EXPERIMENTAL STUDY OF WAVE BREAKING CRITERIA AND ENERGY LOSS CAUSED BY A SUBMERGED POROUS BREAKWATER ON HORIZONTAL BOTTOM

Yi-Chun Liao
Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C

Jyun-Han Jiang
Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C

Yi-Ping Wu
Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C

Chung-Pan Lee
Department of Marine Environment and Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, R.O.C,
cplee@mail.nsysu.edu.tw

Recommended Citation

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Yi-Chun Liao, Jyun-Han Jiang, Yi-Ping Wu, and Chung-Pan Lee

ABSTRACT

Study on the criteria of wave breaking and energy loss caused by a submerged porous breakwater on a horizontal bottom has been performed experimentally in a 2-D wave tank. Wave conditions as well as the freeboard of the submerged breakwater, with the front slope of 1/2 and 1/5, are varying in the experiments. Results show that almost all tested waves can be triggered to break when the ratio of the estimated equivalent deepwater wave height to the freeboard of the submerged breakwater is greater than one. Results also reveal that a milder front slope of submerged breakwater may not trigger wave breaking more efficiently as that with a steeper front slope does. Furthermore, for a given freeboard of submerged breakwater, longer waves are more difficult to be triggered to break than shorter waves as expected. It is found that a submerged breakwater function much more efficiently if waves can be triggered to break by the structure as expected. Furthermore, it is also found that the submerged breakwater with milder front slope consumes more wave energy than that with steeper one through a wider range of porous structure.

I. INTRODUCTION

Sea walls, jetties, and detached offshore breakwaters have been widely used in traditional shore protection in Taiwan coast. Around the main island, 560 km of 1140 km of coastal line are full of concrete structures and armor units. Nonvisible submerged breakwaters are then prevailing to reduce the environmental impact in the recent years for shore protec-

tion in Taiwan.

Submerged breakwaters have been used world-widely more than two decades. In Japan, an 80 m long and 20 m wide submerged breakwater was deployed 85 m offshore in approximately 4 m water depth with 2 m crest level below mean low water (MLW) at Keino-Matsubara Beach [4]. Another 540 m long and 20 m wide submerged breakwater was located 400 m offshore in approximately 8.5 m water depth with 1.5 m freeboard below mean water level (MWL) at Niigata in Japan [6]. In USA, a single submerged breakwater was 300 m long and was placed 75 m offshore in approximately 1 m water depth with crest below MLW at Delaware Bay [5]. And an 1260 m long submerged structure with 330 PEP reef units of size 1.8 m × 3.7 m × 4.6 m was located about 70 m from shoreline in about 3 m water depth with freeboard of 0.7 m below mean lower low water (MLLW) at Palm Beach, Florida [3]. In Australia, a 2 m width multi-functional artificial surfing reef was extended from about 100 m to 600 m offshore and 350 m alongshore in about 2-10 m water depth with 1 m freeboard below MLW at the Gold Coast [10].

Submerged breakwaters function to reduce wave energy in two ways, one is through the viscosity-induced resistant forces including the frictional drag and the form drag as wave-induced flow passing through the porous structure. Another is due to the energy loss when waves are triggered to break by the structure. In non-breaking cases, wave reflection and transmission over a submerged breakwater have been investigated in most previous studies. Dattatri *et al.* [2] showed that wave transmission is mainly affected by the structure crest width (B) and the freeboard of the structure below the sea surface (R). The studies from Van der Meer [16], D'Angremound *et al.* [1], and Seabrook and Hall [13] have resulted in some experimental formula for transmission coefficients (K_T). Furthermore, Van der Meer *et al.* [17] developed a transmission coefficient formula from previous experimental tests for waves passing a low crested structure with a wide range of incident wave conditions and structure geometry conditions. Rojanakamthorn *et al.* [12] derived a modified
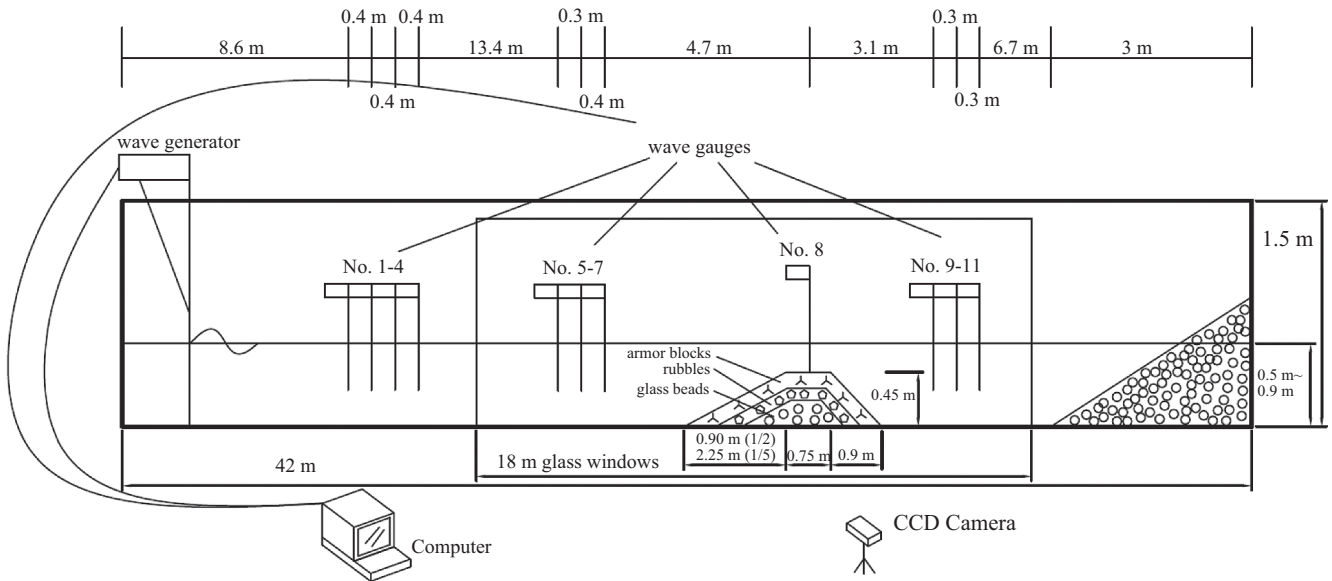
Fig. 1. Experimental layout.

mild-slop equation for modeling wave breaking on a sub-merged permeable breakwater, and a breaking index was used to be a criterion to find the incipient breaking point of breaking waves traveling over a permeable structure. Numerical models have been applied to study wave over sub-merged breakwaters, for examples, by Garcia *et al*. [7] and Johnson *et al*. [11]. The predicted results from numerical models in smooth structures are better than in rubble mound structures partly because the mechanism in the wave-breaking cases no proper turbulent model can be used in the models.

Wave transmission coefficients have been used in most design considerations in constructing a submerged break-water. For examples, Shirlal *et al*. [14] suggested that a sub-merged structure is constructed at a water depth of 1.5-5 m with a front slope of 1:2-1:3 and a height exceeding 0.7 times the located depth water. On the other hand, submerged struc-tures are designed generally for a K_T value of 0.6 [8]. However, wave energy loss caused by wave breaking is known more efficient than that due to viscosity-induced drags.

The purpose of the study is then to investigate the criteria for wave-breaking triggered by a submerged breakwater, and to compare the energy loss in wave breaking and non-breaking cases. A porous submerged breakwater is deployed on the horizontal bottom of a 2D wave flume in National Sun Yat-sen University, Kaohsiung, Taiwan. The details of the experi-mental design and data analysis are showed in section 2. The experimental results and discussions are shown in section 3, and the conclusion is given in section 4 of the article.

II. HYDRAULIC EXPERIMENTS

1. Wave Flume and Experimental Setup

The experiments were performed in the two-dimensional

Fig. 2. Three materials of the porous submerged breakwater. From left to right are the glass bead, the rubble rock, and the armor unit, respectively.

wave flume, Department of marine environmental and engi-neering, National Sun Yat-sen University, Taiwan. It is 42 m long, 1.5 m wide, and 1.5 m deep, one side has 18 m obser-vation-wall of 9×2 m glass windows. Regular and irregular waves can be generated by a position-type generator with a DHI Waves Synthesizer control system. Porous media are deployed at the end of the flume to reduce wave reflection.

The experimental layout is showed in Fig. 1. The porous submerged breakwater containing three layers (the glass beads in the core, covered by rubble rocks and armor units, see Fig. 2) is 0.45 m tall from the bottom with crest of 0.75 m width. Two front slopes of 1/2 and 1/5 were considered to compare the effect of the front slope on the breaking criteria and the energy loss by a submerged breakwater. The poros-ities of different front slope are both about 0.45. Water depth (*h*) will be varied to change the freeboard (*R*) of the sub-merged breakwater. Wave patterns including if waves are breaking have been recorded by a CCD camera. Waves along the wave flume were measured by 11 capacitance wave gauges at four different positions. Wave gauges marked by No. 1~4 were used for reference of incident waves. Data obtained from those marked by No. 5~7 were used to calculate the incident and reflected waves. The No. 8 gauge was setup to measure
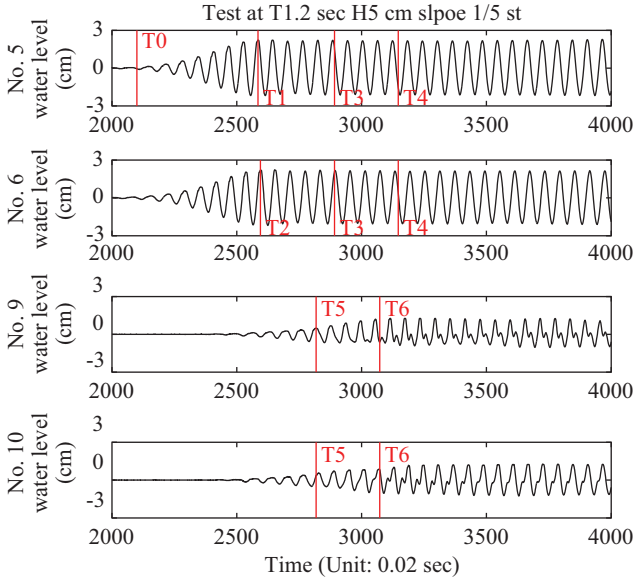
Fig. 3. Illustration of wave record used for analysis of K_R and K_T.

the wave variation above the structure. The transmitted waves behind the submerged breakwater were recorded and analyzed from the No. 9~11 wave gauges. All the signals were digitized by AD/DA at 50 Hz sampling rate and were recorded by a computer.

2. Wave Conditions

Since the purpose of the study is to find the wave breaking criteria, testing wave conditions are first selected according the wave steepness (δ), ranged from 0.02 to 0.05, for 6 wave periods (T_0) from 1.2 sec to 2.7 sec with 0.3 sec interval, and 15 wave heights (H_0) from 0.05 m to 0.33 mm with 0.02 m interval. The water depth (h) is varying from 0.5 m to 0.9 m with 0.05 m interval. The wave steepness is defined by Eq. (1). The deep wave length (L_0) is computed from the dispersion equation (Eq. 2) for linear waves. There were 876 tests including 35 repeated tests for verification in the study.

$$\delta = H_0 / L_0 \tag{1}$$

$$L_0 = \frac{gT_0^2}{2\pi} \tanh(\frac{2\pi h}{L_0}) \tag{2}$$

3. Data Analysis

Wave records used for the analysis of reflection (K_R) and transmission (K_T) coefficients are illustrated in the Fig. 3. The time marked with t0 shows the arrival of the first wave, and t1 marks the time of the first matured wave at No. 5 wave gauge. The incident wave period (T) is extracted from this wave gauge by zero up-crossing. By tracking the arrival time of the waves from Gauges No. 5 to No. 6, e.g. marked with t2, wave speed and the corresponding wave length (L) can be calculated

from the time difference and the distance of the two wave gauges. The arriving time at Gauge No. 5 of reflected waves from the leading edge of the submerged breakwater can also be tracked and marked with t3 in this case. Wave data of Gauges No. 5 and No. 6 from t3 to same later time, t4, are then used to extract the incident and reflected wave heights (H_I and H_R, respectively) by the method of Goda and Suzuki [9]. The same process is used to compute H_I and H_R from the wave data sets of Gauge No. 6-7 and No. 5-7. Average values are then taken from the results. Similar procedure is applied to calculate the transmitted wave height (H_T) from the data in Gauges of No. 9 and 10 where t5 and t6 mark the arrival times of incident waves (the transmitted waves) and reflected waves (from the loss end of the wave tank) on the lee side of the breakwater. The waveforms of Gauges No. 9 and 10 were obviously affected by the waves reflected from end of flume after t6. Therefore, the data between t5 and t6 are the optimal chooses for the analyses despite the waveforms are slightly unstable. The reflection and transmission coefficients, K_R and K_T, are then defined in Eqs. (3) and (4), respectively,

$$K_R = H_R / H_I \tag{3}$$

$$K_T = H_T / H_I \tag{4}$$

III. RESULTS AND DISCUSSIONS

In the followings, the dimensionless parameter $\sigma^2 h/g$, $\sigma = 2\pi/T$, will be used to represent the dependence on waves. An equivalence deepwater wave height estimated from regular waves is considered and defined as $H'_0 = H/K_S$ to replace the deepwater wave height, in which H is the wave height at water depth (h). Shuto [15] showed that the shoaling coefficient K_S depends on Ursell number ($U_r = gHT^2/h^2$) as Eqs. (5) and (6), where $K = 2\pi/L$.

$$\frac{H}{H_0} = \sqrt{\frac{1}{2n} \frac{1}{\tanh kh}} \qquad\qquad U_r < 30$$

$$Hh^{2/7} = \text{constant} \qquad\qquad 30 \leq U_r < 50 \tag{5}$$

$$Hh^{2/5}\left(\sqrt{\frac{gHT^2}{h^2}} - 2\sqrt{3}\right) = \text{constant} \quad U_r \geq 50$$

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

The results of wave transmission coefficient are compared with those obtained from the empirical formulas by Van der Meer et al. [17], as shown in Fig. 4. The values calculated from empirical formulas are averagely higher than the measured values. A possible reason is due to the difference of analysis method on the transmitted wave height. In this study, the waves reflected from the end of the flume were eliminated
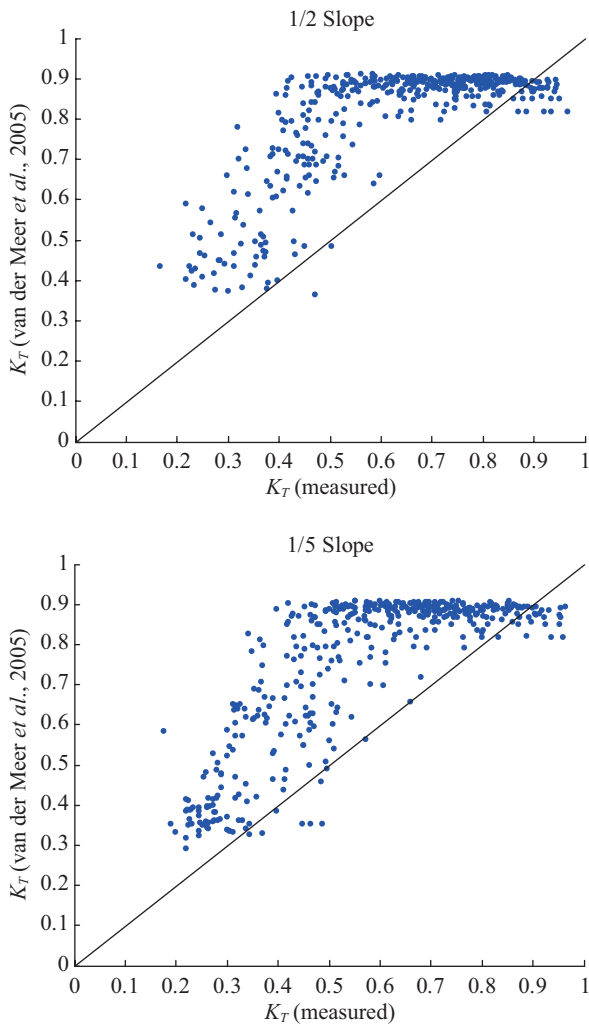
Fig. 4. Comparison of the transmission coefficient between the study and that calculated from the empirical formulas (van der Meer *et al.*, 2005). Top is for 1/2 front slope and bottom is for 1/5 front slope.

Fig. 5. Breaking (color or non-circle) *vs.* non-breaking (black or circle) conditions by a submerged porous breakwater with a front slope of (top) 1/2, and (bottom) 1/5, respectively. Plotted with respect to $\sigma^2 h/g$.

from the leeside wave records before computing the transmitted wave height and this decreased the values of transmission coefficient.

1. Criteria for Breaking wave by the Porous Submerged Breakwater

Whether waves are breaking or not is judged from the recorded tapes for each corresponding wave and structure condition. The positions of breaking waves are further noted to distinguish if the waves are triggered by the submerged breakwater. The non-breaking cases are marked with dark circles, and those of breaking are marked with color legends, including the ones marked by triangles, in which waves broke before they hit the breakwater.

As shown in Fig. 5, plotted with respect to $\sigma^2 h/g$ ranged in between about 0.3 to 2.7, almost all waves are triggered to break as the ratio of the estimated equivalent deepwater wave height to the freeboard of the submerged breakwater is greater
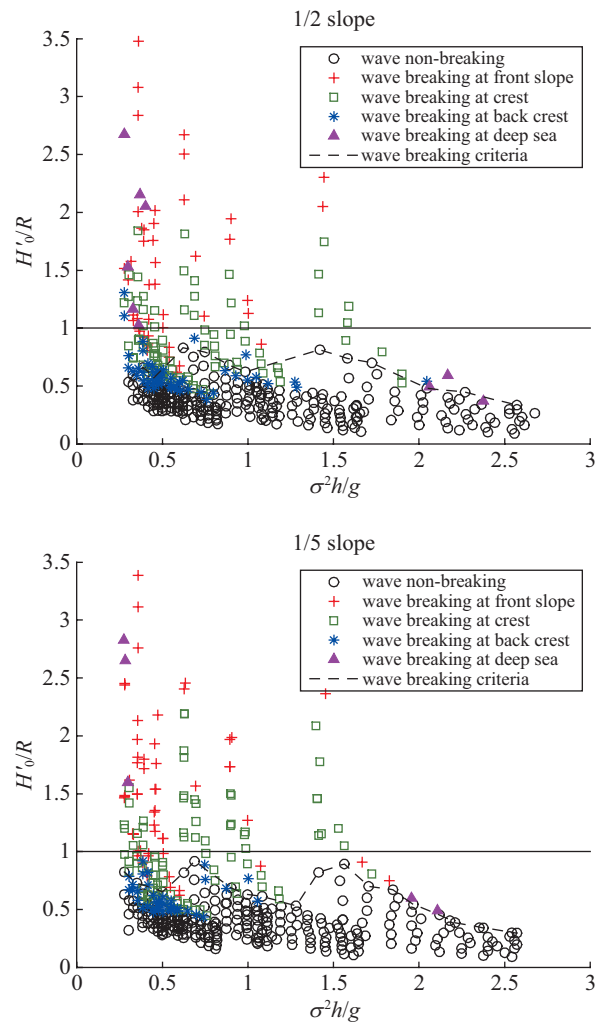
than one, i.e. $H'_0/R > 1$, with only one exception for the breakwater with 1/5 front slope in all tested conditions. It is interesting to note that the milder front slope of submerged breakwater does not trigger wave breaking more efficiently as expected. On the contrast, comparing to the case with 1/2 front slope, waves with larger wave height (or H'_0/R) may survive and not break as they travel over the breakwater as shown in the figure. The reason for this may be because the submerged breakwater with milder front slope dissipates more wave energy caused by the resistance force as the waves travelling over a wider porous area, and therefore reduce the risk to break. This can be found in the next section. Similar trend has been found as the breaking criteria are plotted with respect to *B/L* as shown in Fig. 6.

It is also noted that the data in the figures are seemly fallen in several groups, about three and four in Fig. 5 and Fig. 6, respectively. This is due to only six digital wave periods have been used. In each group of data, the criteria H'_0/R have a
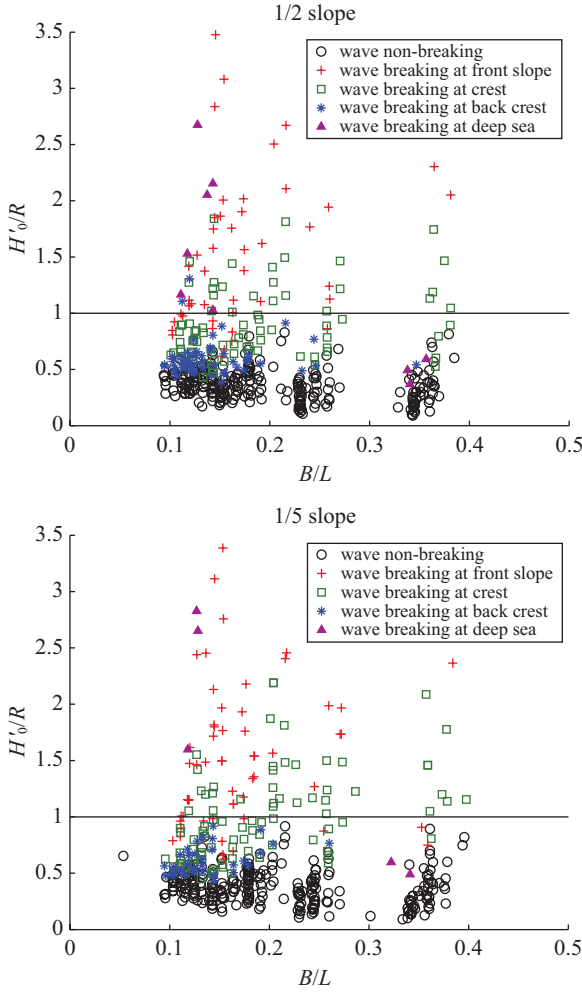
Fig. 6. Breaking (color or non-circle) *vs* non-breaking (black or circle) conditions by a submerged porous breakwater with a front slope of (top) 1/2, and (bottom) 1/5, respectively. Plotted with respect to B/L.
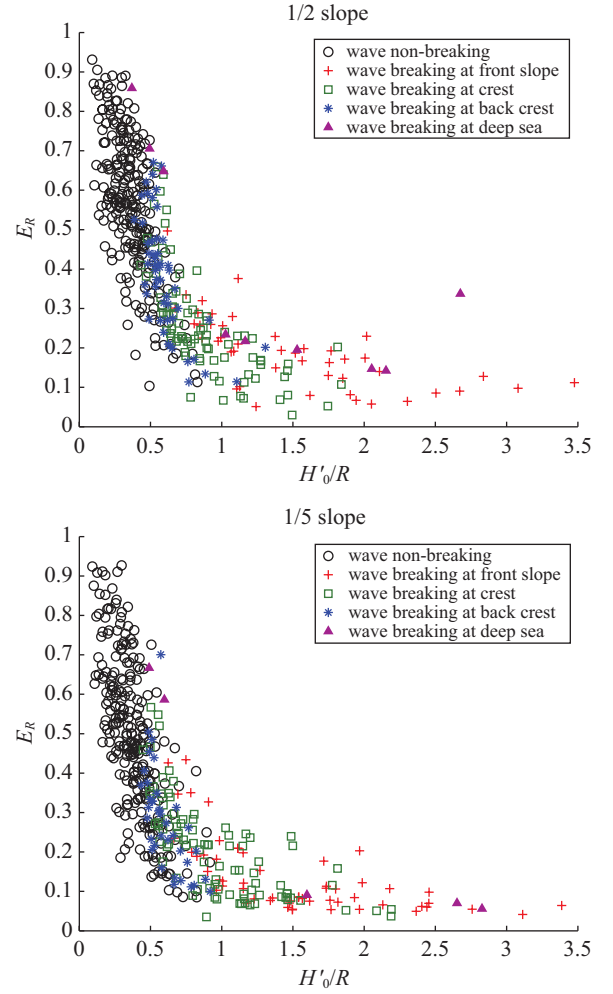

Fig. 7. The residual wave energy for a submerged porous breakwater with a front slope of (top) 1/2, and (bottom) 1/5, respectively.

trend to increase as both of $\sigma^2 h/g$ and B/L decrease as shown in the figures. This reveals that, for a given freeboard of submerged breakwater, longer waves may not be triggered to break while shorter waves break.

2. Wave Energy Loss

In order to study the wave energy loss caused by the submerged porous breakwater, a residual or left energy (E_R) is defined as in Eq. (7), where K_R and K_T represent the reflection and transmission coefficient, respectively. Wave energy loss (rate) is then the difference of 1 and E_R.

$$E_R = K_R^2 + K_T^2 \qquad (7)$$

As shown in Fig. 7, E_R plotted with respect to H'_0/R, wave energy can be greatly dissipated if waves are triggered to break comparing to non-breaking cases in both front slopes as expected. This ensures that a submerged breakwater will
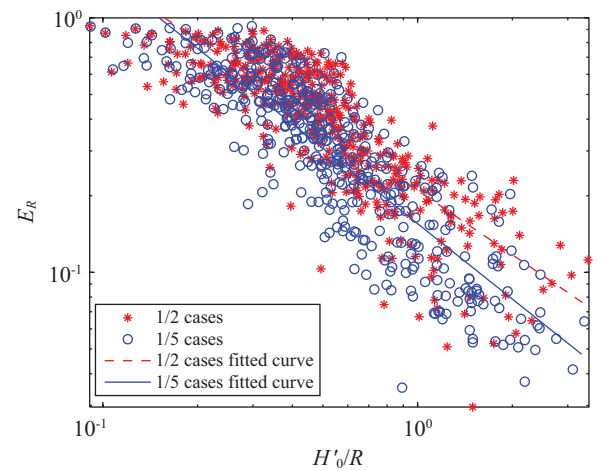

Fig. 8. The residual wave energy in logarithmic coordinates for a submerged porous breakwater with a front slope of 1/2 (red or star), and 1/5 (blue or circle), respectively. The linear fitting results are presented by dash (red) line and solid line (blue), respectively.
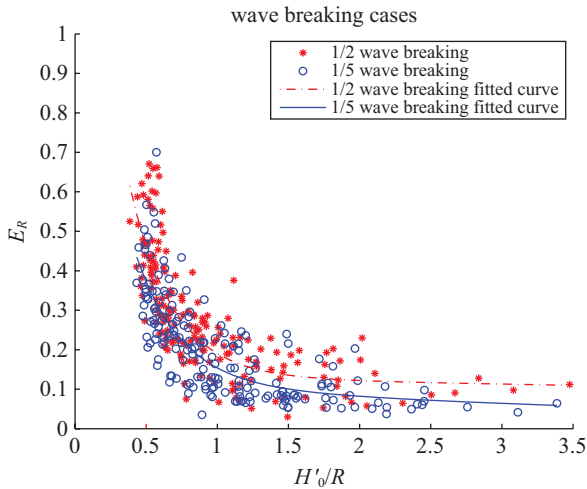
Fig. 9. **The residual wave energy with fitted curves for a submerged porous breakwater with a front slope of 1/2 (red or star), and 1/5 (blue or circle), respectively. Curves are fitted for only the data of wave breaking.**
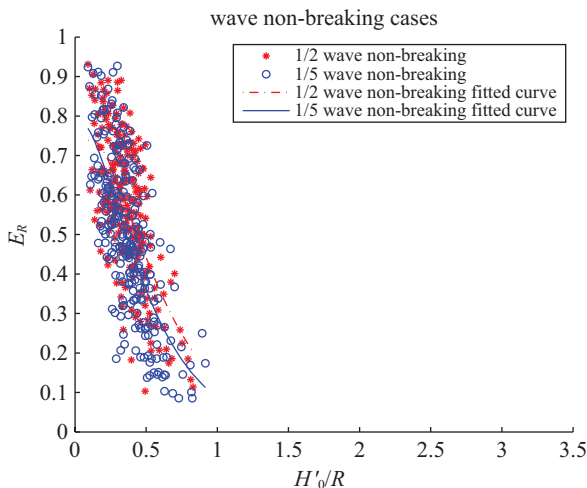

Fig. 10. **The residual wave energy with fitted curves for a submerged porous breakwater with a front slope of 1/2 (red or star), and 1/5 (blue or circle), respectively. Curves are fitted for only the data of non-breaking waves.**

function much more efficiently if waves can be triggered to break by the structure. The trend of Fig. 7 can also be plotted in logarithmic coordinates, and result shows a linear distribution as shown in Fig. 8. Furthermore, it is also found that the submerged breakwater with front slope of 1/5 consumes more wave energy than that with 1/2 front slope as shown in Fig. 9 and Fig. 10 for breaking waves and non-breaking waves, respectively. This may imply that the milder front slope does dissipate more wave energy through a wider range of porous structure comparing to the steeper front slope.

3. Repeated Tests

The conditions of repeated tests were selected randomly to create wave and record. Table 1 shows the results of breaking

Table 1. The result of 35 repeated tests with K_R, K_T, E_R and breaking position.

Condition				Breaking position		K_R		K_T		E_R	
T_0 (sec)	H_0 (m)	H (m)	R (m)	1st	2nd	1st	2nd	1st	2nd	1st	2nd
1.5	0.15	0.9	0.45	0	0	0.072	0.063	0.759	0.726	0.582	0.532
1.8	0.19	0.85	0.4	0	0	0.041	0.066	0.780	0.807	0.610	0.655
2.4	0.13	0.75	0.3	0	0	0.130	0.130	0.803	0.802	0.662	0.661
1.2	0.05	0.55	0.1	0	0	0.079	0.047	0.572	0.575	0.333	0.333
1.2	0.07	0.5	0.05	2	2	0.067	0.032	0.298	0.260	0.093	0.069
1.2	0.09	0.5	0.05	2	2	0.050	0.049	0.302	0.304	0.094	0.095
1.2	0.09	0.85	0.4	0	0	0.048	0.057	0.890	0.921	0.795	0.852
1.5	0.09	0.5	0.05	2	2	0.108	0.055	0.368	0.343	0.147	0.121
1.5	0.11	0.5	0.05	2	2	0.066	0.053	0.485	0.461	0.240	0.216
1.5	0.13	0.5	0.05	1	1	0.069	0.072	0.321	0.328	0.108	0.113
1.5	0.15	0.5	0.05	1	1	0.074	0.070	*0.341*	*0.443*	0.122	0.203
1.5	0.17	0.55	0.1	2	2	0.058	0.049	0.460	0.493	0.215	0.246
1.8	0.07	0.5	0.05	2	2	0.052	0.067	0.258	0.256	0.069	0.070
1.8	0.09	0.5	0.05	2	2	0.050	0.063	0.285	0.273	0.083	0.079
1.8	0.09	0.85	0.4	0	0	0.055	0.038	*0.787*	*0.904*	*0.623*	*0.818*
1.8	0.11	0.5	0.05	2	2	0.070	0.051	*0.217*	*0.395*	*0.052*	*0.158*
1.8	0.11	0.85	0.4	0	0	0.055	0.019	0.724	0.755	0.528	0.570
1.8	0.13	0.5	0.05	2	2	0.040	0.045	0.189	0.229	0.037	0.054
1.8	0.15	0.5	0.05	1	1	0.046	0.049	0.310	0.244	0.098	0.062
1.8	0.15	0.7	0.25	0	0	0.032	0.031	0.537	0.528	0.289	0.279
1.8	0.17	0.55	0.1	2	2	0.062	0.047	0.334	0.287	0.115	0.084
1.8	0.21	0.85	0.4	0	0	0.058	0.024	0.691	0.636	0.481	0.404
2.1	0.09	0.5	0.05	2	2	0.089	0.086	0.277	0.270	0.085	0.080
2.1	0.11	0.5	0.05	1	1	0.064	0.113	0.257	0.261	0.070	0.081
2.1	0.11	0.65	0.2	0	0	0.102	0.102	0.555	0.568	0.319	0.333
2.1	0.13	0.5	0.05	1	1	0.095	0.098	0.260	0.271	0.077	0.083
2.1	0.15	0.5	0.05	1	1	0.100	0.099	0.273	0.276	0.084	0.086
2.1	0.17	0.55	0.1	2	2	0.095	0.115	0.458	0.453	0.219	0.218
2.1	0.21	0.55	0.1	1	1	0.094	0.094	0.448	0.448	0.209	0.209
2.4	0.07	0.55	0.1	0	0	*0.054*	*0.164*	0.367	0.351	0.138	0.150
2.4	0.11	0.5	0.05	1	1	0.065	0.066	0.221	0.225	0.053	0.055
2.4	0.13	0.5	0.05	1	1	0.060	0.079	0.262	0.218	0.072	0.054
2.4	0.15	0.5	0.05	1	1	0.083	0.069	0.242	0.223	0.066	0.054
2.7	0.11	0.5	0.05	2	2	0.083	0.076	0.249	0.244	0.069	0.065
2.7	0.13	0.5	0.05	1	1	0.061	0.078	0.258	0.231	0.070	0.059

*Breaking position: 0 is wave non-breaking, 1 is wave breaking at front slope, 2 is wave braking at crest.

record and analysis. Case 1 to case 3 are at the submerged breakwater with front slopes of 1/5 and case 4 to case 35 are at front slopes of 1/2. The No. 1 at the column of breaking position means wave non-breaking, No. 2 means wave breaking at front slope and No. 3 means wave breaking at crest. The values of fewer cases (marked with italic and boldface) have different over 0.1, most of the repeated cases have the same results. The credibility in this study is good for the present result of the criteria of wave breaking by a submerged porous breakwater.

IV. CONCLUSIONS

Investigation on the criteria of wave breaking and energy loss caused by a submerged breakwater on a horizontal bot-

tom has been studied experimentally in a 2-D wave tank. Wave conditions of T and H as well as the freeboard of the submerged breakwater, with the front slope of 1/2 and 1/5, are varying in the experiments. Reflected and transmitted waves are recorded by wave gauges for the analysis of wave energy loss. Wave pattern around the breakwater is videoed by CCD cameras to judge if waves are triggered to break by the structure.

Results show that almost all waves can be triggered to break when the ratio of the estimated equivalent deepwater wave height to the freeboard of the submerged breakwater is greater than one, i.e. $H'_0/R > 1$, in all tested conditions. Results also reveal that a milder front slope of submerged breakwater may not trigger wave breaking more efficiently as that with a steeper front slope does and allow waves with larger wave height (or H'_0/R) to travel without breaking over a submerged breakwater with milder front slope. This may be because the submerged breakwater with milder front slope dissipates more wave energy caused by the resistance force as the waves travelling over a wider porous area, and therefore reduce the risk to break. Furthermore, the criteria H'_0/R have a trend to increase as both of $\sigma^2 h/g$ and B/L decrease. This implies that, for a given freeboard of submerged breakwater, longer waves are more difficult to be triggered to break than shorter waves as expected.

On concern with wave energy loss, it is found that a submerged breakwater will function much more efficiently if waves can be triggered to break by the structure. Furthermore, it is also found that the submerged breakwater with front slope of 1/5 consumes more wave energy than that with 1/2 front slope. This may imply that the milder front slope does dissipate more wave energy through a wider range of porous structure comparing to the steeper front slope.

Further study will be done for inclined seabed for reality. Longer wave conditions with smaller $\sigma^2 h/g$ values can also be considered to improve the range of applicability.

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