Experimental investigation of wave reflection at a wave energy converter breakwater

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Abstract. The wave energy converter breakwater innovation model with an overtopping mechanism with an impermeable single smooth slope was investigated experimentally in the laboratory. Investigations were carried out to determine how the relative freeboard and slope influence the reflection waves. This research is interesting because the main objective of this model is actually to capture overtopping waves to be collected in the reservoir and used as energy conversion, therefore besides the occurrence of wave overtopping through the model peak, one important parameter which is also interesting to know is how the effect of the relative freeboard and slope of this model to the reflection waves in front of the model. The physical model test research was conducted on a two-dimensional wave flume. The single smooth impermeable slope wave energy converter breakwater model is made of a size that can be mobilized by the flume. Several parameters of the model are varied, such as the slope angle and height of the freeboard model. In hydraulic parameters, variations such as incident wave height and wave period are also carried out. The results showed that the 1: 2 and 1: 2.5 slope models generally produce a greater reflection than the 1: 3 slope model. For the effect of the relative freeboard, it is found that the greater the value of the structure relative freeboard, the greater the wave reflection coefficient, with the range of wave reflection coefficient values obtained in this study are 0.1 - 0.7.

1. Introduction
Shore protection structures are structures built to protect the coast from wave attack. Currently, there are many models of coastal protection structures made in various shapes and materials to protect the coast effectively. The protection performance is to prevent wave transmission, increase wave dissipation, and also minimize wave reflection. Wave transmission, dissipation, and wave reflection that occurs in coastal structures, of course, is highly influenced by the condition of the coastal protection structures. The geometric shape of the coastal structure, materials, slope, porosity, and so on highly influences the performance. Wave transmission, wave dissipation, and reflection of waves that occur in the coastal structure are one of the objects of research that has been widely carried out in the field of coastal engineering. Laboratory investigations related to wave reflection in coastal structures, especially single function breakwaters have been carried out, such as [1,2].

In this study, an innovative breakwater model was created. This breakwater namely waves energy converter breakwater has two functions, first as a wave catcher with an overtopping mechanism to collect water in the reservoir to be used for energy conversion and second as a coastal protection structure. So the breakwater model innovation in this study is also called a dual-function breakwater. Wave reflection research conducted on dual-function breakwaters is still not as much as wave reflection
research on the one-function breakwater or conventional breakwater. Research on wave reflection in dual-function breakwaters was conducted experimentally by [3,4].

The wave reflection on a dual-function breakwater may likely produce slightly different results when compared to the wave reflection that occurs in a conventional breakwater. This is because the dual function breakwater, especially the breakwater which utilizes overtopping to collect water in the reservoir as energy conversion, occurs wave overtopping at the top of the structure. Wave overtopping is possible. The incoming waves hitting the breakwater, some will overflow and some will become other forms. Therefore it is interesting to know how the reflection waves that occur in the dual-function breakwater. This study aims to determine how the effect of the slope model and the relative freeboard of the wave energy converter breakwater on the reflection wave.

2. Wave theory
Several theories describe waveforms with several degrees of complexity and accuracy to describe conditions in nature including the linear wave theory (Airy's theory or small-amplitude wave theory) and non-linear wave theory including Stokes waves, Knoidal waves, Gerstner waves, Mich. and a single wave (solitary wave). Each of these theories has different validity limits the application of wave theory is based on the comparison value of \( \frac{H}{d} \) and \( \frac{d}{L} \) [5].

The simplest and easiest to understand theory is the linear wave theory or small-amplitude wave theory, which was first proposed by Airy in 1845, which became known as Airy's wave theory. In Airy's wave theory, it is assumed that the wave height is very small in terms of its length or depth. Airy Wave Theory (small-amplitude theory) is derived based on the Laplace equation for irrotational flow with boundary conditions on the seabed and the water surface. The water level fluctuation is periodic concerning \( x \) and \( t \), and is a sinusoidal and progressive wave traveling in the \( x \)-axis direction.

3. Wave reflection
In conventional one-function breakwaters, analysis of reflection waves is needed to estimate how they affect the navigation of ships around the breakwater and the possibility of local scouring. In the two-function breakwater wave energy converter innovation, reflection wave analysis is also needed for the same purpose, but more than that, reflection wave analysis may also provide further information on whether the reflected waves that occur in front of or around the breakwater may later provide larger ones wave energy that makes waves more likely to overflow through the model, so that a better discharge for energy conversion is obtained, but this has not been studied further.

Several studies of wave reflection on breakwater wave energy converter innovations have been carried out including innovative rubble mound breakwaters for overtopping wave energy conversion [6], water surface resonance in the L-shape channel of seawater exchange breakwater [7], and other studies.

Waves that propagate through a barrier such as a breakwater structure, some of its energy will be reflected by the barrier, some will be transmitted to the back of the structure and some will be dissipated. Wave reflection is a wave energy reflection event that is usually caused by a breakwater structure. Incoming waves hitting an obstacle will be partially or completely reflected. A review of wave reflection is important in the planning of coastal structures, especially in port buildings. The magnitude of the ability of a building to reflect waves is given by the reflection coefficient, which is the ratio between the reflection wave height \( H_r \) and the incident wave height \( H_i \).

The energy coefficient of the reflected wave can be known if the reflection wave height \( H_r \) and the incident wave height \( H_i \) are known. Incoming wave height and reflection can be calculated by first measuring the water level in front of the building. Based on the maximum wave height \( H_{max} \) and minimum wave height \( H_{min} \) which is measured at some points in front of the model. The \( K_r \) values range from 1.0 for total reflection and 0 for no reflection.

4. Research method
This type of research is experimental physical modeling in the laboratory. The definition of an experiment is observed under conditions artificial (artificial condition). Thus the physical model research is research conducted by making system replicas smaller so that certain simulations/treatments can be controlled with the aim is to investigate the influence of multiple parameters as well as the interrelationships research parameters.

4.1. Equipment calibration
Some equipment calibration was carried out in this study, first: generator calibration wave which aims to determine the correlation between the height of the wave generated by variations in water depth ($d$). Second: routine calibration every time running for a variation of the period ($T$), by resetting the position of the crossbar (scale) the reading on the flume according to the wavelength that occurs.

4.2. Wave flume & wave characteristics
This wave research was conducted on a wave flume with a length of 15 m and a width of 0.3 m. The effective depth is 0.45 m. The wave generator is a flap type. The type of wave that is generated is a regular wave. The wave period is controlled by pulley rotation. The wave height is controlled by a controlling stroke position flap movement. While the water depth in the flume in this study was divided into three types of depth, namely depth of 27.5 cm, 25 cm, and 22.5 cm. Characteristic data obtained before the breakwater model is placed. The data measured during the simulation are wave height data, which is automatically recorded by the recording device wave. Laboratory facilities used in this research consists of two main components, namely the wave flume which is equipped with a wave generator and wave recorder automatically. While the model used is an innovative breakwater wave energy converter model. Two-dimensional wave flume is used in the study shown in figure 1.

![Figure 1](image1.png)

Figure 1. A two-dimensional wave flume was used in the study.

4.3. Breakwater wave energy converter
In this research, an innovative breakwater model is made that allows waves to overflow at the top of the structure towards the reservoir to be used for energy conversion. This breakwater is made smooth and impermeable with a single slope and is equipped with a reservoir pool at the back to accommodate wave overtopping. This wave energy converter model innovation is made in 3 variations of the slope, namely the slope 1: 2, 1: 2.5, 1: 3, and 3 variations of the height of the freeboard ($R_c$), namely 12.5 cm, 10 cm, and 7.5 cm. Model testing is done by varying the wave height of 3 variations, and the wave period of 7 variations. A sketch and photo of a breakwater wave energy converter model are shown in figure 2.
5. Result and discussion

By varying the wave height ($H$), wave period ($T$), at a certain water depth ($d$), and varying the slope of the structure, then measuring the wave height in front of the innovative breakwater wave energy converter model, the incoming wave height $H_i$ and the wave reflection $H_r$ can be calculated. By knowing $H_i$ and $H_r$, Wave reflection coefficient $K_r$ can also be calculated. Because in the $K_r$ presentation, it is a wavelength function, then the wavelength is calculated using equation 1.

$$L = \frac{gT^2}{2\pi} \tanh \left(\frac{2\pi d}{L} \right)$$

(1)

By knowing the value of $K_r$, then a curve of the relationship between relative freeboard ($\frac{R_c}{H_i}$) to $K_r$ is made as shown in figure 3, figure 4, and figure 5.

![Figure 2. Sketches and photos of the breakwater wave energy converter innovation model in this study.](image)

![Figure 3. The effect of the relative freeboard parameter $\frac{R_c}{H_i}$ on the reflection wave coefficient on the 12.5 cm freeboard in three slope variations.](image)
0.1 to 0.6 on three variations of the slope model. The $\frac{Rc}{Hi}$ values for each model, namely: Slope 1: 2 ranges (1,4-2,5); on slope 1: 2,5 ranges (1,3-2,5); and the slope 1: 3 ranges from (1,3-2,7).

Analysis The graph in figure 4 shows that the value of $Kr$ is getting bigger along with the greater the value of $\frac{Rc}{Hi}$ meaning that the greater the relative freeboard value, the greater the reflection coefficient. For the effect of the slope of the model, the value of the reflection coefficient ($Kr$) on the freeboard ($Rc$) 10 cm shows that the model with a slope of 1: 2.5 and a slope of 1: 2 produces the greatest reflection coefficient with a value that is almost coincided, compared to 1 other slope, which is slope 1: 3. At the height of the freeboard ($Rc$) 10 cm, the reflection coefficient value ranges from 0.1 to 0.7 on three variations of the slope model. The $\frac{Rc}{Hi}$ values for each model are: Slope 1: 2 ranges (1-2,4); on slope 1: 2,5 ranges (1,2-1.9); and the slope 1: 3 ranges from (1-2,4).

Figure 4. The effect of the relative freeboard parameter $\frac{Rc}{Hi}$ on the reflection wave coefficient on the 10 cm freeboard in three slope variations.

Figure 5. The effect of the relative freeboard parameter $\frac{Rc}{Hi}$ on the reflection wave coefficient on the 7.5 cm freeboard in three slope variations.
The graph in figure 5 shows that the value of $K_r$ is getting bigger as the value of $\frac{R_c}{H_i}$ increases, meaning that the greater the relative freeboard value, the greater the reflection coefficient. For the effect of the slope of the model, the reflection coefficient ($K_r$) on the freeboard ($R_c$) 7.5 cm shows that a model with a 1:2.5 slope produces the greatest reflection coefficient, compared to the other 2 slopes, namely 1:2 and 1:3 slopes. At the height of the freeboard ($R_c$) 7.5 cm, the reflection coefficient value ranges from 0.1 to 0.5 in three variations of the slope model. The $\frac{R_c}{H_i}$ values for each model are: Slope 1: 2 ranges (0.75-1.5); on slope 1: 2.5 ranges (0.75-1.7); and the slope 1: 3 ranges from (0.75-1.5).

6. Conclusions
Based on the results of this study it can be concluded that the parameters that affect the amount of wave reflection in the breakwater wave energy converter innovation are the wave period ($T$), the incident wave height ($H_i$), the freeboard height ($R_c$), and the slope of the model.

The effect of the relative freeboard ($\frac{R_c}{H_i}$) on the reflection coefficient ($K_r$) is described in the $K_r$ and $\frac{R_c}{H_i}$ relationship curve, that is, the reflection coefficient value increases with the greater the relative freeboard value ($\frac{R_c}{H_i}$). For the effect of the slope of the model itself, a large reflection coefficient ($K_r$) values are obtained for the 1:2 and 1:2.5 slope models and small reflection coefficient ($K_r$) values are obtained at 1:3 slopes.

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