirmed to be small. The maximum value obtained was γ_R=30 % when R=0cm, and the coefficients tended to decrease with increasing crest depth up to γ_R=10 % when R=15cm.

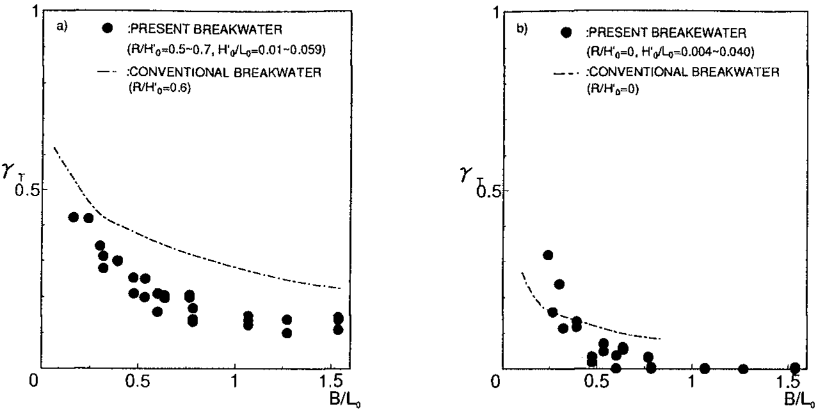

Fig.9 Comparison of transmission coefficients with those of a conventional reef breakwater

5-2. Water level rise distribution over the breakwater

Fig.10 shows relative water level rise distribution over the crest of the present breakwater, η/H_0', when R=5cm. As shown in the figure, the water level rise gradually increases as waves propagate over the crest from the offshore side to the lee side, showing the same tendency as with a conventional breakwater, and becoming maximum at the point just before the lee side edge. Smaller R/H_0' tends to be associated with larger η/H_0', a trend which can also be seen in conventional reef breakwaters.

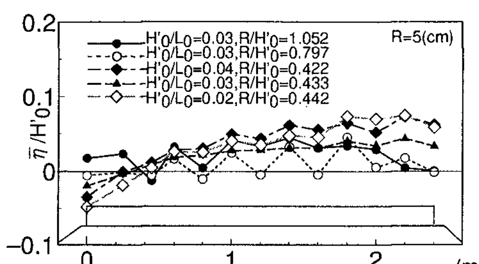

Fig.10 Water level rise over the present reef breakwater

5-3. Comparison of the water level rise with that of a conventional reef breakwater

As mentioned earlier, water level rise over the crest of the reef breakwater may cause scouring at the gap between two adjacent breakwaters. Hence, scouring characteristics should be investigated and compared with those of conventional breakwaters. In **Fig.11**, a comparison of the water level rise at the lee edge of the present breakwater as a function of R/H_0' with that of a conventional breakwater is shown. Much smaller water level rises than those from conventional breakwaters, especially for the range $R/H_0'<2$, can be seen. In addition, the present breakwater presents no massive body obstructing the flow, so that scouring at the gap between two adjacent breakwaters would not become a problem.

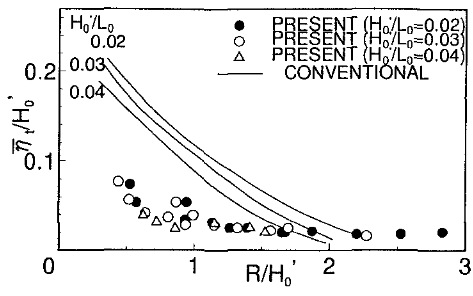

Fig.11 Comparison of water level rise at the lee side edge with that of a conventional reef breakwater

5-4. Wave height distribution over the breakwater

Fig.12 shows a wave height distribution over the crest of the breakwater. In contrast to conventional reef breakwaters, where wave height dissipates rapidly because of waves breaking over the crest, wave height reduces gradually over the crest because of the energy dissipation due to flow separation.

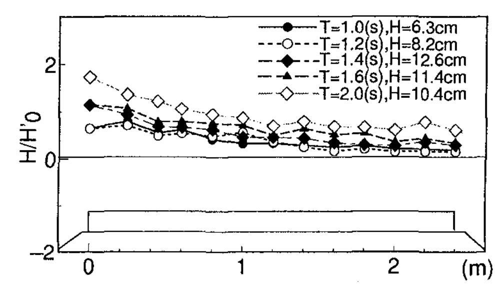

Fig.12 Wave height distribution over the breakwater

5-5. Stability

The present unit is characterized by an upper slab with perforations and a large vacant volume underneath. This configuration leads to concern for the stability of the units under severe wave conditions. Also, as mentioned earlier, the units will be placed in a single layer on a rubble mound, so the instability of the units will be caused by a different mechanism from that for conventional reef breakwaters, which feature sloping units with waves running up and down the slopes. Therefore, characterization of the stability of the present breakwater design should be carried out using a different approach from that for conventional breakwaters.

Experiments to examine the stability showed that waves which were incident upon the breakwater attacked the offshore side edge first, then traveled over the crest, reducing the wave height by energy dissipation. Because of this mechanism, the instability occurred in the row at the very offshore side edge only. Moreover, the instability was observed to be due to incipient motion with large waves, and not due to drag force, which plays a role in conventional breakwaters which have side slopes (see **Fig.13**).

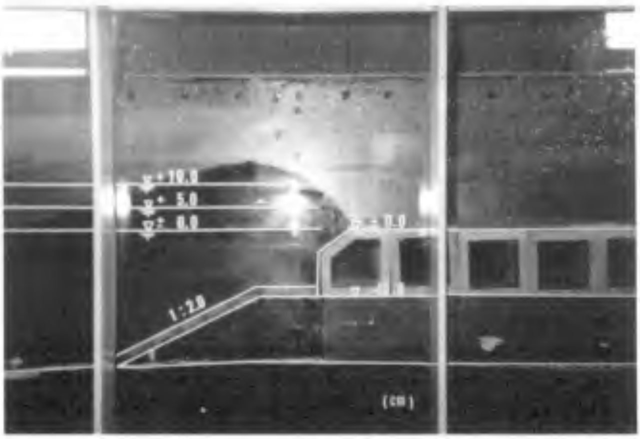

Fig.13 A large wave at the offshore edge of the breakwater

The experiments showed that the units became unstable as the wave period became longer, and as the crest depth became shallower, as anticipated.

5-6. Required weight of the unit

Assuming that the unstable motion occurring in the row at the very offshore side edge is caused mainly by the inertia force, a theoretical formula with an empirical coefficient to examine the stability of the breakwater in the sea was created. This examination was carried out for a unit with the modified cross section which has a greater opening ratio, shown in **Fig.8**, than the regular units which will be placed behind the offshore side row.

The concept of the formula was as follows. The inertial component in the wave force exerted on a plate, which has slits as perforations, is expressed as (Kakuno & Liu 1993)

$$\Delta P = 2\rho C\dot{w} \qquad (1)$$

where ρ is the fluid density, C is the blockage coefficient determined theoretically and corresponding to the inertial resistance, and $\dot{w}$ is the acceleration which acts on the plate in the normal direction. Because the wave force of Eq.(1) is per unit area, the force exerted on the upper slab is

$$F = \Delta P L_B^2 \tag{2}$$

letting L_B denote the side length of the upper slab.

The acceleration $\dot{w}$ in Eq.(1) was assumed to be proportional to the convective term, that is

$$\dot{w} \propto w(\partial w / \partial z) \tag{3}$$

where w is the vertical component of water particle velocity passing through the slits. Moreover, it was assumed that $\partial w / \partial z$ could be evaluated as

$$\partial w / \partial z \propto \alpha(w / b) \tag{4}$$

where b is the thickness of the upper plate, and α is a constant to be determined experimentally. Consequently, the acceleration may be evaluated as

$$\dot{w} = \alpha(w^2 / b) \tag{5}$$

If we substitute the vertical water particle velocity at the depth of the upper slab calculated by the small amplitude theory for w, then the wave force exerted on the plate can be expressed as

$$F = 2\rho\alpha\,(\frac{C}{A})\,(\frac{A}{b})\,\frac{\pi^2 H^2 \sinh^2 k(h-R)}{T^2 \sinh^2 kh}\,L_B^2 \tag{6}$$

where A is half the spacing of adjacent slits of the upper slab. The coefficient α can be determined using Eq.(6) and the minimum unstable weight of the unit obtained in the experiments. **Fig. 14** shows a graph of α against L_M/L_0, for various types of breakwater model. As shown in the figure, α has a strong and unique relationship with L_M/L_0 regardless of the type of the unit, the type of the berm width, the crest depth, etc. A regression curve which best fits the data, shown as a broken line in the figure, is expressed as

$$\alpha = 0.078\,(L_M / L_0)^{-1.20} \tag{7}$$

For simplicity in the derivation of a design formula for the stability of the units, however, we will use

$$\alpha = 0.15\,(L_M / L_0)^{-1} \tag{8}$$

instead of Eq.(7), which is shown as a solid line in the figure.

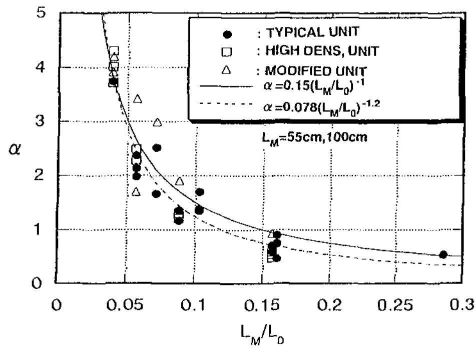

Fig.14 The relationship between α and L_M/L_0

Since we can have C/A=0.4805 and A/b=3.75 for the modified unit, the minimum required weight in water of the modified unit, which is equivalent to the value from Eq.(6), is

$$W_w = 0.85\,\gamma_w \frac{H^2 \sinh^2 k(h-R)}{L_M \sinh^2 kh} L_B^2 \tag{9}$$

where γ_w is the unit weight of sea water, and the relation $L_0=gT^2/2\pi$ was used in the derivation from Eq.(6) to Eq.(9). From the above expression, the required weight in air of the unit with modified cross section can be obtained readily as

$$W_a = 0.85\,\gamma_w \frac{S_r}{S_r - 1} \frac{H^2 \sinh^2 k(h-R)}{L_M \sinh^2 kh} L_B^2 \tag{10}$$

where $S_r = \gamma_c / \gamma_w$, and γ_c is the unit weight of the unit.

The most significant discrepancy from conventional formulae, for example the Hudson formula, is that the required weight is proportional to the square of the wave height, not to the third power of the wave height, as in conventional formulae. This is mainly because the water particle velocity is assumed to be proportional to the wave height in the present derivation, while it is assumed to be proportional to the square root of the wave height in the conventional formulae. Another reason is that a representative length scale of armor unit is treated as the side length of the upper slab, L_B, in the present derivation, while it is assumed to be proportional to the cube root of the wave height in the conventional formulae.

6. Concluding remarks

The present theoretical and experimental study has shown the feasibility and superiority of the proposed breakwater. The characteristics of the proposed reef breakwater may be summarized as follows:

- invisible
- less transmission and reflection
- does not generate current
- does not interfere with existing currents
- reduced wave forces
- good shelter for aquatic creatures and hence,
- totally environment-friendly breakwater.

Acknowledgment

We are grateful to Dr. Douglas B. Moog for his critical reading of the manuscript, and to Tetsuya Tatekawa for his help in preparing the manuscript.

References

Goda, Y. and Suzuki, Y., 1976, Estimation of incident and reflected waves in random wave experiments, *Proc. ICCE*, 828-562.

Kakuno, S. and Liu, P.L.-F., 1993, Scattering of Water Waves by Vertical Cylinders, *J. Port, Coastal, and Ocean Engrg.*, **119**, (3), 302-322.

Kakuno, S. and Zhong, Y., 1993, A basic study on wave height reduction by a perforated horizontal plate placed in water, *Proc. Coastal Engrg., JSCE*, **40**, 666-670, in Japanese.

Uda et al., 1988, "A function and a design method of the reef breakwaters," *Report of the Public Works Research Institute*, **2696**, 79p., in Japanese.

Aoyama, T., Izumiya, T., Isobe, M., and Watanabe A., 1988, A basic study on wave height reduction by a horizontal plate placed in water, *Proc. 35th Japanese Conf. on Coastal Engrg., JSCE,* **35**, 507-511, in Japanese.