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The Effectiveness of Inclined Pile Breakwater on the Transmission Coefficient

Lukman Nurzaman [1*], Pitojo Tri Juwono [2*], Very Dermawan [2], Indradi Wijatmiko [1]

[1] *Department of Civil Engineering, Faculty of Engineering, University of Brawijaya, Malang, Indonesia.*

[2] *Department of Water Resources Engineering, Faculty of Engineering, University of Brawijaya, Malang, Indonesia.*

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Abstract

A breakwater is a structure designed to protect coastal areas by breaking and reducing the force of incoming waves. Waves that propagate through a wave dampening building will have some of their energy reflected (reflection), some of their energy transmitted (transmission), and some of their energy destroyed (dissipation). The effectiveness of wave-breaking structures in protecting coastal and harbor waters can be seen from how much wave energy the building can reduce. In this research, the performance of the wave breaker will be seen from the values of wave transmission (Kt) and wave reflection (Kr) with an inclined pile building structure. Reflection and transmission analysis of the results of 2D physical model testing of wave breakers with inclined pile structures are needed to optimize their use. Laboratory test results prove that this Inclined Pile Structure breakwater is quite effective in scenarios that have smaller Kt values and larger Kr values. In this experiment, testing was carried out with several parameters, namely the slope of the pile, the distance between the piles in one row (or distance between pillars), the distance between the tops of the piles (or distance between rows of piles), and the depth of the water. The Kt value in the model α=45°; D=1.69 cm; b=5 cm is 0.603 compared to the model α=60°; D=1.69cm; b=5 cm, Kt value is 0.652. This shows that the inclined pile structure of breakwater is more effective with a pile slope of 45° than with a pile slope of 60°.

Keywords: Inclined Pile Breakwater; Reflection; Transmission; Wave.

1. Introduction

Coastal areas are an important part of and have a significant influence on a country's economy, including developing and revitalizing coastal tourism and building the environment and stability of the urban environment [1, 2]. Natural phenomena such as waves, winds, tides, and currents near the shore have an impact on the beaches and the stability of the coastal zone [3]. The basic purpose of breakwater is to protect a part of a shoreline, a structure, a harbor, or moored vessels from excessive incident wave energy when the waves hit the breakwater and they lose a lot of energy [4, 5]. Coastal protection has been developed with conventional breakwaters, which have high reliability and efficiency in wave dissipation. The requirement of a breakwater is to allow the least number of waves to be transmitted to its side of the coastal zone. However, the environmental sustainability of coastal structures depends on the need for raw materials and their significant impact on the surrounding environment, which results in permanent changes in the coastline to the surrounding environment [6].

* Corresponding author: lucky_pisces81@yahoo.com; pitojo_tj@ub.ac.id

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To overcome this problem, modern breakwaters have been developed based on geometry, porous materials, and breakwater configurations to increase the efficiency of breakwater structures during wave dissipation. Besides that, the failure of vertical-side breakwaters is generally related to problems with wave conditions. Sea waves can cause structural damage, which can cause structural changes such as sliding and overturning in vertical-side breakwater [7]. To overcome the horizontal and vertical forces from the hydrodynamic conditions that occur, one of the treatments carried out is a hard structure approach, which generally takes the form of a breakwater building [8].

This study investigates inclined pile breakwater as an alternative design. The investigation is conducted by modeling how wave energy is either reflected, dissipated, transmitted, or subjected to a combination of these wave mechanisms. Study related to wave transmission on wave breakers with closely spaced piles compared to wave breakers with piles that are not spaced apart. This comparison shows that the relationship between the space between the pile and the transmitted wave results in a decrease in the transmitted wave at a large speed based on the distance between the piles [9]. In addition, another complex configuration added to D is diameter. The result highlights the influence of relative clear spacing between the piles in a row (b/D) and relative clear spacing between the pile rows (B/D) for transmitted wave coefficient (Kt) and reflected wave coefficient (Kr). The result is that staggered arrangements have a significant impact on reducing Kr; Kt is decreasing when b/D is decreasing. Energy attenuation research was conducted using a 2D physical model that utilizes a 3D wave pool. The position of the piles influences the amount of wave energy that the structure can dampen. The closer the distance between the piles in the rows, the greater the energy reduction [10, 11]. The effectiveness of a breakwater in protecting the coast can be seen from the wave energy that can be reduced by the structure, while the optimum condition is one in which the pile spacing or pile configuration is determined to obtain the desired amount of energy to be reduced or the desired wave height to pass through the pile (damping) with minimal construction cost [11].

This research developed a breakwater design based on Simanjuntak et al. [11], with some modifications. The design considers arrangements for two-row formation and variations of B/D and b/D values. A new design is introduced in this study by using an inclined pile. The structure is also tested for different variations of wave height (H), slope of pile (α), water depth (d), and wave period (T). Based on those configurations, waves that propagate around a wave dampening building will have some of their energy reflected (reflection), some forwarded (transmission), and some destroyed (dissipation). The interaction between the designed inclined pile breakwater and the incident wave is modeled with a physical experiment and a numerical model. A comprehensive approach to developing numerical models for inclined pile breakwater. The author uses the irregular wave model, which is used repeatedly for the irregular wave spectrum. This paper only discusses the result for inclined pile breakwater with a two-row formation with a pile slope of 45°. As for the two-row transformation with the pile slope of 60°, the result was already discussed in another study [12].

2. Material and Methods

Implementation of this modification begins with finding the best layout and dimensions through physical tests in the laboratory. The physical model was carried out at the Marine Engineering Laboratory at Hasanuddin University, South Sulawesi Province.

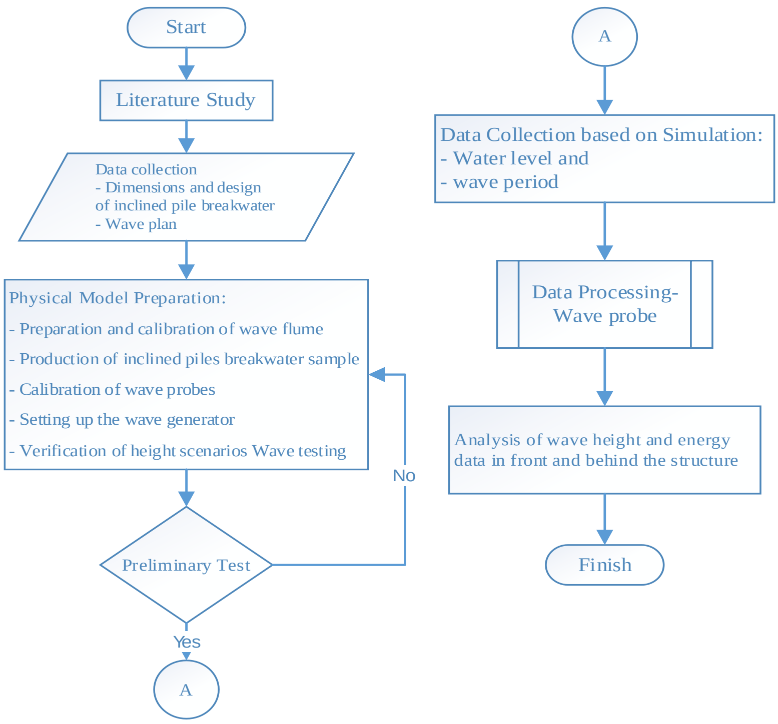

Figure 1. Research Method for Inclined Pile Breakwater

2.1. Material

Laboratory-scale physical model tests were carried out by testing 720 tests. by varying several parameters, including the distance between the piles in one row, the distance between the tops of the structure, wave height formation, wave period, and water surface depth, as shown in Table 1.

Table 1. Physical Model Test Variables

No	Variable	Symbol	Variation
1	Distance between piles in one row	D	1.69 cm; 3.38 cm
2	Water depth	d	0.294 m; 0.353 m; 0.412 m
3	The height of the incoming wave	Hi	5.6 cm; 8.6 cm; 11.6 cm; 14.6 cm; 17.6 cm
4	Number of rows of inclined pile	N	2
5	Distance between top of the structure	b	20.38 cm; 35.76 cm; 5.00 cm
6	Wave period	T	2.425 s; 1.715 s; 1.400 s; 1.213 s
7	The slopes of piles	α	45°; 60°
8	Wave Type	-	Irregular
9	Scale	-	1: 17.72

An overview of the test variables is presented in Table 1 and shown in Figure 2.

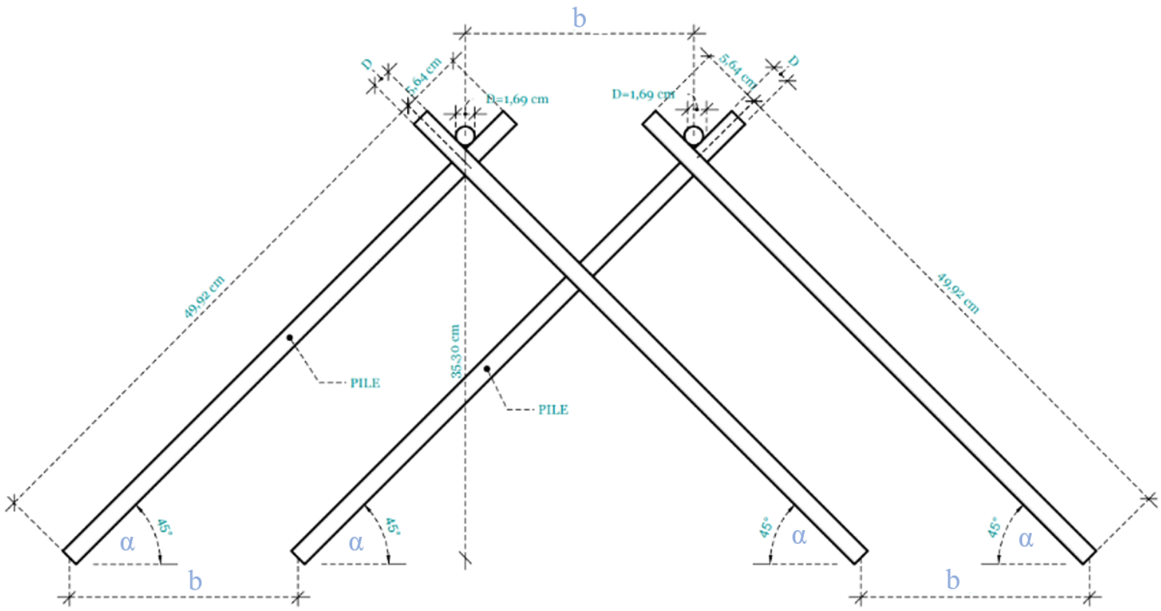

Figure 2. Test parameters b, D and N

Testing of the physical model of the pile wave damper was carried out on a wave channel with a width of 1 meter and a length of 24 meters, and then the breakwater model was placed in the middle of the wave channel. For wave generation, a JONSWAP wave generator machine was used, which can generate irregular wave types. The wave channel setup carried out in the laboratory is shown in Figure 3.

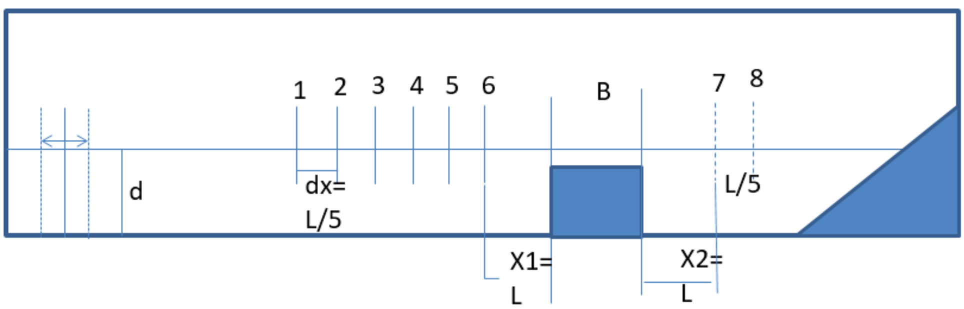

Figure 3. Wave Probe Parameters

2.2. Model Scenario

The scenario in the physical model test can be seen in Table 2. The scenario in this experiment uses a combination of two structural slopes, namely 45° and 60°: distance between piles in one row: 1.69 cm and 3.38 cm; distance between the top of the structure: 20.38 cm, 35.76 cm, and 5.00 cm; water depth: 0.294 m, 0.353 m, and 0.412 m; the combination of wave height and wave period is adjusted to the availability of wave properties generated from the wave generator in the laboratory.

Table 2. Physical Modeling Scenario

Pile Formation	Distance between top of the structure, b (cm)	Distance between piles in one row, D (cm)	Water depth, d (m)	Period, T (s)	The height of the incoming wave, Hi (cm)
45°	20.38; 35.76; 5.00	1.69; 3.38	0.294; 0.353; 0.412	2.425; 1.715; 1.400; 1.213	5.6; 8.6; 11.6; 14.6; 17.6
60°	20.38; 35.76; 5.00	1.69; 3.38	0.294; 0.353; 0.412	2.425; 1.715; 1.400; 1.213	5.6; 8.6; 11.6; 14.6; 17.6

Wave data was taken from WP 01, WP 02, WP 03, WP 04, WP 05, WP 06, WP 07, and WP 08. Data from WP 01 to WP 06 is the height of the incoming wave (Hi); WP 07 data was used to analyze the wave reflection (Hr); and WP 08 data is used for transmission waves (Ht). Wave height (H) and wave period (T) data are obtained from the wave probe.

2.3. Transmission Coefficient

The transmission wave height is the height of the transmitted waves obtained from WP 08, which is located behind the breakwater in this 2D physical modeling. The WP 08 recording results were identified using zero-down crossing. The transmission coefficient (Kt) is the ratio between the transmitted wave height (Ht) and the incident wave height (Hi). The transmission coefficient can be written as follows:

$$Kt = \frac{Ht}{Hi} \tag{1}$$

2.4. Reflection Coefficient

The reflection coefficient (Kr) is the ratio between the reflected wave height and the incident wave height. The reflection coefficient can be written as follows:

$$Kr = \frac{Hr}{Hi} \tag{2}$$

$$Hr = \frac{Hmax - Hmin}{2} \tag{3}$$

$$Hi = \frac{Hmax + Hmin}{2} \tag{4}$$

$$Kr = \frac{Hmax - Hmin}{Hmax + Hmin} \tag{5}$$

2.5. Dimensional Analysis

This dimensional analysis uses the Buckingham method. The results of the reduction using the Buckingham method for the variables involved are: Hi (incoming wave height, unit: m), L (wave length, unit: m), T (wave period, unit: s), h (water depth, unit: m), b (space distance between piles, unit: m), g (gravitational acceleration, unit: m/s^2), the following nondimensional number relationship is obtained:

$$Kt = f\left(\frac{b}{Hi}, \frac{D}{Hi}, \frac{Hi}{gT^2}\right) \tag{6}$$

$$Kr = f\left(\frac{b}{Hi}, \frac{D}{Hi}, \frac{Hi}{gT^2}\right) \tag{7}$$

3. Results and Discussion

3.1. Effect of Hi/L and Hi/gT^2 on Transmission Coefficient

The transmission coefficient (Kt) is the amount of wave energy that is transmitted after passing through a barrier (structure). Based on the results of measurements and calculations, we will see the effect of wave steepness both in parameters (Hi/L) and in parameters (Hi/gT^2) on the values in the combination conditions of 3 water depths (0.294 m, 0.353 m, and 0.412 m) with 2 space scenarios. The distance between piles in one row (D), namely D = 1.69 cm and D = 3.38 cm, and the slope of the structure are 45° and 60°. The Kt value as a function of Hi/L is based on several parameter variations. Based on these parameters, the model configuration can be seen in Table 3.

Table 3. Model Configuration

Configuration	Variation
Model 1	α=45°; D=1.69 cm; b= 20.38 cm
	α=45°; D=3.38 cm; b= 20.38 cm
Model 2	α=45°; D=1.69 cm; b= 35.76 cm
	α=45°; D=3.38 cm; b= 35.76 cm
Model 3	α=45°; D=1.69 cm; b= 5 cm
	α=45°; D=3.38 cm; b= 5 cm
Model 4	α=60°; D=1.69 cm; b= 20.38 cm
	α=60°; D=3.38 cm; b= 20.38 cm
Model 5	α=60°; D=1.69 cm; b= 35.76 cm
	α=60°; D=3.38 cm; b= 35.76 cm
Model 6	α=60°; D=1.69 cm; b= 5 cm
	α=60°; D=3.38 cm; b= 5 cm

Kt is inversely related to the variable Hi/L, i.e. the value of Kt increases as the value of the variable Hi/L decreases, according to the research carried out previously by [13-16]. Based on model test, the Kt value as a function of Hi/L in depth conditions (0.294 m; 0.353 m; 0.412 m) can be shown in the graphs in Figures 4 to 9. The graph shows that the greater the (Hi/L) value, the smaller the Kt value and conversely the smaller the (Hi/L) value, the greater the (Kt) value in both space scenarios. Between the scenarios with 1D spacing and those with 2D spacing models, the value of the transmission coefficient is higher in the 2D spacing models. This indicates that the value of Kt is higher when the spacing between the piles of the inclined pile structure is larger, and the value of Kt is lower when the spacing between the piles is smaller. Kt is small, and this agrees with the research carried out by Koftis et al. [17] and Hayashi et al. [18].

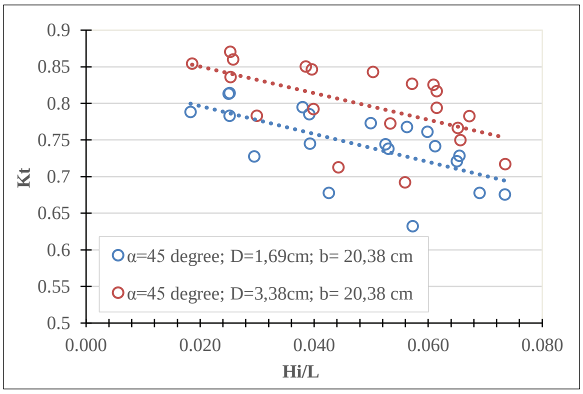

Figure 4. Kt vs Hi/L Model 1

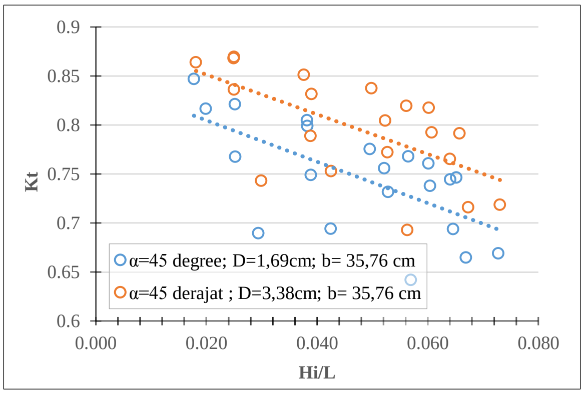

Figure 5. Kt vs Hi/L Model 2

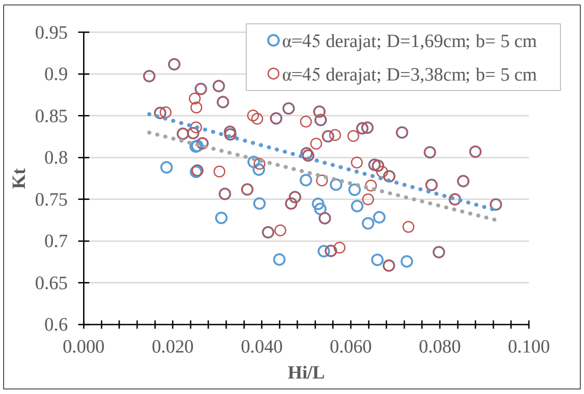

Figure 6. Kt vs Hi/L Model 3

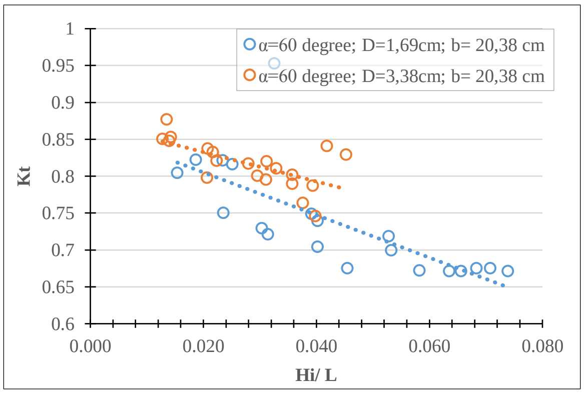

Figure 7. Kt vs Hi/L Model 4

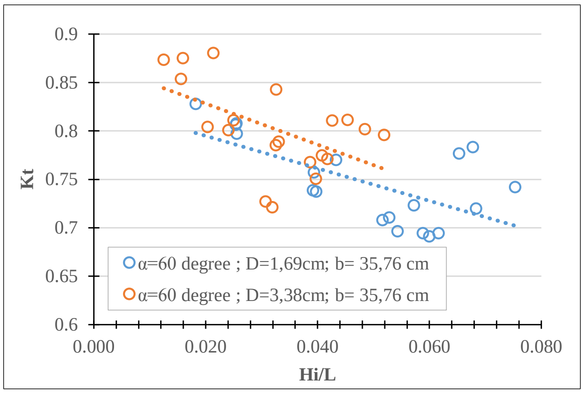

Figure 8. Kt vs Hi/L Model 5

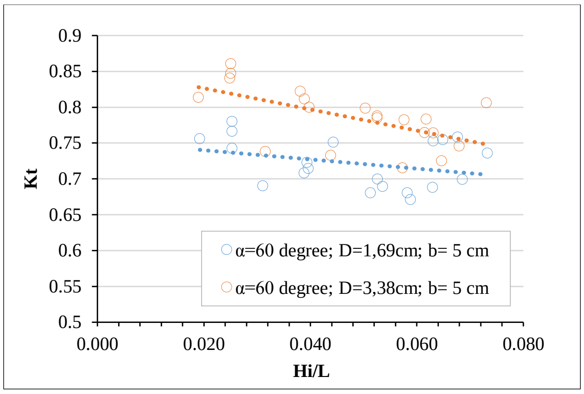

Figure 9. Kt vs Hi/L Model 6

Based on the distance between piles in one row, the distance between the top of the structure, and the slope of the piles, the smallest coefficient value is in model 3 (Figure 6) at 0.603 and 0.665. This shows that model 3 (α=45°; D=1.69 cm; b= 5 cm; α=45°; D=3.38 cm; b= 5 cm) has a more efficient configuration.

Kt is inversely related to the variable Hi/gT^2, i.e. the value of Kt increases as the value of the variable Hi/gT^2 decreases, according to the research carried out previously by [13-16]. The Kt value as a function of Hi/gT^2 in depth conditions (0.294 m; 0.353 m; 0.412 m) can be shown in the graphs in Figures 10 to 15. The graph shows that the more the larger the value (Hi/gT^2), the smaller the Kt value and conversely, the smaller the value (Hi/gT^2), the greater the value (Kt) in both space scenarios. Based on these parameters, the model configuration can be seen in Table 4. Based on the Distance between piles in one row, Distance between top of the structure and the slope of the piles, the smallest coefficient value is in model 3 (Figure 12.). This shows that model 3 (α=45°; D=1.69 cm; b= 5 cm has transmission coefficient value of 0.642) and (α=60°; D=3.38 cm; b= 5 cm has transmission coefficient value of 0.662). This shows that model 3 (α=45°; D=1.69 cm; b= 5 cm) has a more efficient configuration because the smallest transmission coefficient value is 0.642.

Table 4. Model Configuration

Configuration	Variation
Model 1	α=45°; D=1.69 cm; b= 20.38 cm
	α=60°; D=1.69 cm; b= 20.38 cm
Model 2	α=45°; D=1.69 cm; b= 35.76 cm
	α=60°; D=1.69 cm; b= 35.76 cm
Model 3	α=45°; D=1.69 cm; b= 5 cm
	α=60°; D=1.69 cm; b= 5 cm
Model 4	α=45°; D=3.38 cm; b= 20.38 cm
	α=60°; D=3.38 cm; b= 20.38 cm
Model 5	α=45°; D=3.38 cm; b= 35.76 cm
	α=60°; D=3.38 cm; b= 35.76 cm
Model 6	α=45°; D=3.38 cm; b= 5 cm
	α=60°; D=3.38 cm; b= 5 cm

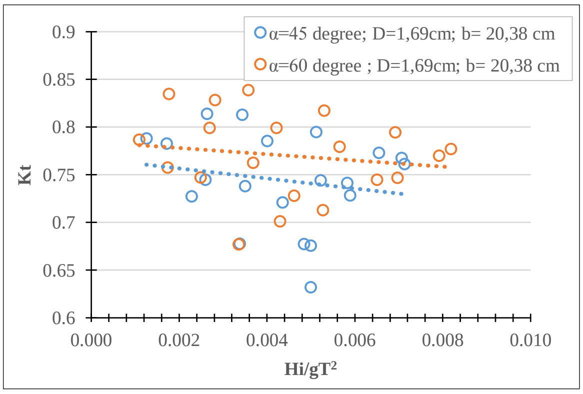

Figure 10. Kt vs Hi/gT^2 Model 1

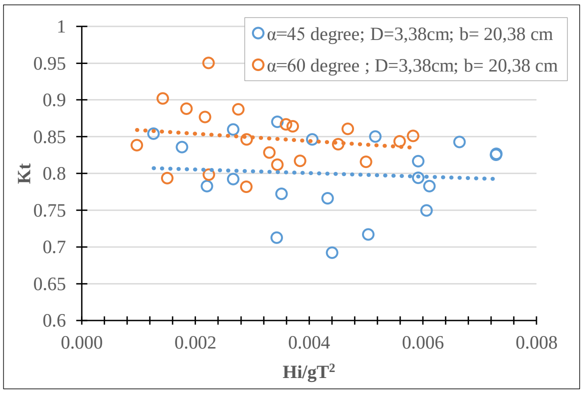

Figure 11. Kt vs Hi/gT^2 Model 2

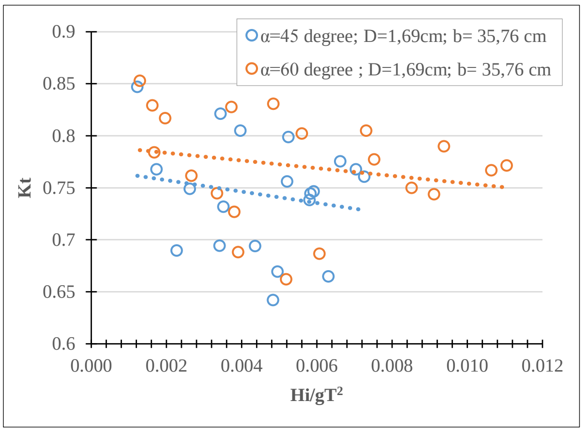

Figure 12. Kt vs Hi/gT^2 Model 3

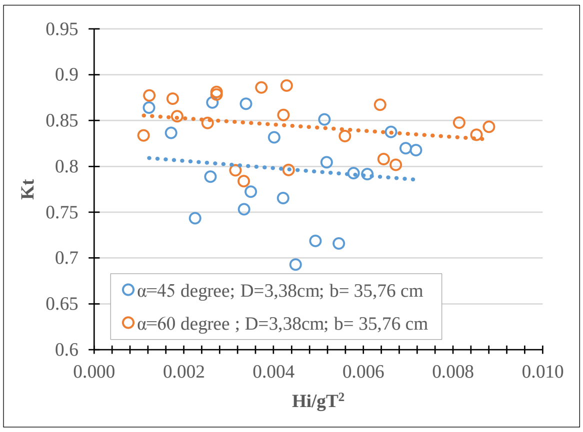

Figure 13. Kt vs Hi/gT^2 Model 4

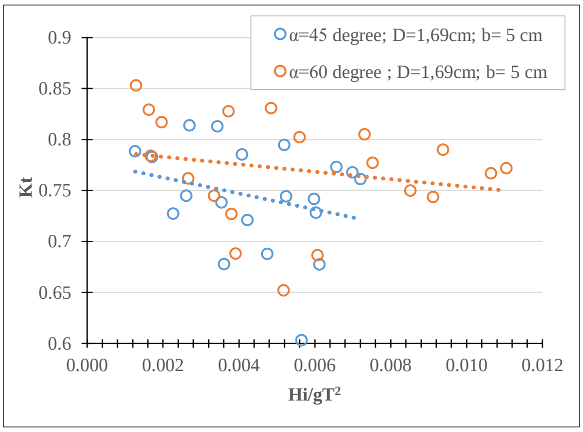

Figure 14. Kt vs Hi/gT^2 Model 5

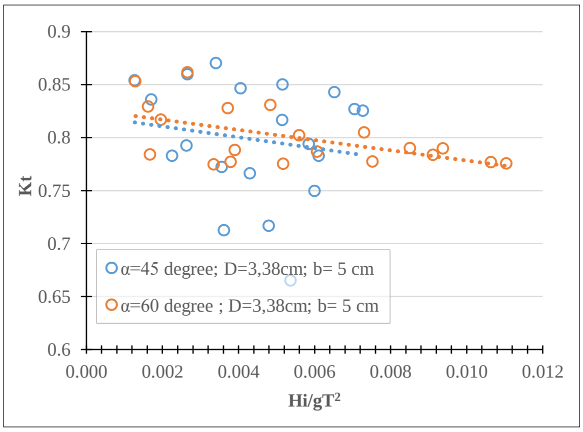

Figure 15. Kt vs Hi/gT^2 Model 6

The results of testing a 2D physical model using an inclined pile structure breakwater show that Kt is inversely related to the variables Hi/L and Hi/gT^2, i.e. the value of Kt increases as the value of the variables Hi/L and Hi/gT^2 decreases. The value of the transmission coefficient is higher in the model with a spacing of 3.38 cm and a structural slope of 60° in the 45° and 60° formations with a spacing of 1.69 cm in a row (1D) and in the model with a spacing of 3.38 cm in a row (2D). It shows that the greater the spacing between rows of piles, the higher the Kt value, and the smaller the spacing between rows of piles, the lower the Kt value. These results are in line with research by Koftis et al. [17] that the smaller the space between piles, the lower the energy transfer. This shows that the 45^0 inclined pile breakwater is more efficient in waters with lower water levels. This is consistent with research carried out by Herbich et al. [19] which shows that the lower the water depth, the lower the Kt.

3.2. Effect of Hi/L and Hi/gT^2 on the Reflection Coefficient

The reflection coefficient is the amount of energy reflected by the waves. Based on the results measurements and calculations, the effect of wave steepness is seen in the parameter (Hi/L) as well as in the parameters (Hi/gT^2) to the Kr value. The calculation results are shown in the Figures 16 to 27. Kr has a direct proportional relationship with the variables Hi/L and Hi/gT^2, which means that the value of Kr increases as the value of the two variables increase, based on the results of testing a 2D physical model using an inclined pile breakwater. These results are consistent with previous research conducted by Rao et al. [20] that the value of Kr increases as the value of Hi/gT^2 increases. This is consistent with research conducted by Anas [13] and Sollitt & Cross [21] based on the Distance between piles in one row, Distance between top of the structure and the slope of the piles.

The Kr value as a function of Hi/L in depth conditions (0.294 m; 0.353 m; 0.412 m) can be shown in the graphs in Figures 16 to 21. Based on these conditions, the configuration of the model can be seen in Table 3. The results showed that when the (d/L) increased, also the (Kr) increases. The reflection coefficient (Kr) in case (45°) was larger than in case (60°). The comparison between the first case and the second case shows that in the first case the energy dissipation was higher than in the second. Figures 16 to 27 shows the comparison of two different drafts based on the slope of pile.

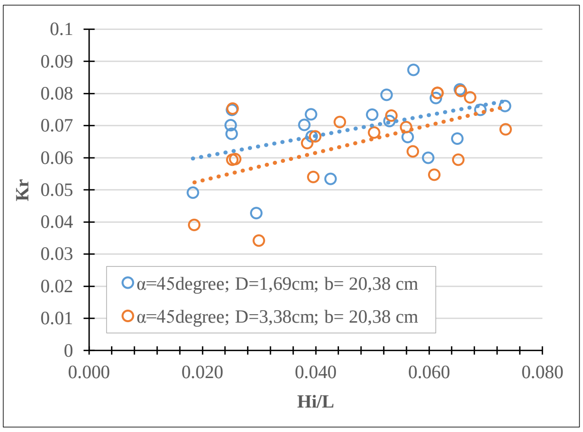

Figure 16. Kr vs Hi/L Model 1

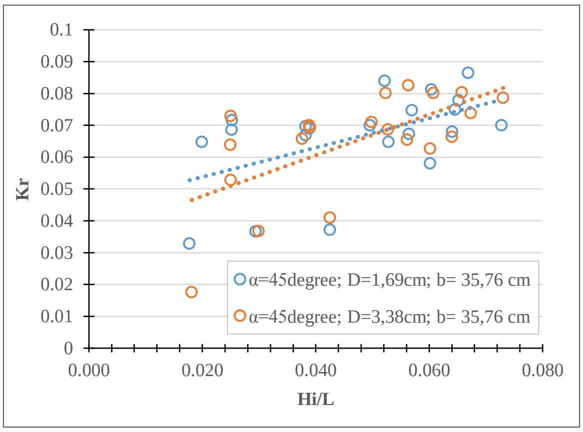

Figure 17. Kr vs Hi/L Model 2

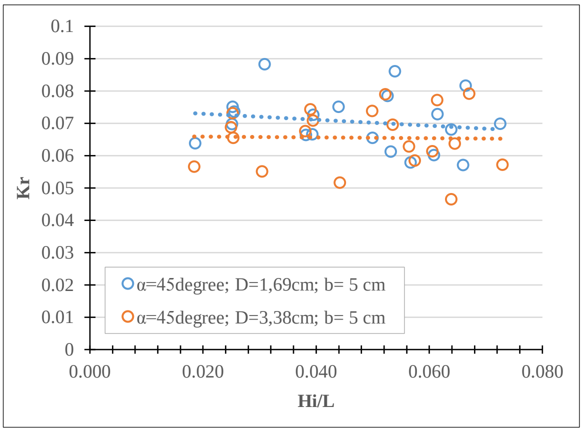

Figure 18. Kr vs Hi/L Model 3

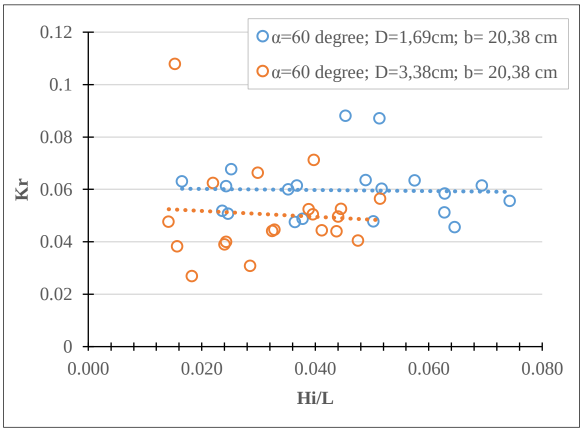

Figure 19. Kr vs Hi/L Model 4

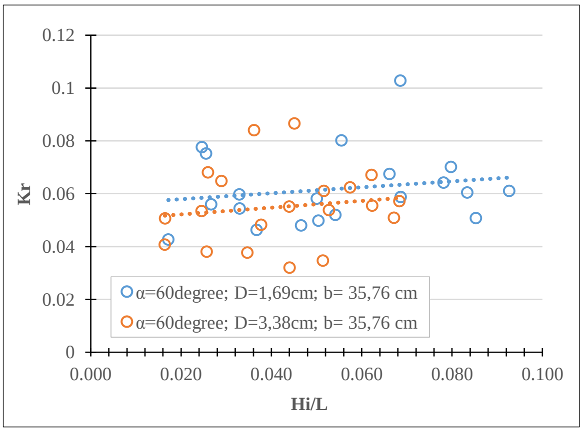

Figure 20. Kr vs Hi/L Model 5

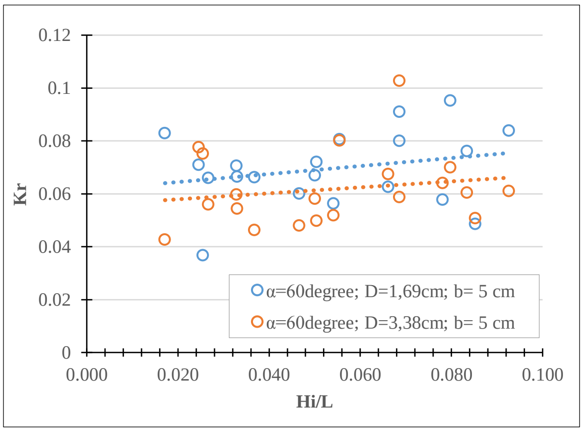

Figure 21. Kr vs Hi/L Model 6

The Kr value as a function of Hi/gT^2 at depth conditions (0.294 m; 0.353 m; 0.412 m) is shown in the graphs in Figures 21 to 26. The graph shows that the greater the Hi/gT^2 value, the greater the Kr value and conversely the smaller the Hi/gT^2 value, the smaller the Kr value in both space scenarios. Based on these conditions, the model configuration can be seen in Table 4. In the comparison between models with water depth conditions, the value of Kr is relatively lower in high conditions and higher in low conditions. These results agree with the study of Hayashi et al. [18] that the deeper the water, the smaller the Kr value. Using numerical models, the transmission coefficient (Kt) is plotted against the relative water depth (d/L). The figure shows that the wave transmission coefficient decreases based the distance between the piles in a row.

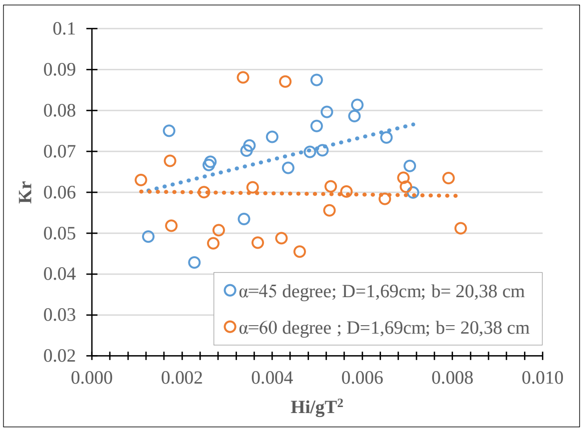

Figure 22. Kr vs Hi/gT^2 Model 1

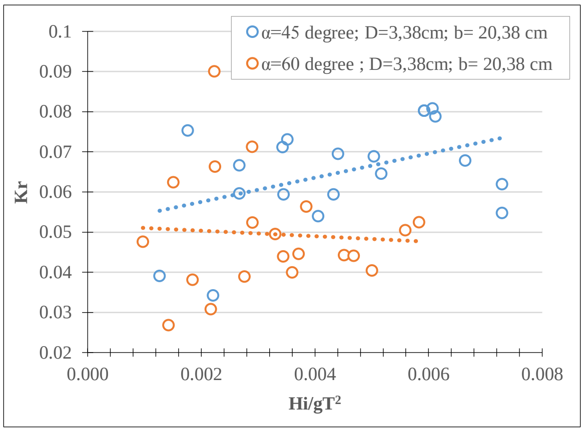

Figure 23. Kr vs Hi/gT^2 Model 2

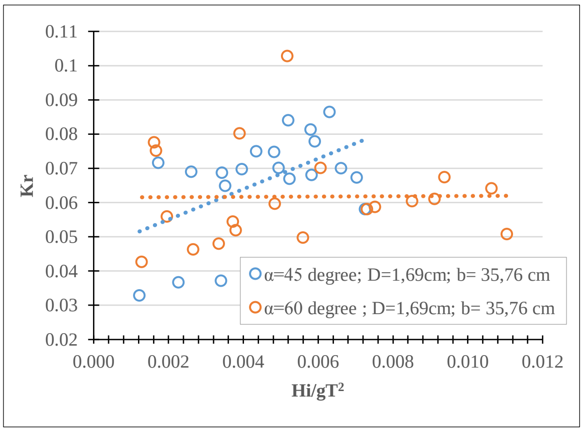

Figure 24. Kr vs Hi/gT^2 Model 3

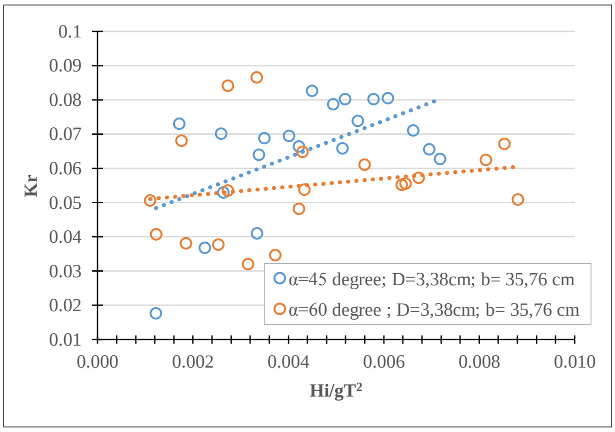

Figure 25. Kr vs Hi/gT^2 Model 4

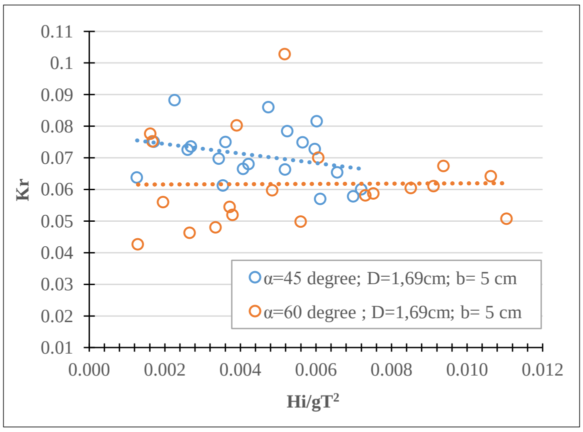

Figure 26. Kr vs Hi/gT^2 Model 5

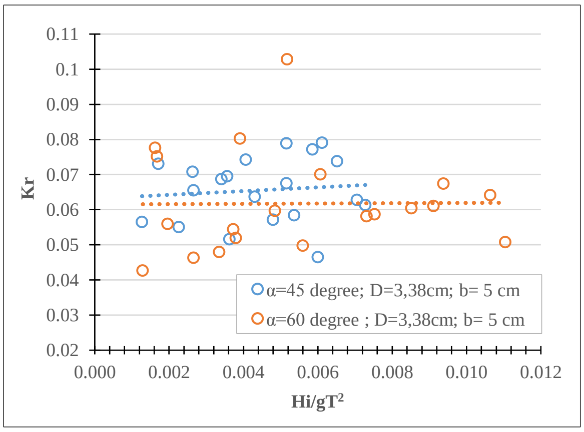

Figure 27. Kr vs Hi/gT^2 Model 6

The results of testing a 2D physical model using an inclined pole structure breakwater, Kr has a directly proportional relationship with the variables Hi/L and Hi/gT^2, which means that the value of Kr increases as the value of these two variables increases. These results show that the Kr value increases as the Hi/L value increases [13], and the deeper the water, the smaller the Kr value [19]. When compared based on depth (0.294 m; 0.353 m; 0.412 m), the Kt value is relatively lower at a depth of 0.294m. A summary of the Kt value results from each experiment can be presented in Table 5. These results are in accordance with research Hayashi et al. [18] which states that the deeper the water, the smaller the Kr value. This shows that the inclined pile breakwater is efficient in waters with lower air levels. Based on the distance between poles in one row, the distance from the top of the structure, and the slope of the poles, the smallest coefficient value is found in the model α=45°; D = 1.69 cm; b= 5 cm with a water depth of around 0.294, which has a more efficient configuration with a transmission coefficient value of 0.603.

Table 5. Recapitulation of Kt values

Model Configuration	Kt based on Water Depth		
	0.294	**0.353**	**0.412**
α=45°; D=1.69 cm; b= 35.76 cm	0.642	0.652	0.685
α=45°; D=1.69 cm; b= 20.38 cm	0.632	0.637	0.662
α=45°; D=1.69 cm; b= 5.00 cm	0.603	0.612	0.660
α=45°; D=3.38 cm; b= 35.76 cm	0.716	0.745	0.756
α=45°; D=3.38 cm; b= 20.38 cm	0.692	0.742	0.752
α=45°; D=3.38 cm; b= 5.00 cm	0.665	0.715	0.740
α=60°; D=1.69 cm; b= 35.76 cm	0.691	0.662	0.708
α=60°; D=1.69 cm; b= 20.38 cm	0.671	0.677	0.710
α=60°; D=1.69 cm; b= 5.00 cm	0.671	0.652	0.710
α=60°; D=3.38 cm; b= 35.76 cm	0.721	0.784	0.796
α=60°; D=3.38 cm; b= 20.38 cm	0.746	0.782	0.790
α=60°; D=3.38 cm; b= 5.00 cm	0.715	0.775	0.790

4. Conclusion

In general, the experimental results show that the value of Kt tends to be inversely proportional to the value of wave slope (Hi/L) and wave steepness (Hi/gT^2), especially in the case of low water depth at 1D spacing. While the values of Kr do not seem to be directly correlated with the slope and steepness of the waves, for high water depth, at 2D spacing, it shows that the values of Kr tend to be directly proportional to the value of the wave slope (Hi/L) and steepness (Hi/gT^2). Compared to the water level conditions, the value of Kt and the value of Kr from the experimental results show that the value of Kt is lower at low water depth compared to high water depth conditions, and the value of Kr is visibly higher at low water depth compared to high water depth conditions. This indicates that inclined pile breakwaters are more effective in reducing wave transmission at low water depth conditions than at high water depth conditions. The effect of the distance between the piles in a row, the distance between the top of the structure and the inclination of the piles, causes greater energy in the transmitted waves (Kt), especially in low water depth conditions. The use of inclined pile breakwaters will be more effective in watery locations with large slopes (classified as short waves) and by using closer pile spacing.

Based on the results of the experiments carried out, conclusions were obtained, including: (1) Figure 3 and Figure 8 show that the Kt value is lower when the average depth is 0.294 m. The lower the water depth, the smaller the Kt value. (2) The greater the Distance between piles in one row, the greater the wave energy transmitted. (3) The Kt value has an inverse relationship with the wave slope (Hi/L) and wave steepness (Hi/gT^2). (4) The Kr value is directly proportional to the wave slope (Hi/L) and wave steepness (Hi/gT^2). (5) The use of inclined pile breakwaters will be more effective in water locations with greater wave steepness and slope (categorized as short waves) and with the use of denser pile spacing, this can be proven by the Kt value in the model α=45°; D=1.69cm; b= 5 cm is 0.603 compared to the model α=60°; D=1.69 cm; b= 5 cm, Kt value is 0.652. (6) Based on these conditions, only 60.3% of the waves can pass through the structure, 7% are reflected and 32.7% are dissipated. These lost waves can be caused by waves traveling escalate through the inclined pile structure, or due to collisions between waves or other things. This shows that the Inclined Pile Structure of breakwater is more effective with the pile slope of 45° than the pile slope of 60°.

5. Declarations

5.1. Author Contributions

Conceptualization, L.N. and P.T.J.; methodology, L.N.; validation, L.N.; formal analysis, L.N.; investigation, L.N. and P.T.J.; resources, L.N. and V.D.; data curation, L.N. and I.W.; writing—original draft preparation, L.N. and P.T.J.; writing—review and editing, V.D. and I.W.; visualization, V.D. and I.W. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

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