Wave Interaction with Single and Twin Vertical and Sloped Slotted Walls

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Abstract: The interaction between waves and slotted vertical walls was experimentally studied in this research to examine the performance of the structure in terms of wave transmission, reflection, and energy dissipation. Single and twin slotted barriers of different slopes and porosities were tested under random wave conditions. A parametric analysis was performed to understand the effect of wall porosity and slope, the number of walls, and the incoming relative wave height and period on the structure performance. The main focus of the study was on wave transmission, which is the main parameter required for coastal engineering applications. The results show that reducing wall porosity from 30% to 10% decreases the wave transmission by a maximum of 35.38% and 38.86% for single and twin walls, respectively, increases the wave reflection up to 47.6%, and increases the energy dissipation by up to 23.7% on average for single walls. For twin-walls, the reduction in wall porosity decreases the wave transmission up to 26.3%, increases the wave reflection up to 40.5%, and the energy dissipation by 13.3%. The addition of a second wall is more efficient in reducing the transmission coefficient than the other wall parameters. The reflection and the energy dissipation coefficients are more affected by the wall porosity than the wall slope or the existence of a second wall. The results show that as the relative wave height increases from 0.1284 to 0.2593, the transmission coefficient decreases by 21.2%, the reflection coefficient decreases by 15.5%, and the energy dissipation coefficient increases by 18.4% on average. Both the transmission and the reflection coefficients increase as the relative wave length increases while the energy dissipation coefficient decreases. The variation in the three coefficients is more significant in deep water than in shallower water.

Keywords: transmission; reflection; energy dissipation; slope angle; porosity; single-wall; twin-walls

1. Introduction

Coastal structures protect ports, harbors, and marinas from waves and currents. Traditional protection structures such as rubble mound breakwaters and concrete caissons provide the required protection, but they have several drawbacks, such as high construction costs and wide space occupancy. Vertical slotted barriers are a cost-effective and environment-friendly alternative that provides protection, reduces the construction cost and time, and provides more effective space for berthing and other facilities. The proposed slotted barrier is a fully immersed type of structure that consists of horizontal slots which permit the passage of water between the open sea and the bounded area.

Many researchers have investigated the effects of the number of walls, wall porosity, and incoming wave heights on the hydrodynamic characteristics of porous barriers [1–9]. Several of those researchers [1–7], agreed that two or more perforated walls might reduce the reflection coefficient of the perforated breakwaters as more wave energy is dissipated within the gap between the structures.
Hagiwara [10] and Huang [11] showed that a second barrier has negligible effects on the scattered waves of a vertical wave barrier if the porosity of the second barrier is greater than or equal to 40%.

Neelamani et al. [12] conducted several experiments to examine the wave reflection and run-up characteristics of one to six slotted vertical walls with a non-porous back wall. They concluded that increasing the wall’s porosity from 10% to 30% decreases the wave reflection. The results of Huang [13] and Isaacson et al. [14] showed that increasing the porosity of a wall decreases wave reflection but increases wave transmission. Koraim [15] studied the performance of a wall consisting of one row of vertical slots theoretically and experimentally. He concluded that the transmission coefficient decreases as the wavenumber, \(kh\), and wave steepness, \(H_i/L\), increase, and as the wall porosity, \(P\) decreases. On the other hand, he concluded the opposite trends for the reflection coefficient.

The studies [16–18] relate the reduction in the reflection coefficient to the increase in the wave steepness in the case of perforated caissons. This relationship is concluded because the energy dissipation increases at the perforated front wall for steeper waves. For the case of fixed wave periods, energy dissipation increases as the incident wave height increases resulting in smaller transmission coefficients and larger reflection coefficients [11].

Most of the studies in this subject focus on the relationship between the wave reflection, transmission, and energy dissipation by varying the wall porosity and the number of walls. Few studies have focused on the effect of the wall slope angle \(\theta\). Neelamani and Sandhya [19] showed that the reflection coefficient, \(K_r\), decreases with increasing the wall slope, \(\cot \theta\), for dentated non-porous seawalls. They also found that seawalls with \(\theta = 50^\circ\) and \(60^\circ\) receive more pressure due to the plunging effects compared to vertical walls.

Muttray and Oumeraci [20] conducted physical experiments to study the wave transformation using vertical and sloping perforated thin walls of varying porosities under regular waves. A series of predictive empirical equations were developed for wave transmission, reflection, and energy dissipation on permeable slopes between \(\theta = 0^\circ\) and \(\theta = 40^\circ\). The results showed that the wave transmission decreases near linearly with increasing wave height and is slightly higher for the cases of slopped walls than for the case of vertical walls. Moreover, they found that the reflection decreases significantly for the case of permeable slopes. Mallayachari and Sundar [21] conducted a detailed study on the behavior of slopped and vertical seawalls. They concluded that porous slopped walls dissipate more wave energy and reduce the reflection coefficient more efficiently than the vertical porous walls.

The motivation of this study is to investigate the effect of the wall slope, wall porosity, and the number of walls on wave transmission, reflection, and energy dissipation. The structures were subjected to a series of random waves of different properties. Laboratory experiments were conducted at the Coastal Engineering Laboratory of Kuwait Institute for Scientific Research (KISR). Eight different random wave conditions were applied to different structural configurations. In Section 2, The materials and methods of this study are presented. Section 3 presents and discusses the results. The conclusions and recommendations of this study are presented in Section 4.

2. Materials and Methods

A sequence of experimental tests were carried out to assess the performance of various slotted walls in terms of the wave transmission, reflection, and energy dissipation coefficients, \(K_t\), \(K_r\), and \(K_l\), respectively. A total of 18 models were tested by varying the wall porosity, the slope angle, and the number of walls at a fixed water depth for different wave conditions. Froude scaling was used to scale the wave properties and structure dimensions. The scale of 1:10 was used to reflect the average wave conditions, water depth, and the typical structure dimensions in the Arabian Gulf (AG) region.

2.1. Model Specifications

The slotted walls, a of which sample is shown in Figure 1, were fabricated from rectangular panels of acrylic sheets that were assembled and fixed to a steel frame by nuts, washers, and bolts. Each model is located 14 m from the wave generator paddle and is fixed to the flume by stainless steel angles and
2.1. Model Specifications

The slotted walls, a sample of which is shown in Figure 1, were fabricated from rectangular panels of acrylic sheets that were assembled and fixed to a steel frame by nuts, washers, and bolts. The models were fully immersed in the flume, extending to the bottom, and measured 0.6 m wide, 0.8 m high, and 0.01 m thick. The geometric porosity of the walls is the ratio of the opening area to the total area of the wall from the still free surface to the bed. The wall slope angle is taken as the measured angle from the sea bed to the face of the model. Table 1 presents the wall parameters used in this study.

![Figure 1. Suggested model design. Conceptual design in (a) and actual model fixed in the flume in (b).](image)

| Wall Parameter | Notation | Range Tested            |
|----------------|----------|--------------------------|
| Porosity       | $P$      | 10%, 20%, and 30%        |
| Number of walls| $N$      | 1 and 2                  |
| Slope angle    | $\theta$ | 30°, 60°, and 90°        |

The model panels have a fixed width of 0.1 m. The vertical spacing between the panels was varied depending on the targeted porosity. For models with identical twin walls, the selection of the wall spacing agrees with the conclusion reached by [22]. Ahmed [22] concluded that the optimum location for wall 2 is at 0.25 L, 0.75 L, and 1.25 L (i.e., at the nodes) where the maximum energy dissipation and least reflection occurs. For the wavelengths to be tested, these nodes first occur at distances ranging between 0.365 and 1.118 m from the front wall. Hence, a spacing of 0.2 m is selected to ensure that the waves at the second wall are at a node. The twin walls were fixed to the flumes in the same manner as the single walls.

2.2. Testing Facilities

The experiment’s wave flume is 20 m long, 0.6 m wide, and 0.4 m deep. The wavemaker is piston type and manufactured by the Danish Hydraulic Institute (DHI). Six capacitance-type wave probes were used to measure the wave heights at different locations along the flume (Figure 2). Probe 1 is located 6.08 m from the wavemaker and is used to measure the incident significant wave height, $H_{\text{is}}$. Probes 2–4 measure the reflected wave heights, and they are located at 10.01 m, 10.47 m, and 10.77 m from the wavemaker, respectively. The wave conditions in front of the first wall were measured using probe 5 which is located 13.96 m from the wavemaker. The transmitted wave height was measured using probe 6, which is located 17.34 m from the wavemaker. The probes were calibrated before each experiment to ensure maximum accuracy. The maximum deviation of the calibration constants from the mean value was less than 0.1%. Basically, for wave reflection analysis, two wave probes are sufficient. Three wave probes (wave probe 2, 3 and 4) to make sure that the wave reflection analysis is possible for all wave conditions without causing singularity issue (i.e., the reflection analysis will not result infinity as output). The locations of the wave probes (probe 2, 3 and 4) is selected such that they
are away from one wave length, so that the evanescent mode of the wave during reflection will not contribute in the measurement of wave climate at location 2, 3 and 4. The location of wave probe 6 is also kept more than the longest wave length generated from this study to reduce the data noise on the wave transmission due to the turbulence effect from the model.

The random waves generated in this study follow the JONSWAP spectrum with a peak enhancement factor of 3.3. Eight wave trains were generated corresponding to peak wave periods $T_p = 1, 1.5, 2,$ and $2.5$ s, and significant incident wave heights $H_{is} = 5$ and $10$ cm. The total time of each experiment was $450$ s.

2.3. Wave Specifications

The important dimensionless parameters in this study are the relative wave height, $H_{is}/d$, the relative wave period (or relative water depth), $d/L_p$, and the wave steepness, $H_{is}/L_p$. The experimental range of each of these parameters is shown in Table 2. These parameters are used to investigate the relationship between the model and the wave parameters.

| Parameter   | Description     | Range        |
|-------------|-----------------|--------------|
| $H_{is}/d$  | Relative wave height | 0.1284–0.2493 |
| $d/L_p$     | Relative wave period | 0.0844–0.2733 |
| $H_{is}/L_p$| Wave steepness  | 0.0106–0.0683 |

The reflection coefficient, $K_r$, is the ratio of the reflected wave height, $H_r$, to the significant incident wave height, $H_{is}$,

$$K_r = \frac{H_r}{H_{is}} \quad (1)$$

$K_r$ is determined by analyzing the experimental results using the least-squares procedure described by [23]. Three wave probes placed on a line parallel to the wave propagation direction and in reasonable distances from each other simultaneously measure the superposition of incident and reflected wave heights. The average reflection coefficient is calculated using Equation (1).

To calculate the transmission coefficient, $K_t$, the data from Probe 6 were analyzed using Fast Fourier Transform (FFT) techniques to produce the spectral density histogram [24]. The histogram plots the spectral energy against the wave frequency, resulting in the spectral variance, $m_o$. The time-domain parameter, $H_{st}$, known as the transmitted wave height, was calculated using the following equation

$$H_{mo} = 4 \sqrt{m_o} = H_{st} \quad (2)$$
Then, $K_t$ is calculated using

$$K_t = \frac{H_{st}}{H_{is}}$$  \hspace{1cm} (3)

Using the energy conservation law, the wave energy dissipation coefficient, $K_t$, is derived:

$$K_t^2 + K_r^2 + K_l^2 = 1$$  \hspace{1cm} (4)

$$K_l = \sqrt{1 - K_t^2 - K_r^2}$$

3. Results and Discussion

3.1. General

The data from the experimental runs have been studied and analyzed to determine $K_t$, $K_r$, and $K_l$. Table 3 presents the highest and lowest values for $K_t$, $K_r$, and $K_l$ obtained from the experiments. Changing the wave conditions and the wall configurations (i.e., $N$, $P$, and $\theta$), as seen in Table 3, caused significant variation in $K_t$, $K_r$, and $K_l$.

Table 3. Highest and lowest resultant hydrodynamic coefficients.

| Coefficient | Highest Value | Corresponding Model | Lowest Value | Corresponding Model |
|-------------|---------------|---------------------|--------------|---------------------|
| $K_t$       | 0.824         | $N=1$, $P=30\%$, $\theta=90$ | 0.314        | $N=2$, $P=10\%$, $\theta=30$ |
| $K_r$       | 0.636         | $N=2$, $P=10\%$, $\theta=90$ | 0.268        | $N=2$, $P=30\%$, $\theta=30$ |
| $K_l$       | 0.889         | $N=2$, $P=20\%$, $\theta=30$ | 0.418        | $N=1$, $P=30\%$, $\theta=60$ |

In the next sections, the effect of the wall parameters and wave characteristics on $K_t$, $K_r$, and $K_l$, respectively, is discussed.

3.2. Wave Transmission Coefficient, $K_t$

3.2.1. Effect of Porosity

The transmission coefficient, $K_t$, was highest for models with $P = 30\%$, as expected based on many examples in the literature. An example of the effect of wall porosity on the variation of $K_t$ with $d/L_p$ for a model with $N = 1$ and $\theta = 30$ and incoming wave condition of $H_{is}/d = 0.2493$ is shown in Figure 3. The figure shows that as $P$ decreases from 30% to 10%, $K_t$ decreases. The maximum reduction in $K_t$ is 35.38%, which occurs when the porosity decreases from 30 to 10% at $d/L_p = 0.2733$. On average, $K_t$ decreases by 25.26% as the porosity decreases from 30 to 10% for the case shown in Figure 3. For similar conditions as in Figure 3, but for twin walls, the maximum reduction in $K_t$ is 38.86%, and the average reduction is 26.28. From $P = 20\%$ to $P = 10\%$, the average decrease in $K_t$ is 16.5% and 14.22% for single and twin wall models, respectively. The average reduction in $K_t$ as the wall porosity changes from $P = 30\%$ to $P = 20\%$ is 10.6% for single wall and 14.21% for twin walls.
3.2.2. Effect of Number of Walls

In agreement with previous literature, the addition of a second wall always resulted in a reduction in $K_t$, as shown in Figures 4–8. The results in Figure 4 represent the conditions of $P = 20\%$, $\theta = 90^\circ$ and incoming wave condition of $H_{oi}/d = 0.2493$. On average, $K_t$ decreased by 25.85% due to the addition of a second wall for waves having $H_{oi}/d = 0.2493$, and by 22.52% for waves having $H_{oi}/d = 0.1284$. Twin-walls are more effective in reducing $K_t$ as $d/L_p$ increases than single-walls. The reason for this increased effect is that shorter waves (larger $d/L_p$) are more likely to interact with the wall than longer waves, which are more likely to pass through the slots of the walls.

Figure 3. Effect of $P$ on $K_t$ for the case of $N = 1$, $\theta = 30$, and $H_{oi}/d = 0.2493$.

Figure 4. Effect of $N$ on $K_t$ with for $P = 20\%$, $\theta = 90$, and $H_{oi}/d = 0.2493$. 

3.2.3. Effect of Slope Angle

The maximum reduction in $K_t$ as the wall slope changed was 26.20%, which occurs when the wall slope angle changed from 90° to 30° for the case of $H_{id}/d = 0.1284$, $d/L_p = 0.2733$, $P = 10\%$, and twin walls (Figure 5d). In general, for all cases of $d/L_p = 0.2733$, $K_t$ decreases as the wall slope angle decreases from 90° to 30° (Figure 5). For the case of $d/L_p = 0.1529$ (Figure 6), the change in $K_t$ was minor as it does not exceed 6.56%. In seven out of 12 experiments of $d/L_p = 0.1529$, $K_t$ increases slightly, remains nearly the same in four experiments, and decreases by 1.70% in one experiment, as shown in Figure 6. The maximum decrease in $K_t$ when $d/L_p = 0.1083$ was 8.16% and the maximum increase was 4.35%, as shown in Figure 7. In general, the change in $K_t$ is minor in most cases when $d/L_p = 0.1083$ (the average percentage of change = 0.36%). An increasing trend is observed in the case of $d/L_p = 0.0844$ (Figure 8). The maximum percentage of increase in $K_t$ when $d/L_p = 0.0844$ was 10.71% for the case of twin-walls, $P = 10\%$, and $H_{id}/d = 0.1284$ (Figure 8d). Figures 5–8 show that changing the wall position from vertical wall to 60° sloped wall has insignificant effect on the values of $K_t$ for the majority of the cases. The maximum changes in $K_t$ as the wall slope changes occur in the cases of twin-walls. For the cases of single-wall and increasing $K_t$, the average percentages of increase are 4.21, 4.56, and 3.87% for slope angles changing from 90° to 60°, 90° to 30°, and 60° to 30°, respectively. For the case of twin walls, the average percentages of increase are 3.45, 4.11, and 3.21% for slope angles changing from 90° to 60°, 90° to 30°, and 60° to 30°, respectively. For the cases of single-wall and decreasing $K_t$, the average percentages of decrease are 1.38, 11.42, and 8.12% for slope angles changing from 90° to 60°, 90° to 30°, and 60° to 30°, respectively. For the case of twin walls, the average percentages of decrease are 4.37, 11.08, and 8.60% for slope angles changing from 90° to 60°, 90° to 30°, and 60° to 30°, respectively.

Tables 4 and 5 present simple statistics for the percentages of increase and decrease in $K_t$ as a function of $\theta$ and $N$.

For $d/L_p$ larger than 0.1527, $K_t$ for models with $\theta = 30°$, is significantly lower than models with $\theta = 60°$ and 90°. Before the aforementioned critical $d/L_p$ points, no single conclusion was reached regarding $K_t$ and the varying slope angles.

**Figure 5.** Variation of $K_t$ with $\theta$ for $d/L_p = 0.2733$ and different porosities and wall configurations. On the left, $H_{id}/d = 0.2493$ (a–c) and on the right $H_{id}/d = 0.1284$ (d–f).
Figure 6. Variation of $K_t$ with $\theta$ for $d/L_p = 0.1529$ and different porosities and wall configurations. On the left, $H_{is}/d = 0.2493$ (a, b, and c) and on the right $H_{is}/d = 0.1284$ (d, e, and f).

Figure 7. Variation of $K_t$ with $\theta$ for $d/L_p = 0.1083$ and different porosities and wall configurations. On the left, $H_{is}/d = 0.2493$ (a–c) and on the right $H_{is}/d = 0.1284$ (d–f).
Figure 8. Variation of $K_t$ with $\theta$ for $d/L_p = 0.0844$ and different porosities and wall configurations. On the left, $H_i/d = 0.2493$ (a–c) and on the right $H_i/d = 0.1284$ (d–f).

Table 4. Simple statistics of the percentage of increase in $K_t$ as a function of wall slope angle and number of walls.

| $\theta$ Change: | 90–60 | 90–30 | 60–30 | 90–60 | 90–30 | 60–30 |
|------------------|-------|-------|-------|-------|-------|-------|
| Statistical Parameter | Single Wall | Twin Walls |
| Mean | 4.21 | 4.56 | 3.87 | 3.45 | 4.11 | 3.21 |
| Standard Deviation | 3.47 | 2.73 | 1.69 | 2.50 | 3.58 | 1.39 |
| Minimum | 0.24 | 0.64 | 1.25 | 0.41 | 0.52 | 1.30 |
| Maximum | 10.16 | 10.39 | 6.78 | 8.84 | 10.44 | 4.89 |

Table 5. Simple statistics of the percentage of decrease in $K_t$ as a function of wall slope angle and number of walls.

| $\theta$ Change: | 90–60 | 90–30 | 60–30 | 90–60 | 90–30 | 60–30 |
|------------------|-------|-------|-------|-------|-------|-------|
| Statistical Parameter | Single Wall | Twin Walls |
| Mean | 1.37 | 11.42 | 8.12 | 4.37 | 11.08 | 8.60 |
| Standard Deviation | 1.17 | 6.63 | 6.31 | 5.03 | 8.96 | 7.37 |
| Minimum | 0.03 | 0.41 | 0.03 | 0.21 | 0.40 | 0.98 |
| Maximum | 2.92 | 20.22 | 17.82 | 14.18 | 24.79 | 23.58 |

3.2.4. Effect of Relative Wave Height, $H_i/d$

The analysis of $K_t$ variation with $d/L_p$ for the two cases of $H_i/d$ showed that $K_t$ is higher for smaller $H_i/d$ ($H_i/d = 0.1284$), as shown in Figures 9 and 10. Figure 9 shows the model conditions when $N = 1$, $P = 20\%$, and $\theta = 90^\circ$, and Figure 10 shows similar conditions but for $N = 2$. All other model conditions show similar trends.
The higher values of $K_t$ obtained when $H_i/d = 0.1284$ are due to the wave build-up phenomenon. For cases with twin walls, the average decrease in $K_t$ due to increasing $H_i/d$ ranged between 16.6–21.2%, while the average decrease was lower for models with single walls (between 8.83–16.3%). The highest average decrease in $K_t$ occurred when $P = 20\%$. 

From the results, it was also concluded that the variation of $K_t$ with $H_i/d$ and $d/L_P$ is more dependent on porosity than wall slope angle for models with single walls, while the opposite is true for cases with twin walls.
3.2.5. Effect of $d/L_p$

As seen in Figures 5–8, the general trend of $K_t$ is to decreases as $d/L_p$ increases. From $d/L_p = 0.1527$ to $d/L_p = 0.2733$ the decrease rate of $K_t$ increases significantly (Figures 5 and 6). The influence of $d/L_p$ on $K_t$ was similar for both cases of $H_o/d$ in the case of single-wall, whereas it was more substantial for models with twin walls. For $\theta = 30^\circ$, however, it was noticed that $K_t$ for both single and twin walls decreased in a similar manner with increasing $d/L_p$. The impact of $d/L_p$ on the results of models with $N = 1$ and $\theta = 90^\circ$ and $60^\circ$ was mild. In brief, $d/L_p$ had the greatest influence on $K_t$ for models with $\theta = 30^\circ$ followed by models with $\theta = 60^\circ$ and $\theta = 90^\circ$, respectively.

3.3. Wave Reflection Coefficient, $K_r$

3.3.1. Effect of Porosity

In terms of wave reflection, the results of the experiments showed that lower porosity increases the reflection coefficient. $P = 10\%$ always resulted in higher values of $K_r$, followed by $P = 20\%$ and $P = 30\%$. Figure 11 shows an example ($N = 1$, $\theta = 90^\circ$, and $H_o/d = 0.1284$) of the effect of $P$ on $K_r$. These results were anticipated since smaller wall porosity means greater wall area for wave reflection. The results showed a maximum increase in $K_r$ by 40.5% for single-wall models and 47.6% for twin-wall models by decreasing $P$ from 30% to 10%. Decreasing $P$ from 20% to 10% resulted in a maximum increase of 27% in $K_r$ for single-wall and twin-walls models. A maximum increase in $K_r$ by 18.9% for single-wall models and 20% for twin-walls models observed when decreasing $P$ from 30% to 20%. The highest average reduction in $K_r$ due to increasing porosity, always occur when $N = 2$, regardless of wall slope.

![Figure 11. Effect of $P$ on the variation of $K_r$ with $d/L_p$. $N = 1$, $\theta = 90^\circ$, and $H_o/d = 0.1284$.](image)

3.3.2. Effect of Number of Walls

The variation of $K_r$ with $d/L_p$ for various structure porosities and slopes are shown in Figures 12–14. The maximum reduction and increase in $K_r$ due to the addition of a second wall are 18.24% and 7.82%, respectively (Table 6). The average decrease in $K_r$ due to the addition of the second wall was found to be highest for models with $P = 20\%$ and $H_o/d = 0.1284$. In six of the nine cases shown in Figures 12–14,
the addition of a second wall causes increase in $K_r$ when $d/L_p$ is less than 0.1529. Generally, there exists a range of changing points in $d/L_p$, where the performance of the models in terms of $K_r$ varies. These changing points mostly occurred in the range of $d/L_p = 0.15–0.18$. Prior to the changing point, models with twin walls resulted in higher reflection values than models with single walls, whereas the opposite was noticed after the changing point. The only exceptions to this rule were models with $P = 20\%$ and $30\%$ and $\theta = 30^\circ$, where single-wall always resulted in higher $K_r$ values. This indicates the low impact of number of walls on $K_r$ against $d/L_p$. 

**Figure 12.** Effect of the number of walls on $K_r$. $\theta = 90^\circ$, and $H/d = 0.1284$. (a) $P = 10\%$, (b) $P = 20\%$, and (c) $P = 30\%$.

**Figure 13.** Effect of the number of walls on $K_r$. $\theta = 60^\circ$, and $H/d = 0.1284$. (a) $P = 10\%$, (b) $P = 20\%$, and (c) $P = 30\%$. 
3.3.3. Effect of Slope Angle

Figures 15–18 show the effect of the wall slope on \( K_r \) for different porosities and wall configurations. Decreasing \( \theta \) from 60° to 30° for models with single-wall, reduced \( K_r \) more than three times than decreasing \( \theta \) from 90° to 60° (a maximum of 24.7% reduction versus a maximum of 7.9% reduction, respectively). Similarly, lowering \( \theta \) from 60° to 30° for models with twin-walls, reduced \( K_r \) by a maximum of 24.2%, while decreasing \( \theta \) from 90° to 60° reduce \( K_r \) by a maximum of 10.6%.

Decreasing \( \theta \) from 90° to 30° reduces \( K_r \) by a maximum of 30.83% for models with single-wall and a maximum of 29.20% for models with twin walls. In most cases, walls with \( \theta = 90^\circ \) produced the highest \( K_r \) values, and walls with \( \theta = 30^\circ \) produced the lowest \( K_r \) values. The reduction in \( K_r \) as the slope angle decreases is justified by knowing that the higher the wall slope, the lesser the interaction between the wall and the waves. However, for some models with \( H_{id}/d = 0.1284, \frac{dL_p}{p} = 0.2733, \) and \( P = 20\% \) (Figure 15c,d), \( K_r \) values for \( \theta = 60^\circ \) were higher than those for \( \theta = 90^\circ \). For the models and wave conditions of Figure 15c,d, \( K_r \) at \( \theta = 90^\circ \) and \( \theta = 30^\circ \) were nearly the same when \( P = 30\% \).

![Graphs showing the effect of wall slope on \( K_r \).](image)

Figure 14. Effect of the number of walls on \( K_r \). \( \theta = 30^\circ \), and \( H_{id}/d = 0.2493 \). (a) \( P = 10\% \), (b) \( P = 20\% \), and (c) \( P = 30\% \).

Table 6. The maximum percentage of decrease and increase, and the average percentage of change in \( K_r \) due to addition of a second wall.

| S     | \( P\% \) | \( H_{id}/d \) | Maximum % of \( K_r \) Decrease | Maximum % of \( K_r \) Increase | Average % of \( K_r \) Change |
|-------|------------|----------------|---------------------------------|---------------------------------|-------------------------------|
| 90°   | 10         | 0.1284         | 5.88                            | 6.22                            | −1.28                         |
| 60°   | 10         | 0.1284         | 5.70                            | 13.98                           | 1.68                          |
| 30°   | 10         | 0.2493         | 7.06                            | 1.69                            | −2.94                         |
| 90°   | 20         | 0.1284         | 7.82                            | 11.22                           | −1.53                         |
| 60°   | 20         | 0.1284         | 5.73                            | 18.24                           | 2.64                          |
| 30°   | 20         | 0.2493         | 1.87                            | 8.97                            | 2.92                          |
| 90°   | 30         | 0.1284         | 5.65                            | 5.21                            | −1.60                         |
| 60°   | 30         | 0.1284         | 1.27                            | 13.44                           | 4.44                          |
| 30°   | 30         | 0.2493         | −                                | 6.29                            | 3.00                          |

The minus sign in the last column of Table 6 indicates an increase in \( K_r \).
Figure 15. Variation of $K_r$ with $\theta$ for $d/L_p = 0.2733$, and different porosities and wall configurations. On the left, $H_i/d = 0.2493$ (a and b) and on the right $H_i/d = 0.1284$ (c and d).

Figure 16. Variation of $K_r$ with $\theta$ for $d/L_p = 0.1529$, and different porosities and wall configurations. On the left, $H_i/d = 0.2493$ (a and b) and on the right $H_i/d = 0.1284$ (c and d).
3.3.4. Effect of $H_{ls}/d$

In most cases, waves approaching with $H_{ls}/d = 0.2493$ resulted in higher $K_r$ values than waves with $H_{ls}/d = 0.1284$ (Figures 19–21), agreeing with previous studies. The highest average increase in $K_r$ due to increasing $H_{ls}/d$ from 0.1284 to 0.2493 was 15.5%, while the lowest was 3.7%. The relationship between $H_{ls}/d$ and the other parameters, namely porosity, number of walls, and slope angle was unclear.
However, for models with $P = 30$ and $\theta = 30^\circ$, as shown in Figure 21c,f, both values of $H_\text{is}/d$ perform equally in terms of reflecting wave energy for $d/L_p \leq 0.1529$. For higher values of $d/L_p$, $K_r$ is higher when $H_\text{is}/d = 0.1284$ in the case of single-wall (Figure 21c,f).

![Figure 19](image1.png)

**Figure 19.** Effect of $H_\text{is}/d$ on $K_r$ for $P = 10\%$ and different wall slopes. Subfigures (a), (b), and (c) are for single-wall, and subfigures (d), (e), and (f) are for twin-wall.

![Figure 20](image2.png)

**Figure 20.** Effect of $H_\text{is}/d$ on $K_r$ for $P = 20\%$ and different wall slopes. Subfigures (a), (b), and (c) are for single-wall, and subfigures (d), (e), and (f) are for twin-wall.
3.3.5. Effect of $d/L_p$

In general, $K_r$ decreases as $d/L_p$ increases (Figures 19–21). As shown in the figures above, the decrease in $K_r$ is higher when $d/L_p$ is in the range between 0.0844–0.1529, and when $P$ is between 20% and 30%. For $d/L_p \geq 0.1529$, $K_r$ is minimally affected by $d/L_p$ in ten out of eighteen cases shown in Figures 19–21. In two cases (Figures 19b and 20b), an increase in $K_r$ when $d/L_p > 0.1529$ was noticed. On average, the effect of $d/L_p$ on $K_r$ was minimum when $P = 10%$.

3.4. Wave Energy Dissipation Coefficient, $K_l$

3.4.1. Effect of Porosity

An example of the impact of $P$ on $K_l$ is shown in Figure 22. For waves approaching with $H/d = 0.1284$, models with $P = 10\%$ resulted in the highest $K_l$ values, whereas for waves with $H/d = 0.2493$, the highest $K_l$ values were obtained when $P = 20\%$. In both cases, however, the lowest $K_l$ values were obtained when $P = 30\%$, as expected. The higher the wall porosity, the more wave energy goes through the wall.

Decreasing $P$ from 30\% to 10\% was more effective in increasing $K_l$ for models with single walls than models with twin walls (up to a 23.7\% increase for single-wall versus 13.3\% increase for twin-walls). An increase by a maximum of 15\% in $K_l$ observed for models with single walls as $P$ decreased from 20\% to 10\% and from 30\% to 20\%. For twin-wall models, decreasing $P$ from 20\% to 10\% increased $K_l$ by less than 5\%, while decreasing $P$ from 30\% to 20\% reduced $K_l$ by up to 11.4\%.
3.4.2. Effect of Number of Walls

The variation of $K_l$ with $d/L_p$ against the number of walls for a model with $P = 20\%$ and $\theta = 60^\circ$ under the wave condition $H_{is}/d = 0.2493$ is shown in Figure 23 as an example. The addition of a second wall has a more significant impact on increasing $K_l$ for waves with $H_{is}/d = 0.1284$ than for waves with $H_{is}/d = 0.2493$, where the average increase in $K_l$ ranged between 6.25–15.7% and 8.5–23.3%, respectively. In general, the addition of a second wall always increased $K_l$, as more wave energy is dissipated due to the second wall.

![Figure 22](image.png)

**Figure 22.** Effect of $P$ on $K_l$ for $N = 1$, $\theta = 90^\circ$, and $H_{is}/d = 0.1284$.

![Figure 23](image.png)

**Figure 23.** Effect of $N$ on the variation of $K_l$ with $d/L_p$. $P = 20\%$, $\theta = 60^\circ$, and $H_{is}/d = 0.25$. 

3.4.3. Effect of Slope Angle

For all experiments of different \( \theta \), the highest \( K_l \) values were found when \( \theta = 30^\circ \). The maximum \( K_l \) occurred when \( N = 2 \) and \( P = 20\% \), \( \theta = 30^\circ \), and \( H_{io}/d = 0.1284 \) (Figure 24).

![Example of the Effect of \( \theta \) on the variation of \( K_l \) for \( P = 20 \), \( N = 2 \), and \( H_{io}/d = 0.1284 \).](image)

Reducing \( \theta \) from 90° to 30° increased \( K_l \) by up to 14.7% for models with single walls and by up to 11.6% for models with twin walls, while reducing \( \theta \) from 60° to 30° increased \( K_l \) by up to 16.2% for models with single walls and by up to 9.2% for models with twin walls. Decreasing \( \theta \) from 90° to 60°, on the other hand, reduced \( K_l \) by less than 5% for all models. Walls with \( \theta = 90^\circ \) lead to higher \( K_l \) values than walls with \( \theta = 60^\circ \) for models with \( N = 1 \) and \( P = 10\% \) as well as models with \( P = 20\% \) under the wave conditions of \( H_{io}/d = 0.1284 \). In all other cases, walls with \( \theta = 60^\circ \) resulted in higher values of \( K_l \). It must be noted that, except for models with \( N = 1 \) and \( P = 10\% \), there exists a range for \( d/L_p \) between 0.844–0.22, where the variation in \( K_l \) between 60° and 90° angles oscillates. In general, reducing \( \theta \) from 60° to 30° is more effective than reducing \( \theta \) from 90° to 30° in increasing \( K_l \), while for other models, such as walls with \( P = 20\% \), it is quite the contrary. As a result, it is hard to conclude this section.

3.4.4. Effect of Relative Wave Height

Examples of the relationship between \( K_l \) and \( d/L_p \) against \( H_{io}/d \) for single and twin wall models with \( P = 20\% \) is presented in Figures 25 and 26, respectively. Waves with \( H_{io}/d = 0.2493 \) generally resulted in higher values of \( K_l \), or dissipated more energy, than waves with \( K_l = 0.1284 \) (18.4% average difference versus 13% average difference). The results showed that \( K_l \) for different wall porosities was highly influenced by \( H_{io}/d \), with models of \( P = 30\% \) resulting in the highest average difference, followed by models with \( P = 20\% \) and models with \( P = 10\% \). The effect of varying \( H_{io}/d \) on \( K_l \) in terms of the slope angle, however, was ambiguous.

The difference in \( K_l \) due to the variation in \( H_{io}/d \) for models with \( P = 10\% \) was found to be marginal, ranging between 1.6–5.7%.
4. Conclusions

In general, $K_l$ increases with increasing $d/L_p$. This increase is higher for models with $N = 2$ and $P = 30\%$. In most cases, the increase becomes more drastic after $d/L_p = 0.1529$. The effect of $d/L_p$ on $K_l$ for both instances of $H_o/d$ was generally similar. On the other hand, the impact of $d/L_p$ on $K_l$ for models with $N = 1$, $P = 10$, and $\theta = 60^\circ$ and $90^\circ$ was insignificant.

3.4.5. Effect of Relative Wave Length

In general, $K_l$ increases with increasing $d/L_p$. This increase is higher for models with $N = 2$ and $P = 30\%$. In most cases, the increase becomes more drastic after $d/L_p = 0.1529$. The effect of $d/L_p$ on $K_l$ for both instances of $H_o/d$ was generally similar. On the other hand, the impact of $d/L_p$ on $K_l$ for models with $N = 1$, $P = 10$, and $\theta = 60^\circ$ and $90^\circ$ was insignificant.
4. Conclusions

The general trend noticed from the results is that there is a slight difference, in terms of $K_t$, between vertical structures and structures sloped at 60° in most cases. In contrast, significant differences are noticed between vertical structures and structures sloped at 30°.

Eight different types of single and twin slotted walls varying in porosity and slope angle were experimentally tested for a series of random waves. The effect of the structure parameters and wave conditions on the hydrodynamic characteristics was studied and analyzed. The reduction in $K_t$ could reach to 35.38% as $P$ is reduced from 30 to 10% for the single-wall cases, and to 38.86% for the twin-wall cases. On average, reducing the structure porosity from 30% to 10% reduces $K_t$ by 25.26% and 26.28 for single and twin walls, respectively.

The effect of the wall slope on $K_t$ was more significant when $d/L_p = 0.2733$ than when $d/L_p = 0.1529$, 0.1083, or 0.0844. For most of the investigated cases, the effect of the wall slope on $K_t$ was negligible when $d/L_p = 0.1529$ and 0.1083. For the case of $d/L_p = 0.0844$, an increasing trend was noticed as the wall angle decreases. The values of $K_t$ were nearly the same when changing the wall slope from 90° to 60°, and the effect of wall slope on $K_t$ was only evident when comparing $\theta = 90°$ with $\theta = 30°$. The effect of the wall slope was larger in the instances of twin-walls. For $d/L_p$ larger than 0.1527, $K_t$, for models with $\theta = 30°$, is significantly lower than models with $\theta = 60°$ and 90°. Before the aforementioned critical $d/L_p$ points, no single conclusion was reached regarding $K_t$ and the varying slope angles.

Twin-walls were more effective in reducing $K_t$ as $d/L_p$ increases than single-walls. The reason for this increased effect is that shorter waves (larger $d/L_p$) are more likely to interact with the wall than longer waves, which are more likely to pass through the slots of the walls.

Regarding the wave reflection, decreasing wall porosity from 30% to 10% increases wave reflection for both single- and twin-wall models. Reducing the slope angle from 90° to 30° reduces the wave reflection by a maximum of 30.83% for models with single-wall and a maximum of 29.20% for models with twin walls. For most of the studied cases, the addition of a second wall was effective in reducing the $K_r$. The maximum average change in $K_r$ due to the addition of a second wall was only 4.44%.

In the case of wave energy dissipation, decreasing wall porosity from 30% to 10% increases $K_d$ by a maximum of 23.7% for the case of single-walls and 13.3% for the case of twin-walls. Reducing the slope angle from 90° to 30° degrees increased $K_d$ by a maximum of 14.7% for the case of single-wall and 11.6% for the case of twin-walls. The addition of a second wall increased energy dissipation by a maximum of 23.3%.

The conclusion from the above is that reducing $K_t$ is most achievable by adding a second wall, followed by reducing the porosity, and finally by decreasing the slope angle. To reduce $K_r$, however, reducing wall porosity is the most effective measure, followed by reducing the slope angle, and lastly, by adding a second wall. Increasing $K_t$ is most achievable when decreasing the porosity, followed by the addition of a second wall, and finally by reducing the structure slope angle.

Regarding the wave parameters, increasing $H_p/d$ from 0.1284 to 0.293 causes an average reduction of 21.2% in $K_t$ and 15.5% in $K_r$, and an increase of up to 18.4% in $K_i$. On the other hand, both $K_i$ and $K_r$ decreased with increasing relative wavelength, $d/L_p$, while $K_t$ followed the opposite trend. In most cases, the variation of $d/L_p$ from 0.153 to 0.273 causes more variation in $K_i$, $K_r$, and $K_t$ than the variation of $d/L_p$ from 0.844–0.152. These results show that as the waves approach deep water, the effects of wave period on transmission, reflection, and energy dissipation become increasingly more substantial.

The results of this study determine the most influential parameters on the performance of vertical and sloped slotted walls. Understanding the performance of such type of coastal protection structures under different hydrodynamic and design configurations, will enhance and optimize breakwater design and improve the design procedure and guidelines. More intensive studies to expand the range of wall parameters and wave conditions are recommended to gain a better physical understanding of the performance of such walls and to develop numerical and empirical design procedures for slotted walls that include the most influential parameters.
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