TWO-DIMENSIONAL PHYSICAL MODELING OF MULTI CHAMBER SKIRT BREAKWATER (MCSB)

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ABSTRACT: Multi-Chamber Skirt Breakwater (MCSB) is a skirt-type breakwater consisting of piles at the lower part, and two chambers skirt with porosity in the upper part of the structure. The additional number of chambers with variations of chambers gap length is expected to increase the breakwater's effectiveness. Physical modeling is conducted to examine the transmission coefficient (CT) and the reflection coefficient (CR). The relationship between environmental and structure independent variables with the transmission and reflection coefficient is investigated. The physical modeling concluded that the structure's transmission coefficient in the deep water is less than 0.31, while the intermediate-depth water condition is 0.31-0.72. The reflection coefficient is 0.36-0.51 for deep water and less than 0.5 for the intermediate depth water condition. It is concluded that MCSB is effective in intermediate-depth and deep water conditions where the range of the depth parameter (kh) is between 2.5 to 3.1.

Keywords: Multi-chamber skirt breakwater, Transmission coefficient, Reflection coefficient, Intermediate depth water, Deepwater.

1. INTRODUCTION

The construction of gravity-type breakwaters such as the rubble mound breakwaters in intermediate-depth and deep waters can be costly due to the high volume of rubble materials [1]. In such a case, the skirt-type pile breakwaters can replace the gravity-type for the less expensive and relatively less complicated construction method. In this study, a Multi-Chamber Skirt Breakwater (MCSB) structure is investigated.

The research aims to examine the effectiveness of the MCSB, which is presented by the transmission coefficient (CT) and the reflection coefficient (CR) relationship with the environment and structure variables in the intermediate depth water and deepwater region. The intermediate-depth is in the region of π/10 < kh < π, and the deepwater is in the region of kh > π [2]. The physical modeling is carried out in the Ocean Engineering Laboratory at Bandung Institute of Technology, Indonesia.

Suh et al. [3] observed the effectiveness of a curtain-wall-pile breakwater using physical and analytical models. The model consists of a vertical wall and piles. The research is conducted in intermediate depth to the deep water condition. The analytical model is carried out using the velocity potential theory applying the monochromatic waves. The kinematic and dynamic boundary conditions are applied within the domain. The research concludes that the curtain-wall-pile breakwater produces larger transmitted and smaller reflected waves than the pile-supported vertical wall breakwater.

Koraim [4] investigated slotted breakwater's behavior, which consists of a vertical slot in one row using regular waves condition. The research observed the hydrodynamic characteristics of the breakwater using an analytic and experimental solution. The structure's effectiveness is represented by the value of the wave reflection and transmission, energy loss, and hydrodynamic forces on the structure for the various values of waves and structural parameters. The reduction of the incoming wave energy is found to be 20-50%.

Wurjanto et al. [5] observed the effect of two chambers perforated breakwater in shallow water conditions. The research studied the effectiveness of the breakwater chamber numbers in terms of the transmission coefficient. It is found that the perforated skirt breakwater with three chambers is more effective than breakwater with two chambers. The chamber's width also influences the effectiveness of breakwater, and it was found that the transmission coefficient increases while the width of the chamber decreases and decreases as the skirt's draft increases.

The study of energy dissipation on the skirt-type breakwater with a single chamber was conducted by Laju et al. [6]. The model consists of piles at the lower part and skirt barriers at the upper part. The eigenfunction expansion of the velocity potentials was applied at the front, middle, and rear skirt barrier. The water depth regime is set in the intermediate depth water region (1.0 < kh < 2.6). It was found that the chamber width has to be between 0.3 to 0.5L (L is the wavelength) for a maximum wave energy dissipation rate of up to 50%.
Suh et al. [7] investigated modified curtain-wall pile breakwater [1] using a circular pile, formulated a mathematical model, and validated it with a physical experiment. The research concluded that the reflection coefficient increases, and the transmission coefficient decreases as the gaps of the pile decreases.

Ajiwibowo [8] conducted three-dimensional physical models of Perforated Skirt Breakwater (PSB) to examine the structure’s effectiveness through the value of the transmission coefficient. The research concludes that the structure can dampen the waves by up to 50% for a short wave period.

Ajiwibowo [9] examined the effectiveness of Single Curtain Pile Foundation Breakwater (SCPFB) by using the transmission coefficient \((C_T)\) parameter in intermediate depth water. The experiment concludes that The SCPFB is almost 90% effective when applied with the curtain extended to half of the water depth and suggested continuing the research in the range of \(kh>\pi\).

Ajiwibowo [10] conducted 2-D physical modeling to evaluate the effectiveness of Perforated Skirt Breakwater (PSB) by the value of the transmission coefficient \((CT)\). The investigation concludes that PSB effectively dampens the wave energy 30-70% for short wave.

2. SCALING AND DIMENSIONAL ANALYSIS

2.1 Scaling

The Froude similarity principle is used to formulate the scaling as written in Eqs. (1) and (2).

\[
(F_r)_{\text{prototype}} = (F_r)_{\text{model}}
\]

\[
F_r = \frac{v}{\sqrt{gL}}
\]

where

\(F_r\) = Froude Number
\(v\) = flow velocity
\(g\) = gravitational acceleration
\(L\) = length dimension

From a consideration of laboratory capacity, a scale of 1:12 is determined. Tables 1 and 2 show the structure and environment variables of the modeling, respectively.

2.2 Dimensional Analysis

The dimensional analysis is conducted to produce the dimensionless parameters that will be varied during the modeling. The dimensional analysis is carried out using the Buckingham \(\pi\) method [11]. The dimensionless variables are shown in Eqs. (3) and (4).

\[
C_T = \Pi \left( kh, \frac{H_I}{L}, \frac{s}{h}, p, \frac{L_c}{h} \right)
\]

\[
C_R = \Pi \left( kh, \frac{H_I}{L}, \frac{s}{h}, p, \frac{L_c}{h} \right)
\]

where

\(C_T\) = transmission coefficient
\(C_R\) = reflection coefficient
\(k = \frac{2\pi}{L}\) = wave number
\(L\) = wavelength
\(L_c\) = length of chamber
\(s\) = draft of the skirt
\(p\) = skirt porosity

The dimensionless variables studied are the correlation between the transmission coefficient \((C_T)\) and reflection coefficient \((C_R)\) with structure and environment variables. The structure variables are relative draft \((s/h)\), porosity \((p)\), and relative length of the chamber \((L_c/h)\). The environment variables are relative depth \((kh)\) and wave steepness \((H/L)\).

| Table 1 Structure variables |
|-----------------------------|
| Variables                  | Symbol | Prototype | Model |
| Draft of the skirt         | \(s_1\) | 3.00 m    | 25.00 cm |
|                           | \(s_2\) | 2.00 m    | 16.70 cm |
| Chamber width              | \(L_c1\) | 7.20 m    | 60.00 cm |
|                           | \(L_c2\) | 3.60 m    | 30.00 cm |
| Porosity                   | \(p_1\) | 50 %      | 50 %    |
|                           | \(p_2\) | 30 %      | 30 %    |

| Table 2 Environment variables |
|-------------------------------|
| Variables                    | Symbol | Prototype | Model |
| Water depth                  | \(H\)  | 9.60 m    | 80.00 cm |
|                              |        | 8.40 m    | 70.00 cm |
|                              |        | 7.20 m    | 60.00 cm |
| Incident wave height         | \(H_I\) | 1.20 m    | 10.00 cm |
|                              |        | 1.80 m    | 20.00 cm |
|                              |        | 3.60 m    | 30.00 cm |
|                              |        | 4.20 m    | 35.00 cm |
| Wave period                  | \(T\)  | 3.46 s    | 1.00 s   |
|                              |        | 6.93 s    | 2.00 s   |
|                              |        | 10.39 s   | 3.00 s   |
|                              |        | 13.86 s   | 4.00 s   |
|                              |        | 17.32 s   | 5.00 s   |
3. METHODS

3.1 Models

The Multi-Chamber Skirt Breakwater (MCSB) configuration can be seen in Fig. 1 and Fig. 2, consisting of piles at the lower part and skirts with multi-chambers on the upper part. The skirt has porosity attached to the upper part of the pile, with the part of the skirt submerged under the water level.

3.2 Laboratory Capacity and Wave Gauges Calibration

The ranges of wave heights and periods that can be generated should be investigated by operating the wave generator at various settings. The wave flume measures 40 m long, 1.5 m deep, and 1.2 m wide. The wave flume can generate wave heights up to 35 cm and wave periods up to 7 seconds.

Four wave gauges are used and calibrated. They are calibrated using the comparison of the wave heights measured manually at the wave flume with data recordings from the wave gauges. Table 3 shows the value of coefficients of calibration for various water depths.

![Fig. 1 Definition sketch of MCSB](image1)

![Fig. 2 Perspective view of MCSB](image2)

Table 3 Value of coefficients of calibration

| Water depth (h) [cm] | WG1  | WG2  | WG3  | WG4  |
|----------------------|------|------|------|------|
| 60                   | 0.024| 0.023| 0.027| 0.023|
| 70                   | 0.033| 0.033| 0.036| 0.034|
| 80                   | 0.041| 0.040| 0.044| 0.039|

3.3 Wave Flume Setup

The MCSB model, wave absorber, wave gauges, wavemaker are prepared in the wave flume in the proper position, as seen in Fig. 3.

The wave gauges position is arranged according to the method of Goda and Suzuki (1976) [10], which is formulated in Eq. (5).

\[ 0.05 < \frac{\Delta \ell}{L} < 0.45 \]  

where

\[ \Delta \ell = \text{the distance between two wave gauges (m)} \]

\[ L = \text{wavelength (m)} \]

The closest wave gauge to the model should be placed at a distance of 0.2L from the model.
4. EXPERIMENTS

The scenarios of the experiments can be seen in Table 4. There are 480 scenarios. The recorded data for each scenario is 3 minutes minimum.

Table 4 Scenarios of the experiment

| Variables          | Symbol | Model | Number of Scenarios |
|--------------------|--------|-------|---------------------|
| Draft of the Skirt | $s_1$  | 25.00 cm | 2                   |
|                    | $s_2$  | 16.70 cm |                      |
| Chamber width      | $L_{c1}$ | 60.00 cm | 2                   |
|                    | $L_{c2}$ | 30.00 cm |                      |
| Porosity           | $p_1$  | 30 %   | 2                   |
|                    | $p_2$  | 50 %   |                      |
| Water depth        | $h$    | 80.00 cm | 3                   |
|                    |        | 70.00 cm |                      |
|                    |        | 60.00 cm |                      |
| Incident Wave height | $H_i$ | 10.00 cm | 4                   |
|                    |        | 20.00 cm |                      |
|                    |        | 30.00 cm |                      |
|                    |        | 35.00 cm |                      |
| Wave Period        | $T$    | 1.00 s  | 5                   |
|                    |        | 2.00 s  |                      |
|                    |        | 3.00 s  |                      |
|                    |        | 4.00 s  |                      |
|                    |        | 5.00 s  |                      |

5. DATA ANALYSIS

The data recorded from the wave gauges are processed using zero-mean processes. The selection of time interval data to be analyzed is determined, i.e., the time-lapse in the wave record that has not been affected by the reflected waves.

The result of the analysis is a nondimensional graph of $C_T$ and $C_R$ versus structure and environmental variables.

5.1 Wave Transmission Analysis

Transmission coefficients ($C_T$) are defined as the ratio between the transmitted and incident wave heights. The incident waves are calculated from the zero up crossing process of water level elevation recorded by the wave gauges in front of the model. The transmitted waves are the zero-up crossing of water level elevation from the model's wave gauges.

The transmission coefficients, $C_T$, are defined in Eq. (6).

$$C_T = \frac{H_T}{H_I}$$  \hspace{1cm} (6)

where

$C_T = $ transmission coefficient  
$H_T = $ average of transmitted wave height (m)  
$H_I = $ average of incident wave height (m)

5.2 Wave Reflection Analysis

The wave reflection analysis is calculated based on a technique to resolve the incident and reflected waves from the record of composite waves. This technique is introduced by Goda and Suzuki (1976) [12].

Reflection Coefficient ($C_R$) analysis is obtained from comparing the incident wave energy and the reflection wave energy, as shown in Eq. (7).

$$C_R = \sqrt{\frac{E_R}{E_I}}$$  \hspace{1cm} (7)
where

\( C_R \) = reflection coefficient
\( E_I \) = incident wave energy
\( E_R \) = reflected wave energy.

The wave energy of incident and reflected waves are obtained from Eqs. (8) and (9).

\[
E_I = \int_{i=0}^{i=N} S_I(\omega) d\omega \quad (8)
\]

\[
E_R = \int_{i=0}^{i=N} S_R(\omega) d\omega \quad (9)
\]

where

\( S_I(\omega) \) = incident wave spectrum (m²s)
\( S_R(\omega) \) = reflected wave spectrum (m²s)
\( \omega \) = wave angular frequency (rad/s)

The incident and reflected wave spectrum are obtained from the component of the amplitude spectrum calculation, according to Eqs. (10) and (11).

\[
S_I(\omega) = \frac{1}{2} a_{Ii}^2 \frac{\Delta \omega}{\Delta \ell} \quad (10)
\]

\[
S_R(\omega) = \frac{1}{2} a_{Ri}^2 \frac{\Delta \omega}{\Delta \ell} \quad (11)
\]

\( a_{Ii} \) and \( a_{Ri} \) are the amplitude of the spectrum components of the incident and reflected waves obtained from Goda and Suzuki (1976) [11].

The amplitude spectrum is obtained from the following Eq. (12) and Eq. (13).

\[
a_{Ii} = \frac{1}{2|\sin k_i\Delta \ell|} \left[ (a_{2i} - b_{1i} \cos k_i \Delta \ell - b_{1i} \sin k_i \Delta \ell)^2 + (b_{2i} - b_{1i} \cos k_i \Delta \ell + a_{1i} \sin k_i \Delta \ell)^2 \right]^{1/2} \quad (12)
\]

\[
a_{Ri} = \frac{1}{2|\sin k_i\Delta \ell|} \left[ (a_{2i} - b_{1i} \cos k_i \Delta \ell - b_{1i} \sin k_i \Delta \ell)^2 + (b_{2i} - b_{1i} \cos k_i \Delta \ell - a_{1i} \sin k_i \Delta \ell)^2 \right]^{1/2} \quad (13)
\]

where

\( a_{1i}, b_{1i} \) = Fourier coefficient of WG1 data
\( a_{2i}, b_{2i} \) = Fourier coefficient of WG2 data
\( k \) = wave number (m⁻¹)
\( L \) = wavelength (m)
\( \Delta \ell \) = distance of WG1 and WG2 (m)

6. RESULTS AND DISCUSSIONS

The results of the physical modeling are described by using nondimensional plots in Figures 4-7. The figures show the relationship between \( C_T \) and \( C_R \) values with the values of environment variables \( kh \) and \( H/\ell \). The optimum performance of MCSB is described in Fig.8.

The plots are varied according to the structure variables \( s/h \), \( L/c/h \), and \( p \) in the intermediate depth water dan deepwater regions.
6.1 Transmission Coefficient, $C_T$

Figure 4 shows the relation between $C_T$ and $k_h$ (environment variable) as a function of $s/h$, $p$, and $L_c/h$ (structure variables). As indicated by the figure, $C_T$ decreases as $k_h$ increases, or the MCSB is more effective in deep water ($0.06 < C_T < 0.29$) compared to intermediate depth water ($0.10 < C_T < 0.70$).

The relation of structure variables ($s/h$, $p$, and $L_c/h$) with $C_T$ in Fig. 4 concludes that $C_T$ increases as $s/h$ decreases, $p$ increases, and $L_c/h$ decreases.

Figure 5 shows the relation between $C_T$ and $H_I/L$ (environment variable) as a function of $s/h$, $p$, and $L_c/h$ (structure variables). As indicated by the figure, $C_T$ decreases following the increase of $H_I/L$.

Fig. 4. Graph of $C_T$ vs. $k_h$ as a function of $s/h$, $p$, and $L_c/h$

Fig. 5. Graph of $C_T$ vs. $H_I/L$ as a function of $s/h$, $p$, and $L_c/h$

Fig. 6. Graph of $C_T$ vs. $H_I/L$ as a function of $s/h$, $p$, and $L_c/h$
The relation of structure variables \((s/h, p, \text{ and } Lc/h)\) with \(CT\) in Fig. 5 concludes that \(CT\) increases as \(s/h\) decreases, \(p\) increases, and \(Lc/h\) decreases.

6.2 Reflection Coefficient, \(CR\)

Figure 6 shows the relation between \(CR\) and \(kh\) (environment variable) as a function of \(s/h\), \(p\), and \(Lc/h\) (structure variables). The values of \(CR\) in the Deepwater is \(0.39 < CR < 0.52\). They are higher than those in the intermediate water depth, which are \(0.14 < CR < 0.49\).

The relation of structure variables \((s/h, p, \text{ and } Lc/h)\) with \(CR\) in Fig. 6 concludes that \(CR\) is increasing if \(s/h\) increases, \(p\) decrease, and \(Lc/h\) decrease.

Figure 7 shows the relation between \(CR\) and \(HI/L\) (environment variable) as a function of \(s/h\), \(p\), and \(Lc/h\) (structure variables). The values of \(CR\) in the Deepwater is \(0.39 < CR < 0.52\). They are higher than those in the intermediate water depth, which are \(0.14 < CR < 0.49\).

The relation of structure variables \((s/h, p, \text{ and } Lc/h)\) with \(CR\) in Fig. 6 concludes that \(CR\) is increasing if \(s/h\) increases, \(p\) decrease, and \(Lc/h\) decrease.
$L_c/h$ (structure variables). The $C_R$ does not change significantly to $H/L_c$ with the value of $C_R$ is $0.28 < C_R < 0.54$.

6.3 Transmission Coefficients, $C_T$ and Reflection Coefficients, $C_R$

Figure 8 shows both $C_T$ and $C_R$ as a function of structural variables ($s/h$, $p$, and $L_c/h$), described as the optimum performance of MCSB. The optimum performance occurred if the wave transmission and wave reflection are small or the value of $C_T$ and $C_R$ are not more than 0.5. The optimum condition of MCSB occurs in the range of $2.50 < kh < 3.10$, which shows the value of $C_T$ and $C_R$ is below 0.5.

These $C_T$ and $C_R$ values explain the physical conditions of the transmission waves behind the MCSB are small. The reflection waves in front of the MCSB are also small (the effectiveness of MCSB is more than 50%).

The most effective MCSB structure configuration based on $C_T$ value is a structure with $L_c/h = 0.75$, $p = 30\%$ and $s/h = 0.313$. While the most effective MCSB structure based on $C_R$ value is a structure with $L_c/h = 0.75$, $p = 50\%$ and $s/h = 0.209$.

7. CONCLUSIONS

The MCSB has an optimum performance if $C_T$ and $C_R$ are small, or the values are less than 0.5. The $C_T$ and $C_R$ are relatively low (less than 0.52) in the deepwater region. The effectiveness of MCSB in deep water occurs because of the skirt porosity, which results in a decrease of $C_R$. It is concluded that the MCSB is useful in deep water.

The $C_R$ is small in the intermediate depth water. The value of $C_R$ is less than 0.52 in the range of depth $2.50 < kh < 3.10$. The $C_T$ is high in the interval of $0.314 < kh < 2.50$ ($C_R < 0.5$) but small in $kh > 2.50$. It is concluded that the MCSB is still effective in the intermediate depth water condition if $kh > 2.50$.

The draft, porosity, and chamber gap width of the MCSB significantly influence $C_T$ and $C_R$. The selection of skirt draft, porosity, and chamber width dimensions need to be considered. The higher s and p, the lower $C_T$ while at the same time, the $C_R$ increases. The higher chamber width ($L_c$), the higher $C_T$. However, the value of $C_R$ decreases.

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