EVALUATION OF HYDRAULIC PERFORMANCE OF WAVE DISSIPATING BLOCK USING POROSITY

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The reflection and transmission of wave dissipating work mainly depend on the shape and porosity of wave dissipating block. However, the influence of the shape and porosity of wave dissipating block on the reflection and transmission has not been investigated sufficiently. The purpose of this study is to investigate the influence of the porosity of wave dissipating block on the reflection and transmission coefficients through a series of hydraulic experiments where four kinds of wave dissipating blocks were used. Wave dissipating blocks with smaller porosity provided a larger reflection coefficient and a smaller transmission coefficient as a whole. However, a wave dissipating block provided a smaller reflection coefficient and a smaller transmission coefficient in spite of relatively larger porosity. The measured reflection and transmission coefficients were compared with those estimated by existing equations.

Keywords: wave dissipating block; porosity; reflection; transmission

INTRODUCTION

Hydraulic performance of wave dissipating work such as the reduction of transmitted wave height, reflected wave height, wave overtopping, wave pressure acting on structures and so on mainly depends on the shape and porosity of wave dissipating block. Particularly, the porosity of wave dissipating block is strongly related to the amount of concrete for wave dissipating work, which means that the porosity of wave dissipating block is related to construction cost. If the wave dissipating blocks with a larger porosity are used in rubble mound structures, the construction cost can be reduced due to smaller amount of concrete.

The reflection and transmission of wave dissipating work have been investigated by many researchers. Sollitt and Cross (1972) theoretically investigated the wave motion in porous media and estimated the reflection and transmission coefficients. Madsen (1974) also theoretically investigated the wave motion in porous structures and obtained the reflection and the transmission coefficients from a linearized theory. Takeda *et al*. (1983) measured the transmission coefficient of rubble mound breakwaters in hydraulic experiments and proposed an equation for estimating the transmission coefficient. Allsop and Hettiarachchi (1988) summarized the reflection coefficient for various type of rubble mound structures. Dalrymple *et al*. (1991) theoretically investigated the fluid motion in porous media under the condition of oblique wave incidence. Losada *et al*. (1997) extended the theoretical model proposed by Dalrymple *et al*. (1991) to irregular wave conditions. Sakakiyama and Kajima (1992), Van Gent (1995) and Liu *et al*. (1999) computed the interaction between waves and rubble mound structures such as wave reflection and transmission. Van der Meer and Daemen (1994) and D'Angremond *et al*. (1996) analyzed the wave transmission through low-crested rubble mound structures and proposed an equation for estimating the transmission coefficient. Van der Meer *et al*. (2005) investigated the wave transmission through low-crested rubble mound structures in 2D and 3D experiments. Zanuttigh and van der Meer (2008) analyzed the wave reflection of sloping structures using an extensive database and derived an equation for estimating the reflection coefficient. Zanuttigh and Andersen (2010) investigated the influence of the wave angle of incidence and the wave directional spreading on the reflection coefficient using the data measured in a wave basin.

The authors have investigated the stability and hydraulic functions of rubble mound structures. Araki *et al*. (2002) measured and computed the deformation of a rubble mound seawall. Araki *et al*. (2005) measured the change in the transmission coefficient with deformation of a submerged rubble mound structure. Kubota *et al*. (2008) measured the wave force acting on an armor unit for a submerged breakwater and the stability of the armor unit. Fukumizu *et al*. (2018) measured and simulated the deformation of a rubble mound seawall under construction, which means the deformation of a rubble mound seawall without armoring. Hydraulic performance such as wave reflection and transmission mainly depends on the porosity and the shape of wave dissipating block for an incident wave as mentioned above. However, the influence of the porosity and the shape of wave dissipating block on the reflection and transmission coefficients has not been investigated sufficiently. In the present study, the influence of the porosity of wave dissipating block is investigated because the porosity directly affects the amount of concrete for wave dissipating work, *i.e.*, the construction cost.

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HYDRAULIC EXPERIMENT

Incident Wave and Measurement

A series of hydraulic experiments was conducted in a two-dimensional wave flume at Osaka University, which is 30 m long, 0.7 m wide and 1.0 m high, shown in Figure 1. A rubble mound structure was placed on the fixed flat bed in the wave flume. Irregular waves were generated and had the target spectrum of Modified Bretschneider-Mitsuyasu spectrum. The significant wave height at the rubble mound structure $H_{1/3}$ ranged from 0.04 m to 0.12 m. The significant wave period $T_{1/3}$ was 1.2, 1.5, 1.8 and 2.1 s. No significant wave overtopping was observed except a few cases. Water surface elevations in front of and behind the rubble mound structure were measured at the sampling rate of 20 Hz for approximately 200 s. The reflection coefficient K_r of the rubble mound structure was estimated by Goda's method as the square root of the ratio of the reflected wave energy to the incident wave energy (Goda and Suzuki, 1976). The transmission coefficient K_t was estimated as the ratio of the significant wave height measured behind the rubble mound structure to the significant wave height measured at the structure position without the rubble mound structure. The water surface elevation was measured twice under the same experimental condition. The reflection and transmission coefficients were given as the average of the estimation from measuring the water surface elevation twice.

Rubble Mound Structure

Each rubble mound structure was composed of the main part of wave dissipating blocks and the mound with the thickness of 0.08 m of crashed stones whose diameter of approximately 0.015 m. The main part was homogeneous and was composed of only one kind of wave dissipating block, which means

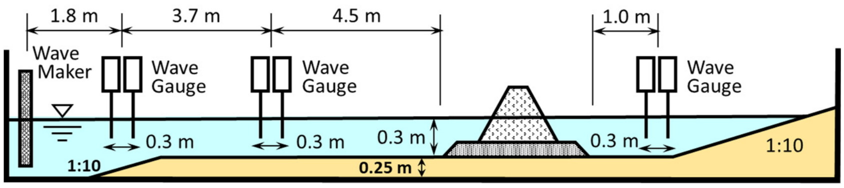


Figure 1. Experimental setup.

Table 1. Wave dissipating block used in experiment.

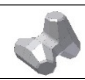
Block	Mass (kg)	Nominal Diameter (m)	Porosity ε	Surface Area (m^2)	Volume (m^3)	Shape
Tetrapod 1	0.1843	0.043	0.50	0.01184	0.8013×10^{-4}	
Tetrapod 2	0.3680	0.054		0.01877	1.600×10^{-4}	
Dolos II	0.1366	0.039	0.51	0.00964	0.594×10^{-4}	
Dolos	0.1280	0.038	0.575	0.01112	0.557×10^{-4}	
Tetraneo	0.3993	0.056	0.60	0.02346	1.736×10^{-4}	

Table 2. Dimension of rubble mound structure.

Block	B (m)	R (m)	cot α
Tetrapod 1	0.188	0.125	1.33
Tetrapod 2	0.236	0.157	1.33
Dolos II	0.156	0.130	1.3
Dolos	0.193	0.154	1.5
Tetraneo	0.210	0.176	1.3

that the main part had no core. Four kinds of wave dissipating blocks (Tetrapod, Dolos II, Dolos and Tetraneo) were used for making the main part of the rubble mound structure. As for Tetrapod, the rubble mound structures composed of smaller and larger Tetrapods were tested in order to investigate the influence of the dimension of the porosity on the reflection and transmission coefficients. Table 1 shows the mass, nominal diameter, porosity ε, surface area A and volume V for each block. Table 2 shows the crest width B and crest freeboard R and the slope cot α of the rubble mound structures. The dimension of the rubble mound structure for each type of wave dissipating block was determined by the design standard in Japan. The crest width B is determined by the diameter of the used wave dissipating block. The crest freeboard R is determined by the critical wave height used in estimating the stable mass of a wave dissipating block. The slope of the rubble mound structures is determined by the used wave dissipating block. The water depth at the toe of the rubble mound structure was 0.30 m in all the cases. Figures 2 shows the cross sections of the rubble mound structures composed of all the wave dissipating blocks. Figure 3 shows photos of the rubble mound structures composed of Dolos II and Dolos. No significant deformation in the profile of the rubble mound structures was observed. The model scale was assumed to be 1:75.

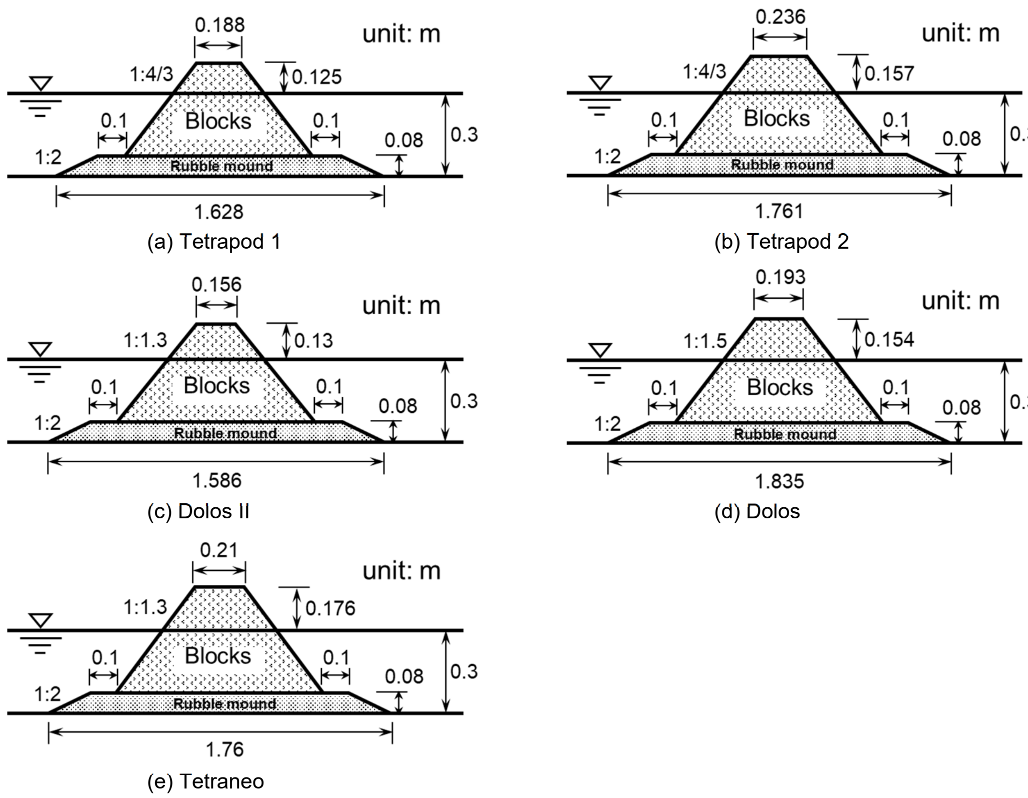


Figure 2. Cross section of rubble mound structure.

(a) Dolos II (b) Dolos

Figure 3. Photo of rubble mound structure.

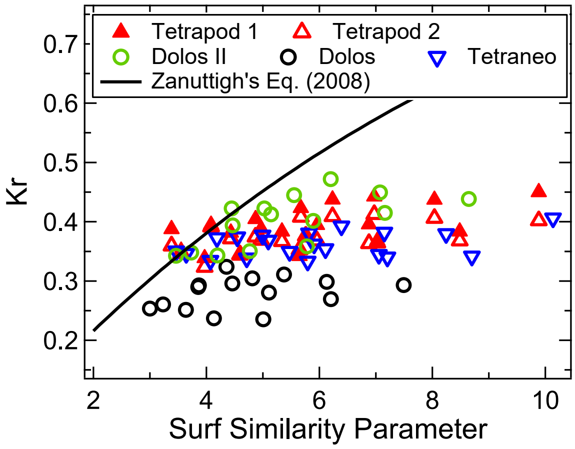


Figure 4. Reflection coefficient.

RESULTS & DISCUSSION

Reflection Coefficient Kr

The reflection coefficient *Kr* of the structure composed of the wave dissipating blocks with smaller porosity was larger as a general trend. Figure 4 shows the relationship between the reflection coefficient *Kr* and the surf similarity parameter ξ. The following equation for estimating the reflection coefficient proposed by Zanuttigh and Van der Meer (2008) was also illustrated.

$$K_r = \tanh(a \cdot \xi^b) \quad (1)$$

where ξ is the surf similarity parameter, and *a* and *b* are the coefficients. The reflection coefficient in the figure was estimated using the values $a = 0.12$ and $b = 0.87$. The influence of the porosity on the reflection coefficient is not included in this equation.

The surf similarity parameter ξ was defined by the following equation.

$$\xi = \frac{\tan\alpha}{\sqrt{(2\pi H_{1/3})/(g{T_{1/3}}^2)}} \quad (2)$$

where *g* is the acceleration due to gravity.

The reflection coefficient slightly increases with the increase in the surf similarity parameter, *i.e.*, with the decrease in the wave steepness of the incident wave. The reflection coefficient for the wave dissipating block with larger porosity is smaller among Tetrapod, Dolos II and Tetraneo. The reflection coefficient for Tetrapod is approximately the same as that for Dolos II because the porosity of Tetrapod ($\varepsilon = 0.50$) is similar to that of Dolos II ($\varepsilon = 0.51$). The reflection coefficient for Tetraneo is slightly smaller than that for Tetrapod and Dolos II because the porosity of Tetraneo ($\varepsilon = 0.60$) is larger than that of Tetrapod and Dolos II. On the other hand, the reflection coefficient for Dolos was smaller than that for Tetraneo although the porosity of Dolos ($\varepsilon = 0.575$) is smaller than that of Tetraneo. It possibly results from the complicated shape of Dolos. However, the reason is still under investigation. There was no significant difference in the reflection coefficients resulting from the difference between the block dimension of Tetrapods 1 and 2.

Zanuttigh and Van der Meer (2008) derived the equation from the results for rubble mound structures with core, which had a small porosity. Therefore, the reflection coefficient estimated by the equation is almost the same as or is larger than the measured reflection coefficient of the rubble mound structure composed of the wave dissipating block with smaller porosity, *i.e.*, Tetrapod and Dolos II. For larger surf similarity parameter, the difference between the reflection coefficients measured in this study and estimated by the equation is larger. This is because the wave transmission increases with the increase in the surf similarity parameter for the rubble mound structures without core in this study as described in the next section.

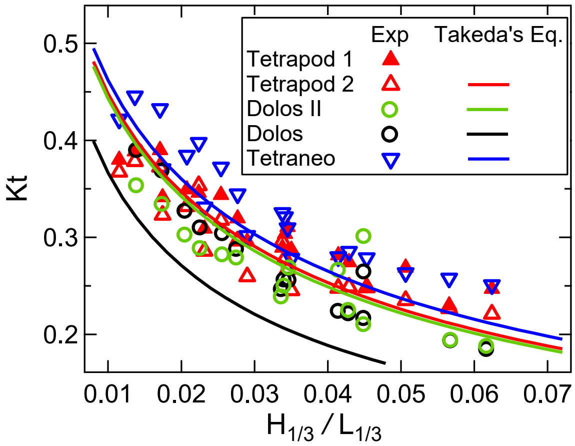


Figure 5. Transmission coefficient.

Transmission Coefficient Kt

The transmission coefficient Kt of the rubble mound structures composed of the wave dissipating blocks with smaller porosity was smaller as a general trend. Figure 5 shows the relationship between the transmission coefficient Kt and the wave steepness $H_{1/3}/L_{1/3}$ ($L_{1/3}$: the wavelength at the toe of the rubble mound structure calculated by the significant wave period $T_{1/3}$). The solid lines show the transmission coefficient estimated by the following equation proposed by Takeda *et al*. (1983).

$$K_t = \frac{1}{\left(1 + 0.32K_A\sqrt{H_i/L_i}\right)^2} \tag{3}$$

$$K_A = \frac{A(1-\varepsilon)B_0}{V} \tag{4}$$

where H_i and L_i are the wave height and wavelength of the incident wave, A and V are the surface area and the volume of a wave dissipating block and B_0 is the width of the rubble mound structure at the still water level.

This equation can be applied only to the cases where no wave overtopping is observed. The equation includes the influence of the porosity ε, the surface area and volume of a wave dissipating block and the width of the rubble mound structure as well as the wave steepness of the incident wave. The significant wave height $H_{1/3}$ and the wavelength $L_{1/3}$ were used as the incident wave height H_i and wavelength L_i in the equation. In the figure, the color of the solid lines shows the transmission coefficients estimated for each of the four wave dissipating blocks.

The transmission coefficient decreases with the increase in the wave steepness. The transmission coefficient for the wave dissipating block with larger porosity is larger among Tetrapod, Dolos II and Tetraneo. The transmission coefficient for Tetrapod is approximately the same as or slightly larger than that for Dolos II because the porosity of Tetrapod ($\varepsilon = 0.50$) is similar to that of Dolos II ($\varepsilon = 0.51$). The transmission coefficient for Tetraneo is larger than that for Tetrapod and Dolos II because the porosity of Tetraneo ($\varepsilon = 0.60$) is larger than that of Tetrapod and Dolos II. On the other hand, the transmission coefficient for Dolos is approximately the same as that for Dolos II although the porosity of Dolos ($\varepsilon = 0.575$) is different from that of Dolos II. It also possibly results from the complicated shape of Dolos. However, the reason is still under investigation. Some of the measured transmission coefficients for Dolos and Dolos II are larger at around $H_{1/3}/L_{1/3} = 0.045$ because relatively significant wave overtopping was observed in these experimental conditions. No significant wave overtopping was observed in other conditions. There was no significant difference in the transmission coefficients resulting from the difference between the block dimension of Tetrapods 1 and 2.

The equation proposed by Takeda *et al*. (1983) approximately estimated the measured transmission coefficients for Tetrapod, Dolos II and Tetraneo whereas the equation did not estimate the measured transmission coefficient for Dolos. However, the transmission coefficient estimated by the equation for Dolos is smaller than that for Tetrapod although the porosity of Dolos is larger than that of Tetrapod,

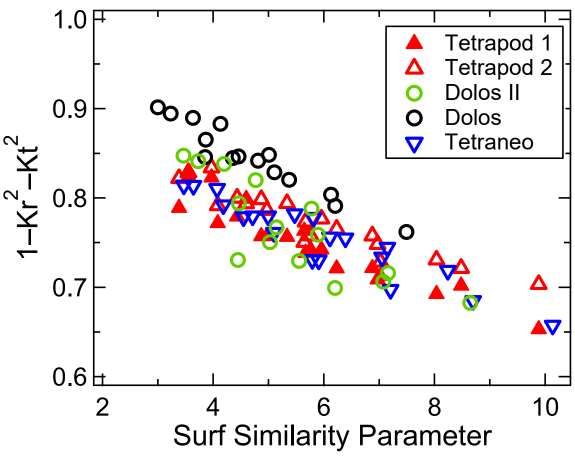


Figure 6. Energy dissipating rate.

which is similar to the transmission coefficients measured in the experiment. This is due to the effect of the shape of the wave dissipating block which is represented by the surface area and the volume of the wave dissipating block in Eq. (4). On the other hand, the equations for estimating the transmission coefficient proposed by Van der Meer and Daemen (1994) and D'Angremond *et al.* (1996) underestimated the transmission coefficient measured in this study because the rubble mound structures in their studies had a core with a smaller porosity under the armor layers.

Energy Dissipating Rate Ke

The energy dissipating rates *Ke* did not depend much on the porosity as a general trend. Figure 6 shows the relationship between the energy dissipating rate and the surf similarity parameter. The energy dissipating rate *Ke* was defined as the following equation.

$$K_e = 1 - {K_r}^2 - {K_t}^2 \qquad (5)$$

The energy dissipating rate decreases with the increase in the surf similarity parameter for all the wave dissipating blocks. The energy dissipating rates for Tetrapod, Tetraneo and Dolos II are almost the same in spite of different porosities, *i.e.* $\varepsilon = 0.50$ for Tetrapod, $\varepsilon = 0.51$ for Dolos II and $\varepsilon = 0.60$ for Tetraneo. This is because the wave dissipating work of Tetrapod has a relatively larger reflection coefficient and a relatively smaller transmission coefficient, and the wave dissipating work of Tetraneo had a relatively smaller reflection coefficient and a relatively larger transmission coefficient. On the other hand, the energy dissipating rate for Dolos is larger than any other wave dissipating blocks although the porosity of Dolos ($\varepsilon = 0.575$) is larger than that of Tetrapod and Dolos II and is smaller than that of Tetraneo. This is because the wave dissipating work of Dolos has a smaller reflection coefficient and a smaller transmission coefficient. If the hydraulic performance of the wave dissipating block is determined by only the energy dissipating rate, Dolos has the best hydraulic performance among the four wave dissipating blocks used in this experiment.

CONCLUSIONS

The reflection and transmission coefficients *Kr* and *Kt* of the rubble mound structures composed of the wave dissipating block with smaller porosity were larger and smaller among Tetrapod, Dolos II and Tetraneo, respectively. The reflection and transmission coefficients *Kr* and *Kt* of the rubble mound structures composed of the wave dissipating block with larger porosity were smaller and larger among Tetrapod, Dolos II and Tetraneo, respectively. On the other hand, the reflection coefficient for Dolos was smaller than that for Tetraneo although the porosity of Dolos is smaller than that of Tetraneo. The transmission coefficient for Dolos was almost the same as that for Tetrapod and Dolos II although the porosity of Dolos is larger than that of Tetrapod and Dolos II. As a result, the energy dissipating rate for Dolos was the largest among the four wave dissipating blocks used in this study whereas the energy dissipating rates for Tetrapod, Dolos II and Tetraneo were similar to each other in spite of different porosity. The equation proposed by Zanuttigh and Van der Meer (2008) overestimated the reflection coefficients measured in this study. This is because Zanuttigh and Van der Meer (2008) proposed the equation for estimating the reflection coefficients for rubble mound structures which had a core with smaller porosity. The rubble mound structures in this study had no core and the main part was composed of one kind of wave dissipating block. The equation proposed by Takeda *et al*. (1983) approximately estimated the transmission coefficients for Tetrapod, Dolos II and Tetraneo measured in this study whereas the equation underestimated the transmission coefficients for Dolos measured in this study.

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