Porosity effects on non-breaking surface waves over permeable submerged breakwaters

Chao-Lung Ting*, Ming-Chung Lin, Chih-Yuan Cheng

National Taiwan University, Department of Naval Architecture and Ocean Engineering, 73 Chow-Shan Road Taipei 106, Taiwan, People’s Republic of China

Received 5 July 2001; received in revised form 10 September 2003; accepted 13 October 2003

Abstract

This study investigated how the porosity of submerged breakwaters affects non-breaking wave transformations. Eight model geometries each with six different porosities, from 0.421 to 0.912, were also considered. Experimental results reveal that the model width has little effect on wave reflection and transmission when the model heights are fixed. The transmission coefficient is maximum at a \( kh \) in the range from 1.3 to 2.0 and minimum at a \( kh \) around 0.7. The wave reflection maximum is at \( kh \) of near 0.5. The energy loss of the primary waves is maximum near \( kh = 0.81 \) and minimum when the porosity of the model is large. Porosity does affect wave transformation and its influence becomes significant as the heights of the models increase. For the range of porosities tested, wave energy loss from the primary harmonic was found to be almost constant at around 0.4 when \( kh > 1.3 \), decreasing slowly when \( kh < 1.3 \); wave energy loss decreases for porosities above 0.75.

© 2003 Elsevier B.V. All rights reserved.

Keywords: Porosity effect; Reflection coefficient; Transmission coefficient; Permeable submerged breakwater; Energy loss

1. Introduction

Preventing land erosion by wave attacks and minimizing the impact of waves on shores is an important topic in coastal engineering. Different protection devices, including submerged breakwater, have thus been developed. Submerged breakwaters are characterized by their minimal impact on disturbance of ship navigation. Some waves may break earlier due to submerged breakwaters which can induce large wave dissipation. The heights of other waves can be reduced by increasing the friction and permeability of these breakwaters. Thus, incident wave energy can be dissipated before hitting the shores. Related research has been done in this area over several decades.

Newman (1965) studied waves propagating over long two-dimensional obstacles. He found that the presence of submerged obstacles could induce totally reflected waves or totally transmitted waves. Similar research, such as that by Davies and Heathershaw (1984), Naciri and Mei (1988), Liu and Yue (1998), has also been done on surface waves’ passing rapidly varying sea bottoms. Bragg resonance was observed. As resonance occurs, the reflected wave height increases significantly.

Most sea bottoms and submerged breakwaters are permeable or porous. The theories elucidated above...
may not describe wave fields accurately. Therefore, the permeability effect was considered. Sollitt and Cross (1972) developed a widely used model of porous flow induced by waves. Izumiya (1990) theoretically examined waves’ propagating over a permeable submerged breakwater. Losada et al. (1993) analyzed the damping effects of upright porous walls on surface waves. Their theoretical results agree very closely with the experimental data of Twu and Lin (1990). Losada et al. (1995) experimentally studied wave-induced flow in a porous structure. Losada et al. (1996a,b) investigated non-breaking regular waves and non-breaking directional random waves’ interacting with permeable submerged breakwaters. Losada et al. (1997) investigated harmonic generation on waves passing porous structures. They found that harmonic generation depends on a Ursell number, a higher Ursell number and a higher chance to generate harmonics. Mase et al. (1995) studied waves’ propagating over one dimensional and two dimensional permeable rippled beds both theoretically and experimentally. Ting et al. (2000) and Zhu (2001), for example, are continuing related research. Although investigators realized the importance of permeability in nearshore wave transformations, the details of the porosity effect are still unknown.

Gu and Wang (1991) experimentally and theoretically investigated wave interactions with rigid granular sea beds. Twelve different porous gravel beds were tested in a laboratory. The tested porosities varied from 0.349 to 0.382. Wave damping rates were measured for different porous sea beds. Dattatri et al. (1978) also experimentally studied the porosity effect on wave transformation, over permeable submerged breakwaters, comprehensively addressing the advantages of submerged breakwaters. The four porosities tested were 1 (a thin plate), 0.42, 0.41 and 0 (impermeable). The authors concluded that porosity does not significantly affect the transmission coefficient. The latter two works addressed the porosity effect in more detail. However, the porosity was confined to a small range of 0.35–0.42. The actual influence of porosity remains uncertain. Therefore, an advanced investigation of the porosity effect on wave transformation is still required.

This research was motivated by a concern for artificial habitats for marine life. Since numerous such habitats are situated near the coast of Taiwan, utilizing them to protect shores efficiently is very important. These habitats appear to be porous submerged breakwaters. Therefore, understanding the influences of porosity on wave transformations facilitates the design of artificial habitats. The porosity examined in this research varied from 0.421 to 0.912. Various porosities with different breakwater geometries were studied to yield more information about porosity effects on wave fields.

2. Experimental setup

Experiments were performed in a wave flume with dimensions of 20 m (length) × 0.83 m (width) × 0.8 m (height). A programmable piston-type wave maker installed at one end of the tank was controlled using a PC 586 personal computer with National instruments’ Labview software. A feedback displacement transducer monitored the wave-maker behavior. At the other end of the tank, a 1:10 sloping beach served as a wave absorber to diminish reflected waves. Experimental results confirmed that this device damped out most incident wave energy and that reflected wave amplitudes were below 5% of the incident wave amplitudes. Therefore, the effects of the tank-end reflected waves were neglected.

Fig. 1 depicts the experimental setup. The operational water depth, h, was maintained at 27.5 cm and \( h_s \) was the vertical distance between the top of the model and the still water level. Tested models were located at the middle of the tank and 9 m away from the wave maker. Four capacitance-type wave gauges were used to measure surface elevations. The upstream three, numbered #1, #2, and #3, were used to record the incident and reflected waves in front of the models. The #4 gauge was located downstream to record waves transmitting over models. The distances between these gauges and models were maintained so as to avoid the effects of evanescent modes.

Fig. 2 displays the features of a typical model unit and of tested models. Fig. 2a is a sketch of a typical model unit. Each model unit is constructed from treated wood with a square cross-section and looks like a frame-type rectangular structure. Six different porous model units were manufactured, representing six different porosities varying from 0.421 to 0.912. Porosity, \( n \), is defined as the volume of empty space in
a model unit divided by the total geometrical volume \((= 82 \times 41 \times 7 \text{ cm}^3)\) of the model unit. Table 1 presents detailed dimensions of each porous model unit. Column 2 in Table 1 contains the porosity values for each model unit. The \(a, b, c,\) and \(t\) values in columns 3–6 represent the physical dimensions marked in Fig. 2a.

Six identical units for each porous model are used to form eight different model geometries as shown in Fig. 2b in which the small rectangular shapes represent the side views \((41 \times 7\) surfaces) of model units. Table 2 gives the geometrical dimensions and relative conditions of each model geometry. The first column gives model types which are named by \(Cxx\). The first digit \(x\) represents the numbers of model units (with the same porosity) in water-depth direction (which means model height is \(x\) times 7 cm equal to \(h - h_s\)) and the second digit \(x\) represents the number of same porous model units along the tank direction (which shows model width is \(x\) times 41 cm equal to \(W\) in Table 2). The second column in the table shows the total length, \(W\), of the model along the tank. The \(h_s\) values are listed in column 3 and the ratios of \(W/h\) and \(h_s/h\) are shown in columns 4 and 5, respectively. The lengths of each model in the cross-tank direction were fixed at 82 cm, less than the width of the flume, 83 cm. Two gaps 0.5 cm wide, on each side between the models and the walls of the tank, were used to insert wedges to fix the models firmly inside the tank. The wave gauges were properly positioned in the center of the tank. No transverse surface oscillations occurred in the tank while measurements were taken.

Table 3 presents incident wave conditions. The incident wave frequencies were selected from 0.5 to 1.8 Hz due to the limitations of the wave-making equipment. Each of the eight model geometries with six different porosities was tested at 14 distinct frequencies in the specified range. The second column in Table 3 present the corresponding wave

---

**Table 1**

<table>
<thead>
<tr>
<th>Model unit type</th>
<th>Porosity</th>
<th>(a) (cm)</th>
<th>(b) (cm)</th>
<th>(c) (cm)</th>
<th>(t) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.912</td>
<td>18.63</td>
<td>4.00</td>
<td>18.25</td>
<td>1.50</td>
</tr>
<tr>
<td>B</td>
<td>0.847</td>
<td>8.56</td>
<td>4.00</td>
<td>8.38</td>
<td>1.50</td>
</tr>
<tr>
<td>C</td>
<td>0.805</td>
<td>5.82</td>
<td>4.00</td>
<td>6.40</td>
<td>1.50</td>
</tr>
<tr>
<td>D</td>
<td>0.736</td>
<td>3.87</td>
<td>4.00</td>
<td>4.14</td>
<td>1.50</td>
</tr>
<tr>
<td>E</td>
<td>0.588</td>
<td>3.71</td>
<td>3.00</td>
<td>3.57</td>
<td>2.00</td>
</tr>
<tr>
<td>F</td>
<td>0.421</td>
<td>3.18</td>
<td>2.00</td>
<td>3.00</td>
<td>2.50</td>
</tr>
</tbody>
</table>
lengths determined from linear theory for the still water depth. The incident wave height and the relative wave steepness are listed in the third and fourth columns of Table 3, respectively. The incident wave heights were chosen according to the principle of no wave-breaking occurrences in the wave field. Therefore, no energy dissipation in wave transformation was caused by wave breaking. The fifth column in the table presents the \( kh \) values, where \( k \) is the wave number.

The sampling rate of recording was fixed at 100 Hz. The recorded time of each measure was limited to 40 s to avoid the second reflection caused by the wave board contaminating the reflected wave field. Data was analyzed according to the method presented by Goda and Suzuki (1976). The time series records from wave gauges #1, #2, and #3 were used to analyze the reflected wave field. The choice of which two records to be analyzed depended on the following condition given by Goda and Suzuki (1976).

\[
0.05 < \frac{\Delta \lambda}{L} < 0.45, \quad (1)
\]

where \( \Delta \lambda \) was the distance between any two wave gauges and the \( L \) was the incident wave length. The reflected wave height, \( H_R \), and incident wave height, \( H_I \), could be obtained following the data analysis. Therefore, the reflection coefficient, \( K_R \), is expressed by,

\[
K_R = \frac{H_R}{H_I}. \quad (2)
\]

The time-series record of wave gauge #4 was Fourier-transformed to obtain the transmitted primary-frequency wave height, \( H_T \), such that the transmission coefficient, \( K_T \), was obtained by,

\[
K_T = \frac{H_T}{H_I}. \quad (3)
\]

The primary wave energy loss, \( E_{\text{loss}} \), is defined by

\[
E_{\text{loss}} = 1 - K_T^2 - K_R^2. \quad (4)
\]

Each test was started with a quiescent surface. The tested model was fixed firmly in the tank and no waves were generated by vibration. Surface elevations were recorded from the time at which the waves were first made. Four 40-s-long time series were recorded simultaneously after the reflected waves caused by models reached wave gauge #1. Each experiment followed the same procedure. Eight cases were arbitrarily selected to examine the repeatability of experiments. Each case was tested at least four times. The results showed that the variances of \( K_R \) and \( K_T \) in each case were less than 5% and 2% of the mean of all measurements, respectively. The results were thus assumed to be repeatable.

### 3. Results and discussion

Eight model geometries, each with six different porosities (48 cases) were examined in the laboratory.
to elucidate the effects of the porosity of permeable submerged breakwaters on wave transformations. Models with identical porous (rectangular) geometry were constructed from the same materials to avoid any other influences on the energy dissipation. Each case was tested under 14 different incident wave conditions (see Table 3).

Fig. 3 shows the experimental results concerning wave reflection and transmission. Six sub-graphs, (a) to (f), demonstrate the results obtained using models with porosities of 0.912, 0.847, 0.805, 0.736, 0.588, and 0.421, respectively. The $K_R$ and $K_T$ values were plotted on the left and right of each sub-graph, respectively. Eight symbols in each graph represent
the experimental results obtained using eight types of models. The graphs indicate the effect of model’s geometry on the wave reflection and transmission at a given model porosity.

As shown in Fig. 3, the geometrical effect of the model becomes apparent as the porosity declines. The value of $K_R$, the left graph in each sub-graph, was considered first. The $K_R$ is maximum near

![Graphs showing wave reflection and transmission coefficients](image)

Fig. 4. Wave reflection and transmission coefficients due to surface waves’ traveling over submerged obstacles with various porosities. Subgraphs (a) to (h) show results for models C12, C14, C16, C21, C22, C23, C31 and C32, respectively. •: porosity = 0.912, ■: porosity = 0.847, ▲: porosity = 0.805, ◆: porosity = 0.736, ●: porosity = 0.588, □: porosity = 0.421.
$kh = 0.5$ since longer incident waves undergo more topographical changes. The value of $K_R$ is minimum at $kh$ between 1.5 and 3.0. When the porosity is as high as 0.912, the maximum variation of $K_R$ is around 0.06. No obvious effects of model’s geometry were observed; however, the results clearly show that the height of model influences $K_R$ as porosity falls. (■, ▲, and ■ represent the results for models of a
model-unit height. \(\bigcirc, \square, \) and \(\triangle\) represent the results for models of two unit heights. \(+\) and \(\times\) represent the results for models of three unit heights.) The maximum variation of \(K_R\) can be as large as 0.35 when model porosity is 0.421. As shown in the left graph of Fig. 3f, higher models yield larger \(K_R\). The value of \(K_R\) indicates that the width of the model slightly affects \(K_R\).

Similar conclusions can be drawn from \(K_T\) in Fig. 3. When porosity is 0.912 (Fig. 3a), the model’s geometrical effect is unclear and most \(K_T\) values lie between 0.85 and 1.0. As the porosity declines, apparent geometrical effects on \(K_T\) were observed. \(K_T\) is likely to be minimum at \(kh\) in the range from 0.5 to 1.0. The figure also shows that higher and wider models correspond to weaker wave transmission. In summary, the model’s geometrical effect becomes important as its porosity gets small. However, no clear conclusion can be drawn on how porosity affects wave transformation. Therefore, Fig. 4 elucidates the effect of porosity on wave reflection and transmission.

Fig. 4 displays the experimental results for wave reflection and transmission. Eight sub-graphs, (a) to (h), present the experimental results for cases of models C12, C14, C16, C21, C22, C23, C31, and C32, respectively. The corresponding model geometries are shown on the top right corner of each sub-graph. The top and bottom graphs in each sub-graph plot the \(K_R\) and \(K_T\) results, respectively. The abscissa of each sub-graph is \(kh\). In each graph, six different symbols are used to represent the experimental results for various porosities.

In Fig. 4a–c (referring to models with a height of one model unit, \(h_s/h = 0.71\)), almost all of the \(K_R\) values are under 0.12. At \(kh\) in the range from 1.5 to 3.0, the \(K_R\) is less than 0.04 and \(K_R\) is minimum at approximately \(kh = 2\). At \(kh > 3\), \(K_R\) increases to approximately 0.06, probably because of Bragg resonance, since the lengths of the structures (82, 164, and 246 cm) are nearly integral numbers of half of the wave length of the linear incident wave (at \(kh = 3.21\), wavelength/2 = 26.9 cm). \(K_R\) grows to 0.15 as \(kh\) approaches 0.5. \(K_T\) is between 0.8 and 1 and declines as \(kh\) approaches 0.5. When \(kh\) is between 2 and 3.6, \(K_T\) remains at approximately 0.9. At a particular \(kh\), the maximum variations (due to porosity) of \(K_R\) and \(K_T\) do not exceed 0.06 and 0.1, respectively. However, maximum \(K_R\) and minimum \(K_T\) occur at a small \(kh\). This phenomenon does not follow from Bragg resonance. Rather, the presence of the submerged breakwaters alters the effective relative water depth. Longer incident waves (lower \(kh\)) feel more strongly topographical changes on the bottom and may therefore exhibit greater wave reflection and lesser wave transmission. The results suggest no obvious effects due to the width of the model. [The widths are 82, 164, and 246 cm in Fig. 4g, and 4h, respectively]. Fig. 4d–f show \(K_R\) and \(K_T\) for a model of height 14 cm (double the model unit height) with \(h_s/h = 0.455\).

In Fig. 4d–f, \(K_R\) is small (below 0.08) when \(kh > 2\) and is as large as 0.23 as \(kh\) approaches 0.5. \(K_T\) is maximum when \(kh\) in the region between 1.3 and 2, and \(K_T\) is minimum when \(kh\) is approximately 0.7. The maximum variations in \(K_R\) and \(K_T\) under any incident wave conditions do not exceed 0.12 and 0.15, respectively. This result implies that the effect of porosity on wave reflection and transmission becomes significant as the models get higher. Also, these sub-graphs do not exhibit any obvious effect of the width of the model on \(K_R\) and \(K_T\). The only clear effect of the width of the model is on minimum \(K_T\). Wider models cause less wave transmission (the minimum \(K_T\) is approximately 0.7 at \(kh = 0.68\) in Fig. 4f). Figs. 4g and 4h present the results for models with a height of 21 cm (\(h_s/h = 0.2\)).

Variations of \(K_R\) and \(K_T\) increase with the height of the models. In Fig. 4g and h, the maximum variations of \(K_R\) and \(K_T\) are 0.28 and 0.45, respectively, implying that the porosity markedly affects wave reflection and transmission. Also, the hollow symbols (representing the results for less porous models) are above the solid symbols (the results for high-porosity models) in the \(K_R\) graphs and the solids are above the hollow symbols in the \(K_T\) graphs. When \(kh > 2\), most \(K_R\) values are below 0.09. \(K_R\) is maximum (about 0.36) as \(kh\) approaches 0.5. The \(K_T\) values are scattered between 0.7 and 0.9 when \(kh > 2\). The maximum and minimum \(K_T\) occur at \(kh\) near 1.3 and 0.7, respectively. No effect of the width of the model on \(K_R\) and \(K_T\) is obvious in either of the two sub-graphs. Fig. 4d–f support the same conclusion: a wider model causes less wave transmission (the minimum \(K_T\) is approximately 0.5). Also, less porous models correspond to larger \(K_R\) and smaller \(K_T\). Porosity significantly affects the
transformations of waves in these two cases. The energy loss of the primary wave is calculated using Eq. (4) and presented in Fig. 5, to clarify the effect of porosity on wave energy loss.

Fig. 5 depicts the primary wave energy loss due to the presence of porous, submerged obstacles. The figure formats are as same as used in Fig. 4. In the cases of models with a height of one unit, most of the data show a loss of less than 20% of the energy of the incident wave. The effect of porosity is not obvious since incident waves are insignificantly affected by the topography of the bottom. However, at small \( kh \) \((kh < 1.5)\), energy loss increases as the model becomes wider and less porous. The energy

---

**Fig. 5.** Primary wave energy loss of surface waves over submerged obstacles with various porosities. Sub-graphs (a) to (h) present experimental results for models C12, C14, C16, C21, C22, C23, C31 and C32, respectively. ●: porosity = 0.912, ■: porosity = 0.847, ▲: porosity = 0.805, ◆: porosity = 0.736, ○: porosity = 0.588, □: porosity = 0.421.
Fig. 6. Primary wave energy loss of surface waves over submerged obstacles with various porosities under fixed incident wave conditions, (a) for model C12, (b) for model C22 and (c) for model C32.
loss is minimum for models with larger porosities. For a particular incident wave condition, the variations in energy losses due to differences in model porosity become larger as models become higher. The energy loss can vary by as much as 0.6. [Please refer to Fig. 5g and h.] In Fig. 5g and h, the effect of porosity was significant at small \( kh \), indicating that the energy loss increases as the porosity of the model decreases. However, the effect of porosity is not obvious at high \( kh \). The effect of porosity on energy loss is not easily determined from Fig. 5. Therefore, the results in Fig. 5a, e and h (for which the width of all the models is 82 cm) were presented in a different format in Fig. 6.

Fig. 6 plots the effect of porosity on energy loss at different \( kh \). Three sub-graphs, (a) to (c), show the results for Models C12, C22 and C32, respectively. Each sub-graph includes 14 small graphs. Each small graph presents the results at a particular \( kh \). The abscissa in the small graphs is porosity and the ordinate represents the primary wave energy loss. In Fig. 6a, energy loss is under 20% and is maximum at \( kh = 0.81 \). The effect of porosity on \( E_{loss} \) is not clear. However, the effect of porosity becomes stronger, as the height of the model increases. In Fig. 6b, the maximum energy loss still occurs at \( kh = 0.81 \). When \( kh < 2 \), the energy loss decreases as porosity increases above 0.75 and remains constant or slightly decreases at porosity in the range from 0.4 to 0.75. The porosity significantly affects \( E_{loss} \) at a model height of 21 cm (\( h_s/h = 0.2 \)). In Fig. 6c, the loss is maximum at \( kh = 0.81 \). When porosity < 0.75, \( E_{loss} \) declines slowly as \( kh < 1.3 \) and remain nearly constant at around 0.4 as \( kh > 1.3 \). The maximum variation in \( E_{loss} \) is approximately 0.3 when porosity < 0.75. However, when porosity > 0.75, \( E_{loss} \) decreases as porosity increases for any \( kh \), and the maximum difference between values of \( E_{loss} \) is around 0.4.

Experimental results have shown that the incident wave conditions and the submerged breakwater geometry influence wave fields. The porosity of the breakwater also affects wave fields. When the measurements were being made, higher harmonic waves were observed after waves passed porous, submerged structures, indicating that harmonic waves tend to be generated at a small \( kh \) (corresponding to a higher Ursell number), as was determined by Losada et al. (1997). Harmonic waves were also more easily seen in tests of higher models with smaller porosity. A discussion thereof is beyond the scope of this research. As stated by Losada et al. (1997), wave energy is transferred to higher frequencies. The energy of the primary wave is thus reduced significantly, as shown in the results presented herein.

4. Conclusions

Coastal protection has been sought for more than a hundred years. Economics and sturdiness are the most important issues in designing coastal structures. Various methods have been developed but most of them are over-designed. Permeable submerged breakwaters are a type of coastal-protection devices. Their proper design can efficiently protect shores from wave attack.

This work addressed how the porosity of submerged breakwaters affects non-breaking wave transformations. The experimental results indicate that increasing breakwater porosity reduces the height of reflected waves and that model widths negligibly influence the \( K_R \) and \( K_T \) when model heights are fixed. \( K_R \) is usually less than 0.1 when \( kh > 2 \) and \( K_R \) is maximum near \( kh = 0.5 \). \( K_T \) is maximum when \( kh \) is between 1.3 and 2.0. It is minimum when \( kh \) is near 0.7. The energy loss is maximum when \( kh \) is near 0.81 and is minimum for models with higher porosities.

The porosity does affect the energy of the primary wave. The effect of porosity becomes significant, as the model gets higher. When harmonic waves are generated, some primary wave energy is transferred to higher-frequency components. The variation in energy loss of the primary wave can be as high as 0.6. When the porosity effect become significant, \( E_{loss} \) decreases as porosity increases and is above 0.75, while \( E_{loss} \) decreases slowly as \( kh < 1.3 \) and remain almost constant at around 0.4 as \( kh > 1.3 \) when porosity < 0.75. This study systematically measured wave transformations over porous submerged obstacles. The results can provide engineers with useful information for designing coastal structures. However, further study must be conducted to determine the dissipation and energy transference mechanism.
Acknowledgements

The authors would like to thank National Science Counsel for financially supporting this research under Contract No. NSC-89-2611-E-002-024.

References


