Physical Model Test on Wave Transmission to Culvert Pipes Block with Constrictive Sections

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ABSTRACT

A series of physical model tests were conducted in a wave flume to investigate hydraulic characteristics of the culvert pipe block with constrictive section (CPBCS). Different experimental conditions of CPB without constriction as well as permeable and impermeable rubber mounds were also tested to compare their performance of wave transmission from experimental results. Physical variables in the model test including relative water depth, wave steepness, height and width of CPBCS were varied in the test. All data sets were combined and analyzed to obtain a regression formula which can be applied to engineering practice.

1. INTRODUCTION

Conventional coastal structures such as seawalls, revetments, groins, detached breakwaters and bulkheads are frequently used for dissipating wave energy in the coastal protection works. More recently, the issue of coastal defense becomes more complicated because additional non-physical parameters are introduced to the conceptual design of a coastal project. Such considerations for the design of coastal structures may include environment, landscape, ecology and attraction to the water. For these purposes, rubble mound breakwaters are widely used as coastal structures to coastal protection all over the world. However, rubble mound breakwaters have its certain disadvantages such as inferior quality of water circulation, sediment movement and fish actions between inner and outer region of the structure. On the other hand, sufficient quality and quantity rubbles are not available in the vicinity of the construction site, in contrast the concrete caisson may be used. However, both situations are generally expensive for the case of deep waters. For such conditions, a special type of a concrete caisson having culvert pipes with constrictive sections, which requires less concrete per unit block is possible to apply in engineering practice.

It is well known that waves propagate from deep water to shallow water could produce wave energy, strong turbulence and disturbance. As expected, the CPBCS is capable of dissipating turbulence and reflecting the incident wave energy by constriction to protect the coast suffering from beach erosion or decrease wave forces acting on the coastal structures. Some of the culvert pipes structures were used to provide a calm water basin of the cooling water intake for the nuclear power plant. Many related researches have been performed to assess the validity of the culvert pipes. Twu (1978, 1979) derived a theory to estimate transmission coefficients using potential

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theory by an assumption of vertical displacement of the water particle is negligible within the restrictive area of the culvert pipe. Based on the designed transmission coefficient, the diamater and length of culvert pipes can thus be calculated using the theory. Along this line, the influence of wave energy loss on the wall was also added in Twu’s (1980) theory. His result addressed that the wave energy loss when waves passing through the culvert pipes is mainly due to the strong turbulence, friction, reflection and re-reflection within the pipe wall. The theoretical results are shown in good agreement with experimental data. Oda (1988) designed a permeable breakwater having tubes with a constriction for wave attenuation and water exchange. His model tests consist of six different constrictive shaps and three different locations of the area constriction. He concluded that both constrictive locations and shapes for a culvert pipe breakwater are not significant, but a sudden constriction produces a higher energy loss than those of tapered constriction. Moreover, the experimental results showed that the wave transmission decreases with the increase of wavelength for the breakwater having tubes with a constriction.

Many key parameters such as relative water depth, wave steepness, dimensionless length and height of CPBCS influence the wave energy dissipation for a real application. This paper presents physical model tests to explore the performance of CPBCS under different wave conditions and dimensions of CPBCS. A series of model tests were conducted in a wave flume for permeable and impermeable rubble mound and CPB with and without constriction under the action of regular waves. The transmission, reflection and energy dissipation coefficients were obtained from the analysis of experimental data. The most important variables that influence the effectiveness of CPBCS are also studied. An extensive regression was carried out and the empirical formulas were obtained to estimate the transmission coefficient is proposed.

2. EXPERIMENTAL SETUP

Fig. 1 presents the definition sketch of CPBCS with area constriction. The length of the CPBCS with and without constrictions are $L_1 = 10.7 \text{ cm}$ and $L_2 = 14.6 \text{ cm}$, respectively. The diameter of the nozzle in CPBCS is $D_1 = 5.7 \text{ cm}$, and the diameter of the culvert pipe in area constriction is $D_2 = 2.7 \text{ cm}$. The thickness of the solid block between two culvert pipes in the area constriction is $D_3 = 3.8 \text{ cm}$.

The experiment was conducted in a wave flume having a dimension of 37 m long, 1.2m high and 1m wide in a laboratory of National Cheng Kung University. A piston-type wave generator is equipped on the right end to generate regular and irregular waves and a gravel beach of 1:4 slope is placed on the left end to dissipate wave energy from reflection. CPBCS model was deployed at a distance of 27.8 m from the wave board. The dimension of CPBCS is shown in Fig. 1. Fig. 2 shows the wave flume system and CPBCS model placement. There are totally 16 capacity wave gauges are displayed at different locations to measure the water surface elevation in the experiments. Three wave gauges placed in region A are used to measure and calibrate the incident wave condition, three wave gauges are installed in region D to monitor the transmitted waves, and the other three wave gauges are setup in region B to estimate the reflected wave. Five wave gauges are displayed in region C for measuring wave profiles over CPBCS.
A transition area with a slope of 1:10 is installed to guide waves travelling from deep water to shallow water. The shallow water depths at the flat part are designed to vary from 0.2 ~ 0.4 m.

Fig. 1. Definition sketch of culvert pipe block with area constriction.  
\( D_1 \) = nozzle diameter; \( D_2 \) = diameter of the culvert pipe with area constriction; \( D_3 \) = thickness of solid block between two culvert pipe in area constriction; \( L_1 \) = length of culvert pipe without constriction; \( L_2 \) = length of culvert pipe with area constriction.

Fig. 2. Schematic diagram of the experimental arrangement.

A preliminary test without CPBCS was performed to estimate wave reflection in the wave flume. The wave reflection is less than 10% which ensures that the back waves are small, indicating that the influence due to reflection in the wave flume is negligible. Three wave gauges (No.6 ~ No.8) placed in region B matches the calculation criteria of wave reflection coefficient using Mansard and Funke’s (1980) method. The wave profiles were recorded at a 20 Hz frequency to achieve an accurate resolution of the generated wave periods.

As shown in Fig. 2, the height of CPBCS is varied as \( h_s = 14 \) cm, 28cm and 42cm. Three shallow water depths of \( h = 20 \) cm, 30 cm and 40cm at the flat bottom are adopted. The incident wave heights is varied \( H_i = 4 \) cm, 6 cm and 8 cm were selected for three different water depths. In a testing case the wave height keeps constant but the wave periods are varied from 0.65 ~ 3.0 s. This implies that the wave steepness is changed from 0.013 to 0.08 which is within the range of linear wave theory. The detailed experimental conditions are summarized in Table 1.

The CPB without constrictive sections has a diameter of 5.7 cm. The volumetric void ratio is \( \lambda_v = 0.52 \). For the permeable rubble mound, the gravel nominal diameter is \( D_{n50} = 4.7 \) cm, \( \lambda_v = 0.47 \) and the permeability coefficient \( K_p \) and resistance coefficient \( C_f \) are taken as \( K_p = 2.28 \times 10^{-7} \) m² and \( C_f = 0.14 \), respectively, on the basis of the constant head permeability experiment.
Table 1 Summary of designed experimental conditions of selected tests for CPBCS

<table>
<thead>
<tr>
<th>Test Cases</th>
<th>Water depth ( h ) (cm)</th>
<th>Wave Conditions</th>
<th>CPBCS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Height ( H_i ) (cm)</td>
<td>Period ( T ) (s)</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>4</td>
<td>0.65 to 2.2</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>6</td>
<td>0.80 to 2.5</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>8</td>
<td>0.80 to 3.0</td>
</tr>
</tbody>
</table>

3. EXPERIMENTAL RESULTS

3.1 Wave Height Transformation over CPBCS

To investigate the variation of the wave height for waves passing over different blocks, wave gauges placed different locations were setup to measure wave profiles. Fig. 3 shows the spatial variation of wave height for four kinds of blocks with a dimensionless height of \( h_s / h = 28 / 30 \). We notice that the effect of permeability on wave reflection is distinguishable. For the case of impermeable solid block, the variance of dimensionless wave height in front of breakwater is larger than those permeable structures case. On the other hand, the difference of wave height variances between cases of culvert pipes with and without constriction is slight due to the small discrepancy between the surface porosity for these two cases. By comparing the wave height at shelter part of breakwater, it is found that the wave attenuation over the CPBCS is almost the same as impermeable block, and much calmness than the culvert pipes without constriction. In consequence, the efficacy of energy loss for wave propagating over the CPBCS is higher than the one without constrictive section.

![Fig. 3. Comparison of wave height transformation over submerged blocks.](image)

The effect of crest height of the CPBCS on wave propagation for three different \( R_c / H_i \) values \((R_c / H_i = -2.67, -0.33, 2.00)\) for the water depth \( h = 30 \) cm is provided in Fig. 4. For low crest breakwater height, say \( h_s = 14 \) cm, the wave height above the breakwater increases slightly due to the nonlinear effect in shallow water. Afterward, the wave height recovers. Consequently, the effect of low crest CPBCS on wave is negligible. On the other hand, the increase in crest height cause increased wave energy
dissipation because of the wave breaking, flow friction and other interaction within the CPBCS. An optimum crest height needs to add in the considerations of finance, economics, environment, landscape and so on.

3.2 Influence of Key Parameters

Block Height

The effect of block height for CPBCS on wave transformation is depicted in Fig. 5. It is worthwhile to note that the result of the analysis approximately appears to a linear relationship between the relative crest height $R_c/H_i$ and wave transmission coefficient $K_t$ within the range of $R_c/H_i < 0.5$. As shown in Fig. 5, CIRIA/CUR (1991) has performed a hydraulic model test and obtained an empirical formula to estimate the transmission coefficient from a given block height of conventional low crest permeable structure. Note that $K_t$ value of CPBCS seems to be smaller than that of the conventional submerged rubble mound breakwaters. For the case of $R_c > 0$, i.e. the block height is emersed the water surface, the $K_t$ value is not better than those of rubble mound breakwaters. This is because less water is transmitted into the constrictive pipes resulting in a lower energy loss.
Block Width

The influence of lock width of CPBCS is demonstrated in Fig. 6. We notice that a larger block width would produce a smaller $K_t$ value for $R_c/H_l > -1.50$. And the result of the analysis approximately appears to an exponential relationship between the relative block width $B/L$ and wave transmission coefficient $K_t$. This means that a longer pipe could reduce a larger amount of wave energy for an efficient block height of CPBCS. However, this phenomenon is not true for $R_c/H_l < -1.50$ because most of water can pass through the pipes of CPBCS. It is found that transmission coefficients $K_t$ is smaller than 0.4 for CPBCS with $R_c/H_l \geq -0.33$ and $B/L > 0.15$.

![Effect of block width](image)

**Fig. 6.** Variation of block width versus transmission coefficient.

Influence of Constrictions

As aforementioned, a block with constrictive sections is able to dissipate turbulence and reflect the wave energy which leads to a small transmitted wave energy in the lee site of the block. It can be seen from Fig. 7 that performance of the CPBCS is contrast to that without constricting section. First of all, the wave reflection coefficients increases slightly due to add the constrictive section within the culvert pipes block. Although the volumetric void ratio $\lambda_v$ of the CPBCS is 0.35 and much smaller than the culvert pipes block without constrictive section ($\lambda_v = 0.52$), however, the difference in wave reflection is not apparently. This phenomenon can be explained as being cause by the surface void ratios facing incident wave of both blocks are unity. Regarding to effect of constrictive section on $K_t$, the wave are attenuated by the constrictive section. The efficiency of wave attenuation by constrictions increases with decreasing the relative water depth $kh$. In other words, the culvert pipes block with constrictive section is conductive to the calmness at rear of the breakwater, especially for long wave in shallow water. This notable features is important and useful in engineering aspect, because of the storm waves in coastal zone are usually be greater in not only wave height but also wave period and length.
Comparision with Conventional Block

The difference in the performance on wave reflection, transmission and energy loss due to interaction between wave and different structures is discussed. Comparison of performance of the CPBCS with CPB without constriction and the other two types of conventional block is displayed in Fig. 8 to Fig. 10.

Fig. 8 shows the wave reflection, transmission and energy loss over low crest structure, \( R_c/H_i = -2.67 \), there are no apparent effect on different block. On the other hand, as the increase in breakwater crest height, the apparently discrepancies in wave propagates of different block types are distinguishable. Note from Fig. 9, the culvert pipes block with constrictive section cause higher energy loss than that without constrictive section, especially for \( kh < 1.5 \). Furthermore, it offer more wave reflection than the rubble mound block. These characters of the submerged CPBCS conducts to a better performance than the rubble mound block and culvert pipes block without constriction. Furthermore, for the emersed structure (see Fig. 10), the efficiency of the culvert pipes with constrictive section on wave energy loss is clear, especially for long wave or in shallow water. And the wave transmission performance of the CPBCS is almost the same with rubble mound block.

Consequently, deal with transmitted wave energy, the culvert pipes block with constrictive section offer the efficiency between impermeable and rubble mound block. Moreover, the CPBCS overcomes the imperfection of the culvert pipes block without constrictive section in long wave condition also.

Fig. 7. Influence of constriction on the coefficients of \( K_r, K_t \) and \( K_{el} \).

Fig. 8. Performance of different blocks with \( h = 30 \text{ cm} \) and \( hs = 14 \text{ cm} \).
Wave Transmission Coefficient for CPBCS

In engineering practice, some important information like the transmission coefficients is very useful for a preliminary assessment of function of a structure. It can be seen in Eq. 1 that various parameters affecting wave transmission have been discussed according to experimental results in the past investigations.

\[
K_t = f(kh, h_s/h, R_c/H, R_c/h_s, B/h_s, B/L, H/L, B^2/LD^2, \ldots)
\]  

(1)

Makris and Memos (2007) evaluating number of the semi-empirical formulae conducted in the past to quantify the transmission coefficient and discuss the dimensionless variables controlling the wave transmission. The main dimensionless variables that control wave transmission over offshore permeable structures are relative water depth \(h_s/h\), freeboard height \(R_c/H\), crest width \(B/h_s\) and internal flow parameter \(B^2/LD^2\). Previous studies in this issue indicated that these parameters are associated with the wave transmission coefficients.

Based on the analysis of experimental data within the range of \(R_c/H < 0.5\), the correlation coefficient between these dimensional parameters and wave transmission have been analyzed and summarized in Table 2. The superscript numbers are used to indicate the ranking of the correlation coefficients of these parameters with \(K_t\).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>(kh)</th>
<th>(h_s/h)</th>
<th>(R_c/H_i)</th>
<th>(B/L)</th>
<th>(H/L)</th>
<th>(B^2/LD^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation coefficient</td>
<td>-0.191 (^3)</td>
<td>-0.838 (^2)</td>
<td>-0.838 (^1)</td>
<td>0.362 (^3)</td>
<td>-0.191 (^3)</td>
<td>-0.362 (^3)</td>
</tr>
</tbody>
</table>
For the condition with \(-2.67 \leq R_c / H_i \leq 0.5\), the ‘best fit’ model for estimating wave transmission coefficient of the CPBCS with a coefficient of determination \((R^2)\) value of 0.88 and a standard deviation of 0.26 is listed as Eq. 2 and plotted in Fig. 11.

\[
K_t = -0.04838(B^2 / LD) + 1.40235(R_c / H_i) - 8.1472(h_c / h) + 8.571
\]

Comparison with the measured data is displayed in Fig. 11. The agreement is rather good, especially for the relative crest height \(R_c / H_i\) within the range \(-1.5 \leq R_c / H_i \leq 0\). Nevertheless, some outliers seem to come from the low crest structure conditions which \(R_c / H_i < -1.5\). For the experiments which \(R_c / H_i < -1.5\), the wave transmission \(K_t\) is higher than 0.7 means an inefficiency work on wave energy vanishment. The outliers of predicted \(K_t\) are belong to low crest height conditions \(R_c / H_i < -1.5\) and wave breaking over structure \(R_c / H_i > 0\). This may have significantly difference on energy dissipation over the CPBCS, making \(K_t\) remarkably scatter than predicted.

![Fig11. Comparison of measured and predicted Kt.](image)

### 4. CONCLUSIONS

The physical model tests were carried out to investigate the performance of culvert pipes block with constrictive section. The experimental results were compared with conventional blocks. Based on the analysis from experiment data, we make the following conclusions:

1. The efficiency of the culvert pipes block with or without constrictions for wave attenuation has been assessed based on the physical model tests. It is found that the performance of the culvert pipes block with constrictive section has a damping action than those of CPB without constrictive sections.

2. Because of the influence of constriction within the culvert pipes, the performance of wave attenuation over CPBCS is remarkable for small \(kh\) values. This implies that wave energy is easy to decay by CPBCS even in conditions of long waves or in shallow water.
(3) A comparison of wave transmission for CPBCS and a permeable rubble mound indicates that the effectiveness of the wave damping is almost the same. If CPBCS is placed above the sea level, the efficiency of reducing wave transmission becomes lower.

(4) According to the analysis of influence parameters on wave transmission of CPBCS, a regression line is obtained on the basis of experimental data.

(5) Comparing the CUPBCON block with the conventional rubble mound block, the CUPBCON block is a considerable substitute due to lower wave energy transmitted when the submerged breakwaters is projected. However, the CUPBCON block be placed above the water level is not efficiency due to the insaturation of the emersed CUPBCON block and then the function leads to energy loss owing to the constrictive section is not apparent.

(6) Finally, a semi-empirical formula based on the ‘best-fit’ analysis performs satisfactory, and is suggested by considering factors such as crest height, crest width, water depth at toe, magnitude of the wave height and length, etc.

REFERENCES


