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Wave Transmission and Energy Dissipation in a Box Culvert-Type Slotted Breakwater

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Abstract

This research is conducted to examine the transmission wave and energy dissipation of a box culvert-type slotted breakwater, which is designed as a breakwater structure with a watertight wall at the top and a box culvert type hole at the bottom. The process involves physical modeling of this structure in the laboratory. The hole and wave parameters are varied to determine the breakwater performance. The results show that the transmission coefficient (K_T) value is reduced as the relative hole height (h_L/d) value is decreasing and the relative hole length (B/L) and wave steepness (H/L) values are increasing. The energy dissipation coefficient (K_D) value increases with an increment in h_L/d, H/L, and B/L but starts to decrease after reaching the maximum, which is the optimum $H \times B/L^2$ value. This optimum value is found to be $0.0034(h_L/d)^{2.618}$ depending on the (h_L/d) value, while the maximum K_D value is recorded to be 0.70.

Keywords: breakwater, box culvert, wave transmission, energy dissipation

1. Introduction

Coastal protection using rubble mound breakwaters requires a large amount of construction material, and the dimensions required for deeper waters are usually higher, leading to an increase in the quantity of materials needed [1-4]. The use of natural stone in large quantities for construction, however, can damage mining sites and quarries and deplete limited natural resources. It is also not advisable to use rubble mound breakwaters because they require a good subgrade bearing capacity [1, 5-6].

One of the efforts directed towards solving this problem is using a wall-style perforated breakwater which can save on the quantity of construction material required and is also considered environmentally friendly due to its ability to ensure effective water circulation [4, 7-9]. However, the design of the model, in the form of a wall, shows it has a very small and negligible relative wall thickness (b/L) [10], making it less effective in reducing the incident wave height when the porosity of the hole (ε) and wave length (L) is large. Theoretically, the energy dissipation coefficient (K_D) of the thin wall perforated breakwater model is 0 when the porosity of the hole is 0, or 1 while the maximum is only 0.3 [11].

Several studies have been conducted on the box culvert-type slotted breakwater with a focus on different types, since it was first proposed by Jarlan [12], after investigating the hollow barrier model in front of the upright wall structure. For example, Mackay and Johanning [13] studied the hollow vertical wall model using analytical and numerical models. Vijay et al.

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[14] examined a multi-layer perforated wall model using physical and numerical models. Furthermore, George and Cho [11] analyzed a single wall model with a continuous horizontal perforation in the middle, while Nikoo et al. [15] focused on a two-layer perforated wall model. Ahmed and Schlenkhoff [16] also studied a double wall model with holes in the middle, Ahmed [9] examined a single wall model with vertical holes in the middle using a numerical model, and Rageh and Koraim [10] analyzed a single wall model with horizontal holes at the bottom. Another study by Rageh and Koraim [1] focused on the vertical wall model with holes at the bottom, and Ariyarathne [17] examined a massive structural model with holes at the top, while Suh et al. [2] focused on the Kaison model with vertical holes in some of the walls.

However, no attention has been paid to the cross-sectional shape of the hole used, despite the important effect of the hole height (h_L) and length (B) on the performance of a perforated breakwater in reducing wave height (H_i) and incident wave energy (E_i). Furthermore, the use of a box culvert-type with a relatively large hole length (B) is expected to increase the effectiveness of the breakwater in reducing wave height and energy with a large hole porosity (ε). It is, therefore, important to note that the box culvert-type of the slotted breakwater has two parts: the upper (in the form of a waterproof wall structure) and the lower (in the form of a box culvert model).

This research aims to examine the transmission and dissipation of wave energy through a box culvert-type slotted breakwater. The process involves determining the important parameters of hole and wave structure, such as relative hole height (h_L/d), relative hole length (B/L), and wave steepness (H/L), using non-dimensional analysis. Moreover, the parameters are varied to determine the breakwater performance using the transmission coefficient (K_T) and energy dissipation coefficient (K_D) values as indicators.

2. Experimental Program

The research is conducted by physically modeling a wave flume, which is equipped with a wave generator, a wave damper, and a wave probe. The experiments are conducted to determine the transmission coefficient (K_T) and energy dissipation coefficient (K_D) of waves in the box culvert-type perforated breakwater model using different wave and hole structure parameters, obtained through non-dimensional analysis [18].

2.1. Materials

The schematic diagram of the wave flume, model location, and wave probe tool is presented in Fig. 1. The wave flume used has a length (P) of 15 m, a width (l) of 0.3 m, and a height (t) of 0.45 m, with one flap-type wave generator installed at one end and a wave absorber at the other end, to reduce reflections. Moreover, three wave probes (WP) installed at the front and back of the model, with 0.01 cm accuracy, are used to measure the water level elevation. Each of these probes is calibrated before being used for measurements. Furthermore, the breakwater model is placed in the middle of the wave flume, or approximately 0.5 flume lengths from the wave generator or the wave absorber.

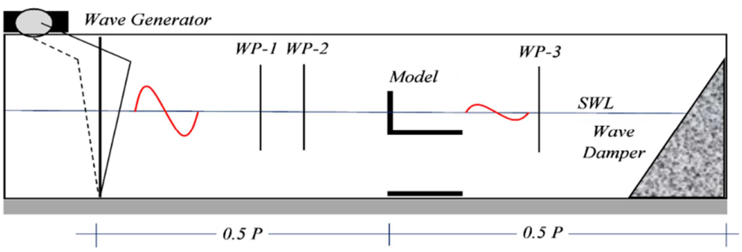
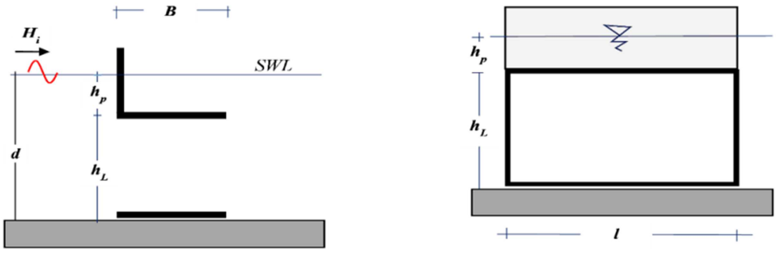


Fig. 1 Wave flume, model location, and wave probe tool

2.2. Physical model

The breakwater model is produced using an acrylic material with a thickness (b) of 0.01 m and divided into two parts. The upper part is in the form of a watertight wall structure with a constant thickness (b) of 0.01 m. Sinking height (h_p) is varied at

0.100, 0.050, 0.025, and 0.000 m from the still water level, while the bottom is in the form of a box culvert model hole with the height (h_L), varying at 0.100, 0.150, 0.175, and 0.200 m from the bottom of the flume and the length (B) at 0.2, 0.4, and 0.6 m. This means that 12 models are used for the experiment. The sketches and pictures of the box culvert-type slotted breakwater model are presented in Fig. 2 and Fig. 3.



(a) Side view (b) Front view

Fig. 2 Sketch of the box culvert-type slotted breakwater model

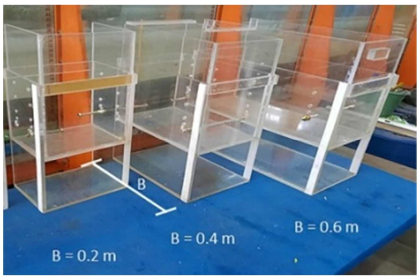


Fig. 3 Model of the box culvert-type slotted breakwater

2.3. Wave height measurement

Wave heights, including the incident (H_i), reflection (H_{max} and H_{min}), and transmission (H_t), are measured using a wave probe connected to the wave tide meter (WTM), and a computer is used to record the waves from the tide meter. Two wave probes are used to measure the incident wave (H_i) and reflection (H_{max} and H_{min}) wave heights. Wave Probe 1 (*WP-1*) is placed at a location 1.25L in front of the breakwater model to measure the minimum reflection wave height (H_{min}), and Wave Probe 2 (*WP-2*) is placed at a location as far as L in front of the breakwater model, to measure the maximum reflection wave height (H_{max}). This is according to the two-point method of Dean and Dalrymple [19], Mani [20], Murali and Mani [21], Koraim [22], Koraim [5] and Koraim [23]. To measure the transmission (H_t) wave height using one wave probe, *WP-3* is located at a distance of 2.0 m behind the breakwater model (wave damper side) [5, 22-23].

The wave length (L) based on the wave period (T) is calculated by using the dispersion equation, according to the linear wave theory. The position of the wave crest or the highest water level (the quasi-antinodes), as far as L from the breakwater model, is visually observed and marked as the *WP-2* position. The position of the lowest water level (the quasi-nodes), as far as 1.25L in front of the breakwater model, is determined based on the L value which is calculated as the position of the *WP-1* location. The measurement of wave height is repeated three times by shifting the positions of *WP-1* and *WP-2* slightly to the right and to the left from the initial position, so that the values of H_{min} and H_{max} are obtained. These placements are indicated in Fig. 4.

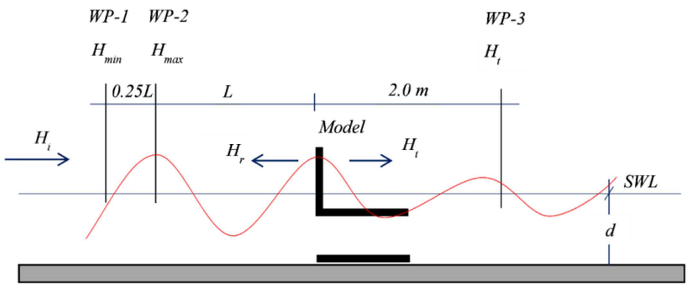


Fig. 4 Placement of the wave probe location on the model

The experiment is conducted at a constant water depth (d) of 0.2 m with the wave period T varied at 1.61, 1.34, 1.15, and 1.02 seconds or (H/L) at 0.0161, 0.0238, 0.0329, and 0.0452. Moreover, four variations of relative hole height (h_L/d) are used: 0.500, 0.750, 0.875, and 1.000, while the twelve variations of relative hole length (B/L) employed are: 0.093, 0.115, 0.138, 0.160, 0.186, 0.230, 0.277, 0.279, 0.319, 0.345, 0.415, and 0.479. Analysis is conducted to determine the relationship between the transmission coefficient (K_T) and energy dissipation coefficient (K_D) of waves using non-dimensional parameters of the hole and wave structures, such as the relative hole height (h_L/d), relative hole length (B/L), and wave steepness (H/L), as shown in Eq. (1).

$$K_T, K_D = f(h_L/d, B/L, H/L) \tag{1}$$

The transmission coefficient (K_T) is calculated using the transmission wave height data (H_t), as indicated in Eq. (2), while the energy dissipation coefficient (K_D) is determined using Eq. (4) [16, 24]. Moreover, the incident wave height (H_i) and reflection wave height (H_r) are calculated based on the maximum (H_{max}) and minimum reflection wave height (H_{max}) using partial standing wave theory in Eq. (5) and Eq. (6) [19].

$$K_T = H_t/H_i \tag{2}$$

$$K_R = H_r/H_i \tag{3}$$

$$K_D = \sqrt{(1 - K_T^2 - K_R^2)} \tag{4}$$

$$H_i = \frac{H_{\max} + H_{\min}}{2} \tag{5}$$

$$H_r = \frac{H_{\max} - H_{\min}}{2} \tag{6}$$

3. Results and Discussion

3.1. *Effect of the relative hole height (h_L/d) and wave steepness (H/L) on the transmission coefficient (K_T) and energy dissipation coefficient (K_D)*

The experiment is conducted using a constant hole length of the breakwater model (B) of 0.6 m, while (h_L/d) is varied at 0.500, 0.750, 0.875, and 1.000as well as H/L at 0.0161, 0.0238, 0.0329, and 0.0452. The effect of the relative hole height (h_L/d) and wave steepness (H/L) on the transmission coefficient (K_T) is presented in Fig. 5, while the effect on the energy dissipation coefficient (K_D) is depicted in Fig. 6.

Fig. 5 shows that a higher H/L and lower h_L/d produce a lower K_T, as indicated by B = 0.6 m, h_L/d = 0.5 – 1.0, and H/L = 0.0161 – 0.0452 which produces a K_T = 0.41 – 0.11 or causes a 73.17% reduction. The smallest value (0.11) is found at h_L/d = 0.5 and H/L = 0.0452, while the largest (0.41) is at h_L/d = 1.0 and H/L = 0.0161. This is associated with the ability of a greater H/L value to cause a steeper wave while a smaller h_L/d value can cause a smaller porosity of the structure. This condition makes it difficult for the wave to pass through the breakwater, thereby making the transmission wave height smaller. The multivariate nonlinear regression analysis of the experimental data shows the relationship between the wave transmission coefficient (K_T) with the h_L/d and H/L functions, as shown in Eq. (7), where R^2 = 0.967.

$$K_T = -6.594(H/L)^{0.016} + 0.321(h_L/d)^{1.087} + 6.226 \tag{7}$$

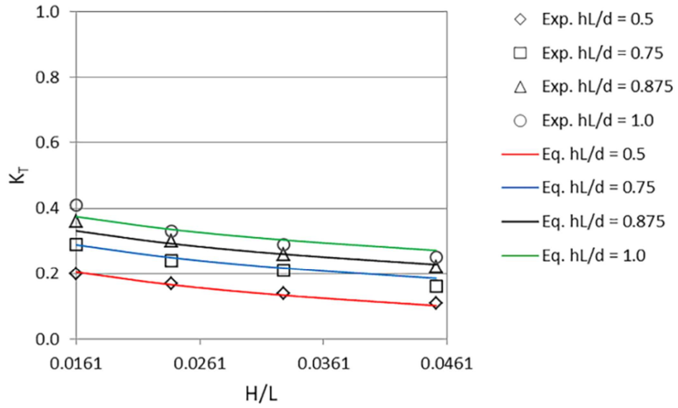


Fig. 5 K_T function of h_L/d and H/L

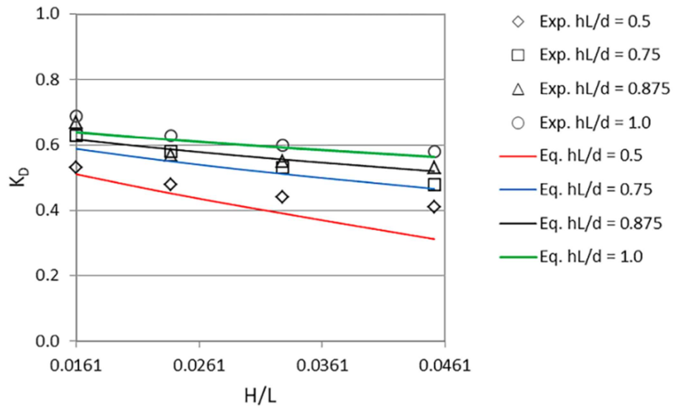


Fig. 6 K_D function of h_L/d and H/L

Fig. 6 shows that an increment in h_L/d and the reduction in H/L lead to an increase in the K_D as indicated by $B = 0.6$ m, $h_L/d = 0.5 – 1.0$, and $H/L = 0.0161 – 0.0452$, which produces a $K_D = 0.41 – 0.69$ or causes a 68.29% increase. The smallest value (0.41) is recorded at $h_L/d = 0.5$ and $H/L = 0.0452$, while the highest (0.69) is at $h_L/d = 1.0$ and $H/L = 0.0161$. This reveals that a higher h_L/d or porosity of the structure and smaller H/L or wave steepness can significantly reduce the wave energy.

3.2. Effect of the relative hole length (B/L) and relative hole height (h_L/d) on the transmission coefficient (K_T) and energy dissipation coefficient (K_D)

The experiment is conducted using a constant steepness wave value H/L of 0.0452 while the length of the breakwater model hole (B) is varied at 0.2 m, 0.4 m, and 0.6 m and the h_L/d at 0.500, 0.750, 0.875, and 1.000. The effect of the relative hole length (B/L) and relative hole height (h_L/d) on the transmission coefficient (K_T) is presented in Fig. 7, while the effect on energy dissipation coefficient (K_D) is specified in Fig. 8.

Fig. 7 shows that a higher B/L and lower h_L/d cause a reduction in K_T, as indicated by the use of $H/L = 0.0452$, $B/L = 0.160 – 0.479$, and $h_L/d = 0.5 – 1.0$, which produces a $K_T = 0.43 – 0.11$ value or causes a 51.16% decrease. The smallest value (0.11) is found at $B/L = 0.479$ and $h_L/d = 0.5$, while the highest (0.43) is recorded at $B/L = 0.160$ and $h_L/d = 1.0$. This is associated with the ability of a greater B/L value to produce a greater frictional effect of fluid turbulence with the hole length B, as well as the smaller h_L/d, which causes a smaller porosity of the structure. This condition makes it difficult for the wave to pass through the breakwater, thereby making the transmission wave height smaller. The multivariate nonlinear regression analysis of the experimental data shows the relationship between the wave transmission coefficient (K_T) with the h_L/d and H/L functions as presented in Eq. (8), where $R^2 = 0.977$.

$$K_T = -0.932(B/L)^{0.128} + 0.245(h_L/d)^{1.050} + 0.849 \tag{8}$$

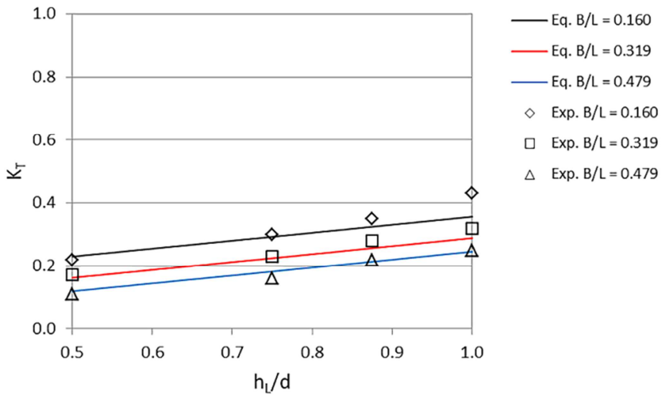


Fig. 7 K_T function of B/L and h_L/d

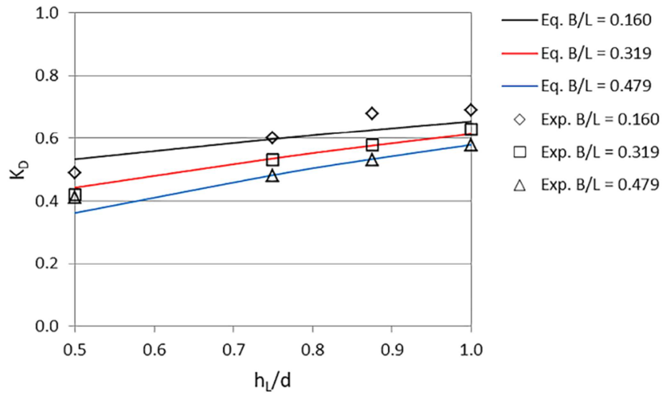


Fig. 8 K_D function of B/L and h_L/d

Fig. 8 shows that a lower B/L and higher h_L/d cause an increase in K_D, which is indicated by 0.41 – 0.69 on the 68.29% increment recorded with H/L = 0.0452, B/L = 0.160 – 0.479, and h_L/d = 0.5 – 1.0. Meanwhile, the smallest value (0.41) is recorded with B/L = 0.479 and h_L/d = 0.5, while the highest (0.69) is found with B/L = 0.160 and h_L/d = 1.0. This indicates that higher h_L/d or porosity of the structure and smaller B/L can significantly reduce the wave energy.

3.3. *Effect of the wave steepness* (H/L)*, relative hole length* (B/L)*, and relative hole height* (h_L/d) *on the value of transmission coefficient* (K_T) *and energy dissipation coefficient* (K_D)

The experiment is conducted with the length of the breakwater model hole (B) varying from 0.2 m to 0.4 m and 0.6 m, while the h_L/d is 0.500, 0.750, 0.875, and 1.000 and H/L is 0.0161, 0.0238, 0.0329, and 0.0452. The effect of the wave steepness (H/L), relative hole length (B/L), and relative hole height (h_L/d) on the transmission coefficient (K_T) is presented in Fig. 9, while the effect on the energy dissipation coefficient value (K_D) is illustrated in Fig. 10.

Fig. 9 shows a higher H/L and B/L, which is represented as $H \times B/L^2$, and a lower h_L/d is able to reduce K_T as indicated by the use of H/L = 0.0161 – 0.0452 and B/L = 0.093 – 0.479, as well as h_L/d = 0.5 – 1.0, to produce K_T = 0.58 – 0.11 or 81.03% reduction. Meanwhile, the smallest value (0.11) is found at H/L = 0.0452, B/L = 0.479, and h_L/d = 0.5, while the highest value (0.58) is recorded at H/L = 0.0161, B/L = 0.093, and h_L/d = 1.0. This is associated with the ability of a greater H/L and B/L to cause a steeper wave and hole length, leading to a greater frictional effect of fluid turbulence with hole length B, while a smaller h_L/d is observed to cause a smaller structural porosity. This makes it difficult for the wave to pass through the breakwater, making the transmission wave height smaller. Moreover, the multivariate nonlinear regression analysis of the experimental data shows the relationship between the wave transmission coefficient (K_T) and H/L, B/L, and h_L/d functions, as shown in Eq. (9), where R^2 = 0.979.

$$K_T = 0.075(h_L/d)^{0.839} + [(H \times B/L^2)]^{-0.323} \tag{9}$$

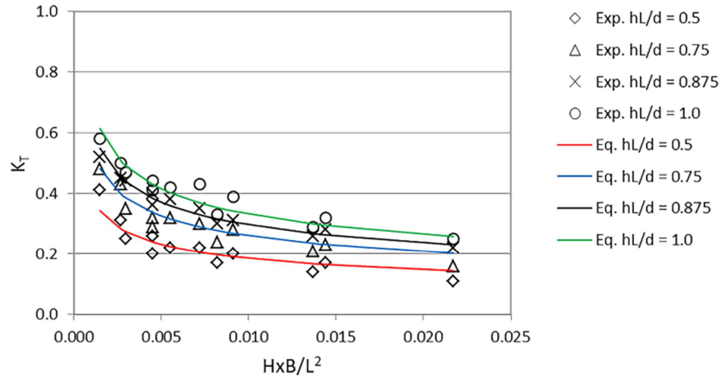


Fig. 9 K_T function of h_L/d, B/L, and H/L

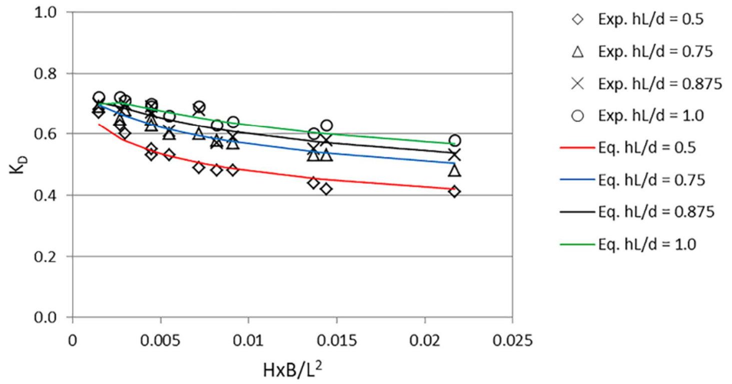


Fig. 10 K_D function of h_L/d, B/L, and H/L

Fig. 10 shows the increment in h_L/d, H/L, and B/L, which is represented by $H \times B/L^2$ and able to increase the K_D, but the value decreases when the maximum value is obtained and the $H \times B/L^2$ is at its optimum. This means more $H \times B/L^2$ lead to a reduction in the K_D. This optimum $H \times B/L^2$ is recorded to be $0.0034(h_L/d)^{2.618}$ depending on the h_L/d value. Meanwhile, the maximum K_D value is 0.7. This is because the higher h_L/d can produce greater structural porosity so that the energy reduction is greater. Furthermore, the greater the value of H/L and B/L, the effect of frictional fluid turbulence with the length of the hole will also be larger, so the energy reduction will be even greater. However, after reaching the optimum value of $H \times B/L^2$, the frictional effect of fluid turbulence with the hole length of B will be more of the wave resistance. As a result, the waves will be more likely to be reflected as reflection waves, and the energy reduction process will be reduced. The optimum value of $H \times B/L^2$ is influenced by the value of h_L/d used. The greater the value of h_L/d, the higher the optimum value of $H \times B/L^2$.

Figs. 11-12 present the graphic nomogram of the relationship between K_T and K_D box culvert-type slotted breakwater with functions H/L, B/L, and h_L/d for regular waves based on Eq. (9) and Eq. (4). This nomogram can, therefore, be used to determine the values of K_T and K_D while planning box culvert-type slotted breakwater for beach protection in the field.

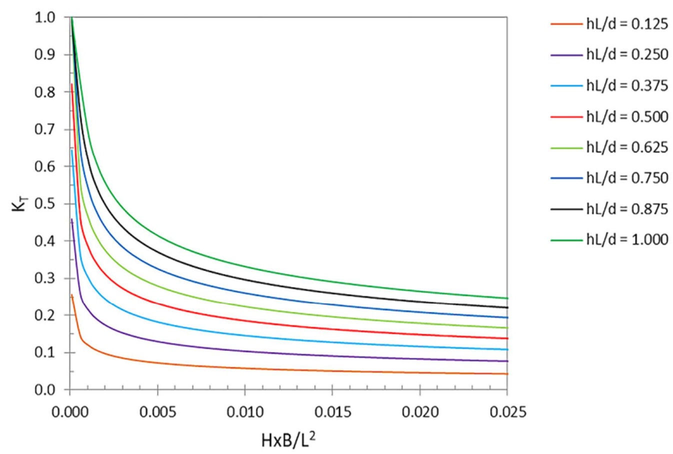


Fig. 11 Nomogram of K_T function of h_L/d, B/L, and H/L

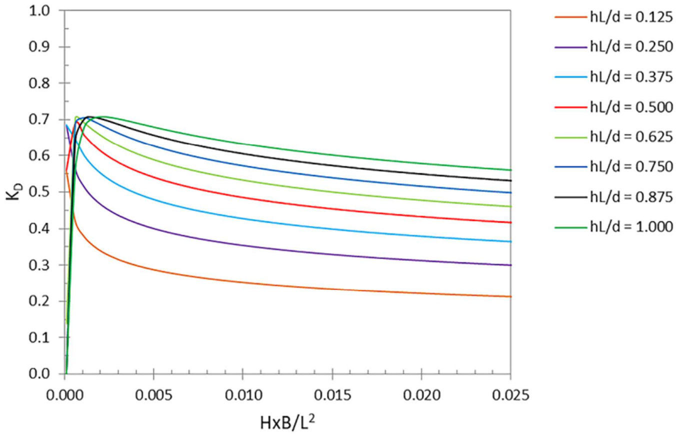


Fig. 12 Nomogram of K_D function of h_L/d, B/L, and H/L

4. Conclusions

In this study, the transmission and dissipation of a box culvert-type slotted breakwater was designed as a breakwater structure (with a watertight wall at the top and a box culvert type hole at the bottom) and investigated. The results show that the wave transmission coefficient (K_T) was reduced as the h_L/d decreased and B/L and H/L increased, as indicated by $H/L = 0.0161 - 0.0452$, $B/L = 0.093 - 0.479$, and $h_L/d = 0.5 - 1.0$ which produced a $K_T = 0.58 - 0.11$ or caused an 81.03% reduction. Moreover, the equation for the relationship among K_T, H/L, B/L, and h_L/d is $K_T = 0.075(h_L/d)^{0.839} \times [(H \times B/L^2)]^{-0.23}$. The energy dissipation coefficient (K_D), however, increased as the h_L/d, H/L, and B/L increased but later started reducing after reaching the maximum value at the optimum $H \times B/L^2$. This means that more $H \times B/L^2$ led to a reduction in the K_D. This optimum $H \times B/L^2$ was recorded to be $0.0034(h_L/d)^{2.618}$ depending on the h_L/d value. Meanwhile, the maximum K_D value was 0.7.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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