International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V70I10P218

Volume 70 Issue 10, 188-194, October 2022

Original Article

Wave Deformation on Sloping Hollow Breakwater

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Received: 29 July 2022 Revised: 28 September 2022 Accepted: 06 October 2022 Published: 20 October 2022

Abstract *- Hollow breakwaters have varied models as wave absorbers. The ability of hollow breakwaters to absorb a wave of energy becomes beneficial of hollow breakwaters in reducing incoming wave energy. Experiments were performed on a hollow-sloping breakwater model using the model parameters of the cavity shape. The cavity parameters are made in 3 variations, the ratio between the volume of the cavity and the volume of the hole (Vr/Vl) of 2.0; 2.5, and 3.1, and the ratio of cavity volume and volume of the breakwater body (Vr/Vs) is 0.11; 0.14 and 0.17. The wave parameters are wave height (H), wave period (T) 1.1, 1.3, and 1.5 seconds, and water depth (d) 30, 35, and 40 cm. The reflection coefficient (Cr) of the sloping hollow breakwater increases if the values of the wave steepness parameter (H/L), relative depth (d/L), cavity volume parameter (Vr/Vl) as well as the structure volume parameter (Vr/Vs) increase. The transmission coefficient (Ct) decreases if the values of the wave steepness parameter (H/L), relative depth (d/L), and cavity volume parameter (Vr/Vl), as well as the structure volume parameter (Vr/Vs) increase. Larger cavity volumes (Vr/Vl =3.1) dampen wave energy better than smaller ones (Vr/Vl= 2.0 – 2.5)*

Keywords *- Submerged breakwater, Wave reflection, Wave transmission.*

1. Introduction

Breakwaters are coastal structures used to anticipate and control abrasion. This building has functioned as an alternative to protect the shoreline from the onslaught of waves or by reducing wave energy. Several studies have been carried out to develop the structure of the wave absorber. Therefore, the advancement of wave absorbers in structure construction has developed significantly. One of the breakwater structures is a porous or hollow breakwater. Hollow breakwaters have different models that minimize wave reflections due to their ability to absorb wave energy and reduce incoming wave energy. Studies on aerated concrete blocks have shown that the holes, slit length, surface porosity of the concrete block, and the number of block rows strongly affect the transmission and reflection coefficients [1-4].

The transmission coefficient (Ct) decreases with increasing wavelength and wave height. The reflection coefficient (Cr) increases with increasing wavelength and incident wave height. When submerged, a certain wavelength decreases due to the increase in transmission coefficient [5-8]. Extensive research has been conducted on porous breakwaters, which results in an increase in the reflection coefficient and a more efficient reduction in the reflection coefficient with longer pipes [9]. The roughness of the pipe wall reflects waves and transmits them. When the pipe wall's roughness coefficient increases, the wave height becomes higher [10]. A breakwater submerged from a perforated shore reduces wave velocity and wave reflection on the seawalls due to changes in seawalls' width, porosity, relative water depth, and wave steepness [21]. The breakwater function is better when the porous slot diameter is wider, the concrete jet dissipation ability is reduced, and the reflection in front of the breakwater is smaller. Still, the larger transmitted wave increases for the concrete block slot diameter [12]. Holes, slot lengths, surface porosity of concrete blocks, and the number of column blocks greatly affect the values of transmission and reflection coefficients [13]. The outer permeable layer's porosity helps dissipate most of the wave energy, reducing the impact of wave forces on the interior of the submerged structure. An increase in the friction coefficient of a perforated material is more effective at dissipating wave energy in a submerged structure than increasing the thickness of the outer permeable layer [14]. This study considers how wave parameters affect waves transmitted from a submerged hollow breakwater. This study aims to obtain the relationship between the wave parameters and structural parameters of sloping hollow breakwaters and the magnitude of the reflected and transmitted waves and to obtain an equation of the relationship of the parameters.

2. Waves Reflection and Transmission

A reflected wave is a reflection of a wave that occurs when the incident wave hits a wall or barrier, such as a breakwater. The port pool is one example of the phenomenon of reflection. Different kinds and types of buildings determine the coefficients of reflection of waves. When a wave hits an obstacle, some of its energy is destroyed (absorbed/dissipated) by friction, turbulence, and breaking wave; the rest is reflected and transmitted. The magnitude of the reflection, dissipation, and transmission wave energy can be determined by the characteristics of the coming wave, the type of coastal protection (flat or rough surface, permeable or not) and the dimensions and geometry of the protection (slope, elevation and width of the barrier) and local environmental conditions (water depth and contours of the coastal bottom). Waves passed on or transmitted through a permeable structure are influenced by parameters such as wave conditions, structure width, structure size, porosity and differences in vertical porosity of the material, structure height, and water depth. Waves with a small steepness, such as tidal waves, are likely to be transmitted as a whole through a structure or transmission coefficient close to 1, while wind waves will be effectively suppressed [20]. Research on wave transmission under friction conditions has been carried out a lot. It was reported that wave transmission through the top of the submerged breakwater building was affected by the width of the building peak, the depth of the water above the peak, and the friction coefficient of the peak material [16]. Wave transmission through breakwaters in horizontal pipe installations shows that the longer and smaller the pipe diameter, the less the wave transmission will be [17]. Waves passed on due to obstacles, such as waves passing through the breakwater construction, are called transmission waves. According to the theory of small amplitude waves, the fluctuations in the water level of the coming waves are:

$$\eta_i = \frac{Hi}{2}\cos\,(kx - \sigma t) \tag{1}$$

The water level in front of the water structure is the sum of η_i and η_r :

$$\eta = \eta_i + \eta_r = \frac{Hi}{2}\cos(kx - \sigma t) + x\frac{Hr}{2}\cos\,(kx - \sigma t);$$

can be written:

$$\eta = \frac{Hi}{2}(coskx\ cos\sigma t + sinkx\ sin\sigma t) + \frac{Hr}{2}(coskx\ cos\sigma t + sinkx\ sin\sigma t)$$

$$\eta = (\frac{Hi+Hr}{2})coskx\ cos\sigma t + \frac{Hi-Hr}{2}sinkx\ sin\sigma t \tag{2}$$

Thus (Hi+Hr)/2 is greater than (Hi-Hr)/2, then the peaks and valleys found in π/2, 3π/2 are smaller than the peaks and valleys found in 0, π, 2 π. In regular wave simulations in the channel, the transmitted wave height (Ht) is obtained by summing the maximum wave height (Hmax) and minimum wave height (Hmin) to obtain the incident wave height (Hi). Reflected wave height (Hr) and transmitted wave height (Ht) are as follows.

$$H_i = \frac{H_{max} + H_{min}}{2} \tag{3}$$

$$H_r = \frac{H_{max} - H_{min}}{2} \tag{4}$$

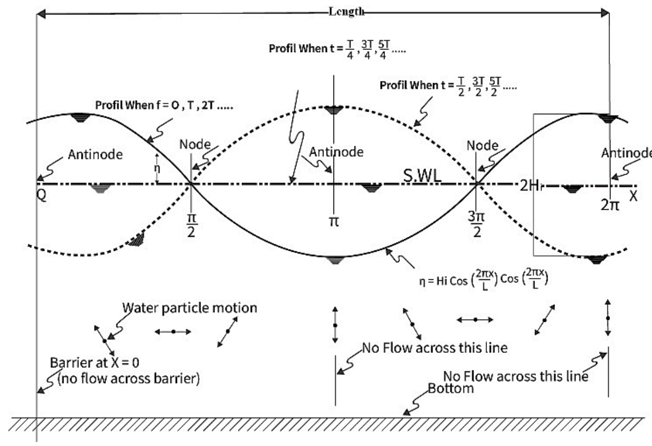

Fig. 1 Standing wave (clapotis) system (SPM, 1984)

$$H_t = \frac{H_{max} - H_{min}}{2} \tag{5}$$

The incident wave height (Hi) is used to obtain the reflection coefficient (Cr) and transmission coefficient (Ct) expressed as a comparison of the height of the reflection wave (Hr) and the transmission wave (Ht) with the incident wave height (Hi).

$$C_r = \frac{H_r}{H_i} \tag{6}$$

$$C_t = \frac{H_t}{H_i} \tag{7}$$

3. Sloping Hollow Breakwater

Previously conducted studies mainly used relatively long tubes, many holes, and large holes to influence the decrease in values of reflection coefficient, transmission coefficient, and wave energy reduction. The number, length and diameter of holes in breakwaters are related to the extent of the holes themselves. For this reason, breakwaters with sloping hollows have been proposed. This model solves the problem of pebble accumulation. The breakwater is designed, so the front hole model is relatively high against the incoming waves, and the exit hole is buried in the ground or covered with sediment.

By several specifications, the sloping hollow breakwater is designed with a model scale of 1:30. Scale the width of the model is 30cm, the length of the upper part is 30cm, the length of the lower part is 90cm, and the length of the model is 30cm. It comes in four height variants: height (h) 30 cm and depth (d) 30, 35 and 40cm. Wave periods of 1.1, 1.3, and 1.5 seconds are used.

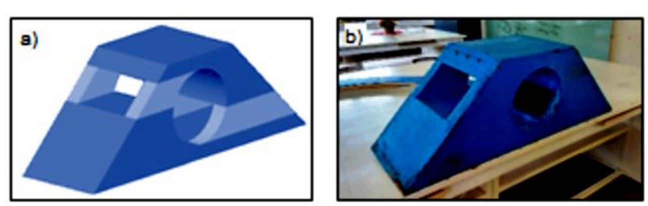

Fig. 2 Sketch (a) and (b) models of sloping hollow breakwaters

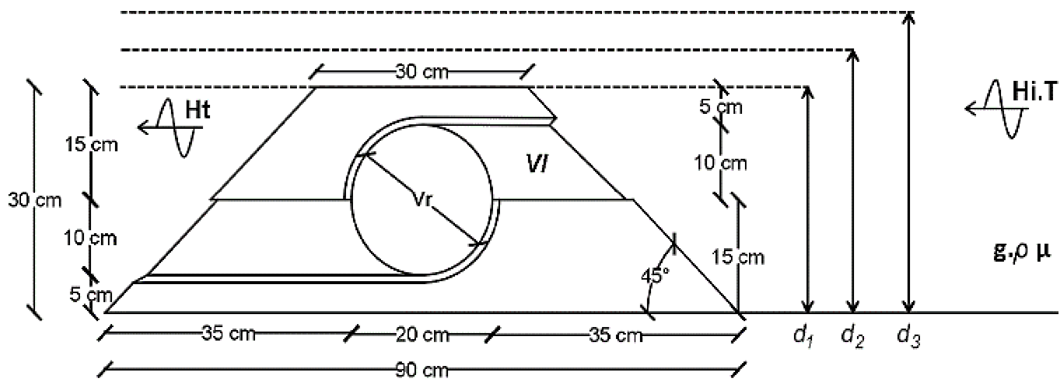

Fig. 3 The model with three variations of a cavity

The bound variables studied were transmission wave height (Ht). In contrast, the free variables in this study were wave period (T), incident wave height (Hi), water depth (d), model height (h), hole volume (Vl) where the wave entered the hollow breakwater, cavity volume (Vr) that was inside the breakwater and breakwater structure/body volume (Vs). The variations of the breakwater parameters are given in Table 1.

Table 1. Variations in research parameters

Types of variations	Value of variations
Wave period (T, sec.)	3 (1.1; 1.3; 1.5)
Water depth (d,m)	3 (0.30; 0.35; 0.40)
Structure height (h, m)	1 (0.30)
Hole volume (Vl, m^3)	1 (0.003)
Cavity volume (Vr, m^3)	3 (0.006; 0.008; 0.009)
Structure volume (Vs, m^3)	1 (0.054)

4. Results and Discussion

4.1. Wave Height Data Validation

Validation is conducted on wave height data in wave tests without breakwater to show that the data obtained is valid. Validation is also carried out to show the accuracy of the measuring instrument in obtaining wave height data so that further testing can be carried out. In addition, wave height data validation is carried out by comparing the data obtained with the results of previous studies. In addition, validation of wave height data is carried out by comparing the data obtained with the results of previous research. A comparison was made with the study of Koraim et al. (2014), a comparison of wave period (T) and wave height (H) variables with Dean and Dalrymple's calculations on the hydrodynamic properties of porous seawalls protected by submerged breakwaters. Fig. 4 shows that the wave height data in this study have the same trend and are close to the results of Koraim's research and calculations from Dean and Dalrymple.

4.2. Water level fluctuations

Water level fluctuation data is obtained by converting time series data recorded by wave probes with the results of wave probe calibration according to water depth variations for each wave probe. For example, with a record duration of 60 seconds, the fluctuations in the water level on probe waves 1, 2, and 3 can be depicted in Fig. 5. The experiment is recorded using water depth variations (d) such as 30, 35, and 40 cm and a wave period (T) of 1.1, 1.3, and 1.5 seconds as designed variations for each model.

4.3. Wave height

Wave height data is obtained from the processing of advanced fluctuation data. By calculating the maximum wave height (Hmax) and the minimum wave height (Hmin), the wave height data can be known based on the number of samples per period.

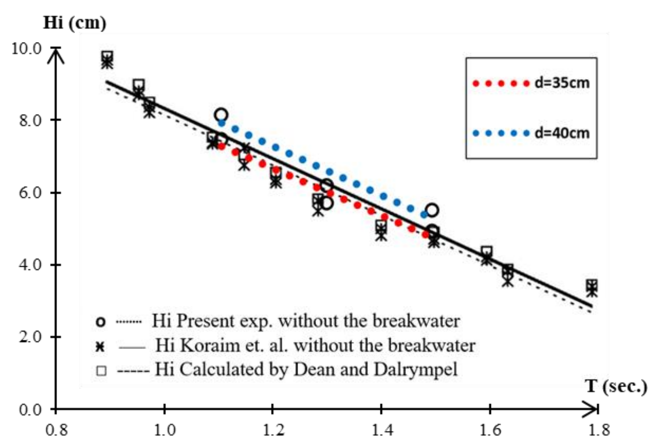

Fig. 4 Wave height data validation

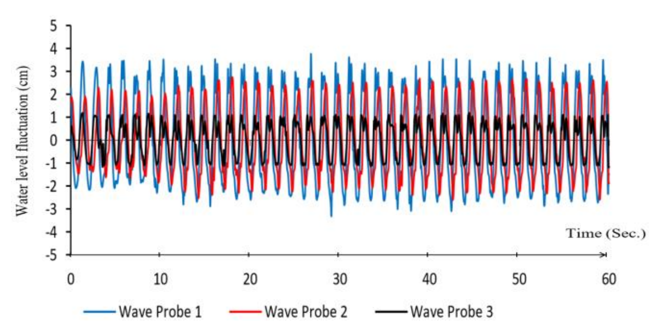

Fig. 5 Water level fluctuations with a duration of 60 seconds

Table 2. Results of maximum and minimum wave height analysis

Model	Water depth (d,m)	Wave period (T, Sec.)	Hmax (m)	Hmin (m)
R1	0.30	1.1	0.079	0.046
R2	0.30	1.3	0.062	0.039
R3	0.30	1.5	0.060	0.041
R1	0.35	1.1	0.073	0.050
R2	0.35	1.3	0.073	0.051
R3	0.35	1.5	0.064	0.047
R1	0.40	1.1	0.090	0.058
R2	0.40	1.3	0.077	0.055
R3	0.40	1.5	0.068	0.052

When it changes the wavelength, the calculation of wave height is carried out using equations (3) to (5). Wave height data with variations in water depth (d) 30, 35, and 40 cm and wave period (T) 1.1, 1.3, and 1.5 seconds for each model are processed and arranged in table 2. The maximum wave height (Hmax) and minimum wave height (Hmin) data are used to obtain the data wave height (Hi) and the reflection wave height (Hr). Furthermore, equations (6) and (7) obtained the value of the coefficient of reflection (Cr) and the coefficient of transmission (Ct).

4.4. *Dimensional analysis*

Dimensional analysis performed by the Langhaar Method obtained dimensionless parameters as follows.

$$\pi_1 = \frac{Hi}{d};\ \pi_2 = \frac{h}{d};\ \pi_3 = \frac{Tg^{0.5}}{d^{0.5}};\ \pi_4 = \frac{Vr}{d^3};\ \pi_5 = \frac{Vl}{d^3};\ \pi_6 = \frac{Vs}{d^3}$$

The coefficient reflection and the coefficient transmission in this study are functions of the following parameters.

$$Cr = \frac{Hr}{Hi} = f\left[\frac{H_i}{L};\ \frac{d}{L};\ \frac{d}{h};\ \frac{V_r}{V_l};\ \frac{V_r}{V_s}\right];\text{ and}$$

$$Ct = \frac{Ht}{Hi} = f\left[\frac{H_i}{L};\ \frac{d}{L};\ \frac{d}{h};\ \frac{V_r}{V_l};\ \frac{V_r}{V_s}\right]$$

with $\frac{Hi}{L}$ is the wave steepness, $\frac{d}{L}$ is the relative depth. $\frac{d}{h}$ is the ratio of water depth and structure height (*relative submergence*); $\frac{Vr}{Vl}$ is the ratio of the volume of the cavity and the volume of the hole and $\frac{V_r}{V_s}$ is the ratio of the volume of the cavity and the volume of the structure/body of the breakwater [18].

4.5. *Influence of Wave Steepness (Hi/L)*

The relationship between wave height (Hi/L) and reflection coefficient (Cr) can be seen in Fig. 6, where the value of reflection coefficient (Cr) is higher than the value of wave steepness (Hi/L)and will fall with an increase in the relative value of submergence (d/h). Tests at relatively low structure heights (d/h=1.0) have the highest Cr values, while those at relatively higher structure heights (d/h=1.3) have the lowest average Cr values. The rise into the water will be the longer the wavelength; not all the wave energy hits the breakwater, so the smaller the wave reflected on the relatively high height of the structure (d/h=1.3). Fig. 7 shows the transmission waves that have the effect of wave steepness. The figures in Fig. 7 indicate a clear trend of wave steepness towards an increase in transmission waves with an increased relative structure height. It is possible because higher relative structure heights have a higher water depth, so the waves mostly escape and do not hit the breakwater. As a result, the cavity is ineffective in reducing the waves. Tests at relatively low structure heights (d/h = 1.0) have the lowest Ct values, while those at relatively higher structure heights (d/h = 1.3) have the highest average Ct values.

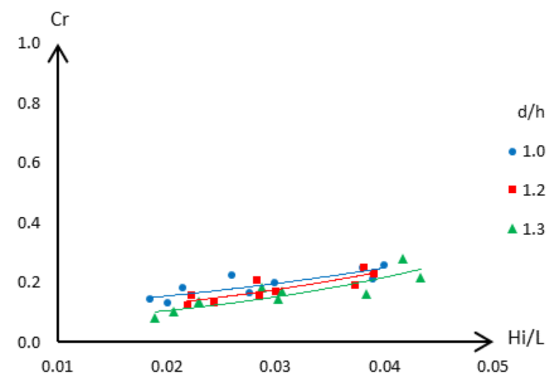

Fig. 6 The influence t of wave steepness on transmission coefficient

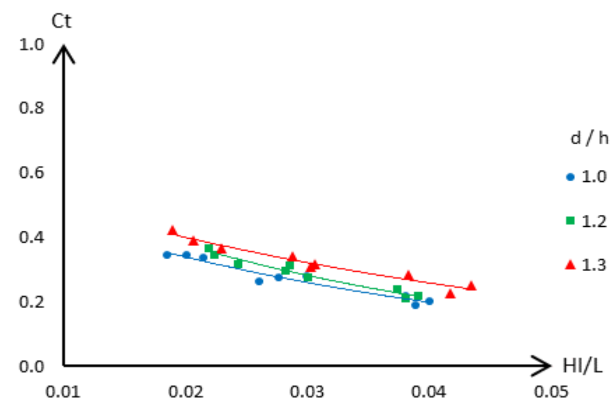

Fig. 7 The influence of wave steepness on transmission coefficient

4.6. *Influence of relative depth* (d/L)

Fig. 8 shows that the reflection coefficient (Cr) value will increase with the relative depth (d/L) value. With the rising depth of the water, not all wave energy hits the breakwater, so the smaller the reflected wave. The reflection coefficient (Cr) will decrease with an increase in the relative cavity volume value (Vr/Vl). The factor that plays a role in wave reflection is the breakwater field against the coming wave in terms of the cavity volume parameter (Vr/Vl), which plays a role in the volume of the hole; the smaller the volume of the hole, the value of the Vr/Vl parameter increases, the reflection coefficient (Cr) also increases.

Testing at relatively high cavity volume (d/h=3.1) has the highest Cr value, while at lower relative cavity volume (d/h=2.0) has the lowest average Cr value. Relatively larger cavities have a wider friction field; thus, the captured waves experience better attenuation; this is evidenced by the smaller value of the transmission coefficient (Ct) with the increase in the relative depth (d/L) value.

The influence of relative depth on the transmission wave for the hollow breakwater is presented in Fig. 9, with three different relative cavity volumes. Fig. 9 shows that the transmission wave decreases with increasing relative depth because of the wavelength, which affects the transmission coefficient (Ct) value.

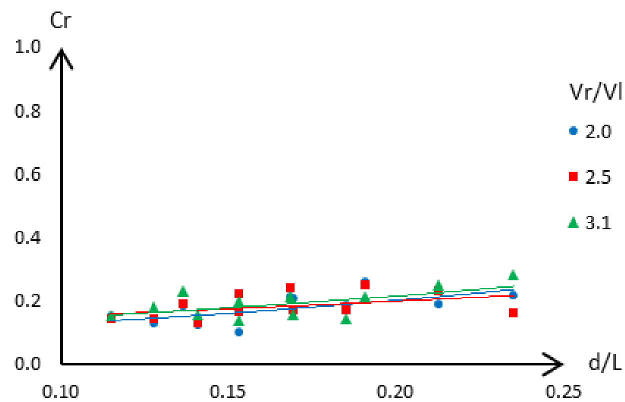

Fig. 8 The influence of depth relative to the reflection coefficient

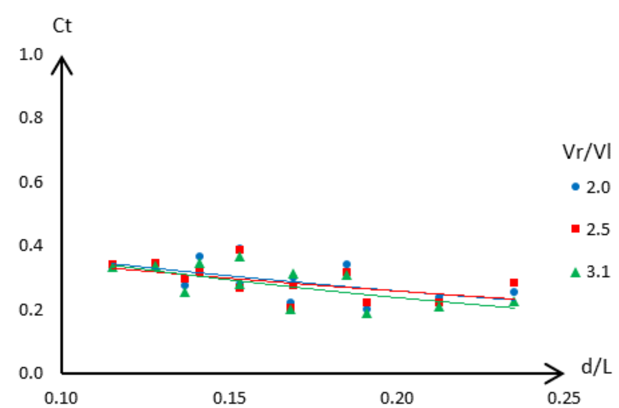

Fig. 9 The influence of depth relative to the transmission coefficient

The shorter the wave, the greater the relative depth (d / L) value so that the value of the transmission coefficient will be smaller. The transmission coefficient will also get smaller with the larger the relative cavity volume (Vr/Vl). Testing at a relatively high cavity volume (d/h=3.1) has the lowest Ct value, while at a lower relative cavity volume (d/h=2.0) has the highest average Ct value.

4.7. Influence of cavity and hole volume (Vr/Vl)

The volume function of the cavity and hole (Vr/Vl) connected to the reflection coefficient (Cr) obtained the relationship that the greater the value of the cavity volume parameter (Vr/Vl), the more the value of the reflection coefficient (Cr) will increase, as shown in Fig. 10. Related to the reflection wave, the factor that plays a role is the breakwater field against the coming wave; in terms of the cavity volume parameter (Vr/Vl), which plays a role in the volume of the hole, the smaller the volume of the hole, the value of the Vr / Vl parameter increases, the reflection coefficient (Cr) also increases.

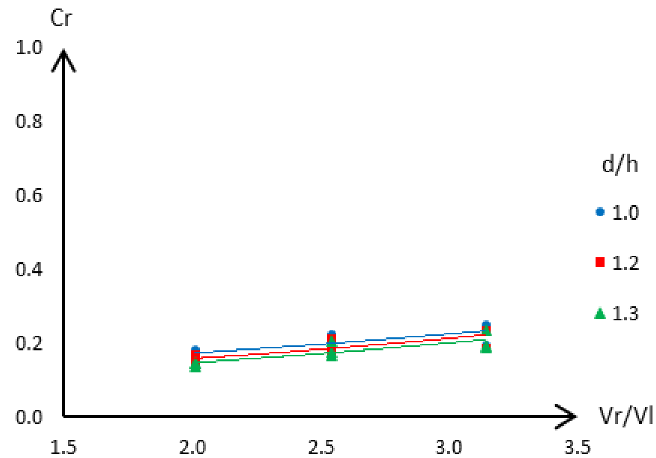

Fig. 10 The influence of the volume of the hole cavity relative to the reflection coefficient

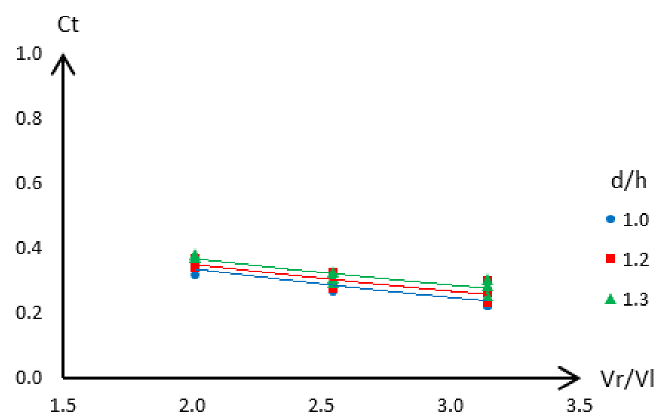

Fig. 11 The influence of the volume of the hole cavity relative to the transmission coefficient

Fig. 11 shows the relationship between the volume parameters of the cavity and the hole (Vr / Vl) connected to the transmission coefficient (Ct) found relationship that the greater the value of the cavity volume parameter (Vr/Vl), the smaller the value of the transmission coefficient will be at the height of the smaller relative structure. This is because cavities with a larger cavity volume also have a larger cavity area, so it is better at capturing and dampening waves with a wider friction field; thus, the transmitted waves become smaller. Therefore, variation is performed against the volume of the cavity (Vr) while the volume of the hole (Vl) is fixed or constant. Tests at relatively low structure heights (d/h=1.0) have the lowest Ct values, while higher relative structure heights (d/h=1.3) have the highest average Ct values.

4.8. Influence of cavity volume and structure (Vr/Vs)

Fig. 12 shows the relationship of the volume parameter of the structure cavity (Vr/Vs) to the coefficient of reflection (Cr), where the relationship is obtained that the greater the value of the structural volume parameter (Vr/Vs), the more the value of the reflection coefficient (Cr) will increase. Variation is performed against the volume of the cavity (Vr) while the volume of the structure or body of the breakwater (Vs) is fixed or constant. Tests at relatively low structure heights (d/h=1.0) have the highest Cr values, while higher relative structure heights (d/h=1.3) have the lowest average Cr values. It means that the larger the volume of the cavity, the more the relative wave energy is muffled; this is evidenced by the value of the transmission coefficient (Ct), which gets smaller with the increase in the value of the structural volume ratio (Vr/Vs), but the energy reflected is also greater, increasing the value of the reflection coefficient (Cr).

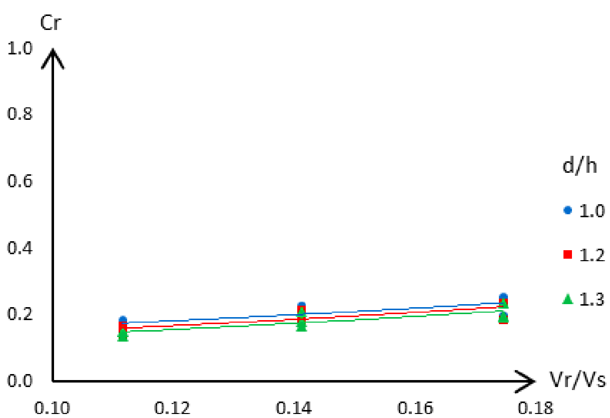

Fig. 12 The influence of the volume cavity and structure on the reflection coefficient

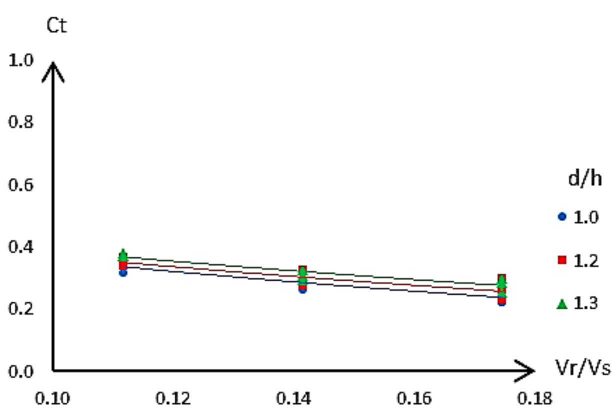

Fig. 13 The influence of the volume cavity and structure on the transmission coefficient

Fig. 13 shows the relationship of the relative structure cavity volume parameter (Vr/Vs) connected to the transmission coefficient (Ct), and the relationship is that the larger the value of the structural volume parameter (Vr/Vs), the smaller the transmission coefficient value will be at the smaller relative structure height.

Cavities with a larger volume have a larger cavity area, so they are better at capturing and dampening waves with a wider friction field. Variation is performed against the volume of the cavity (Vr) while the volume of the structure or body breakwater (Vs) is fixed or constant. Tests at relatively low structure heights (d/h = 1.0) have the lowest Ct values, while higher relative structure heights (d/h = 1.3 m) have the highest average Ct values.

4.9. Comparison with other studies

The results of this study compared to other studies' results were conducted using the same parameters. The comparison was made to previous research conducted by Armono and Hall (2014) using the water depth variable (d) against the transmission coefficient (Ct) [19]. The result of the comparison in the form of a graph is presented in Fig. 14.

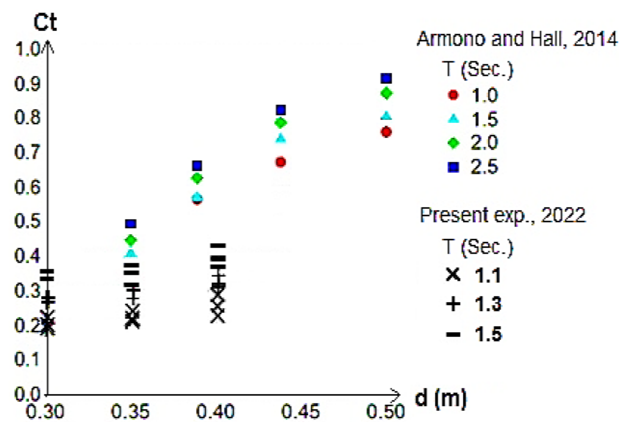

Fig. 14 Comparison of research results of Ct value as a function of depth based on wave period

Fig. 14 shows that Armono and Hall's research uses water depth (d) with a range of 0.3 – 0.5 meters and a wave period (T) of 1.0; 1.5; 2.0, and 2.5, while this study used water depth (d) with a range of 0.3 – 0.4 meters and a wave period (T) of 1.1; 1.3 and 1.5. It is shown that the transmission coefficient (Ct) value for the water depth variable (d) has the same trend, but with the Ct value in this study being smaller or the waves transmitted are relatively more minor, which means that the hollow breakwater model in this study with water depth conditions and a certain wave period is relatively better than the coral reef model (Hemispherical Shaped Artificial Reefs, HSAR) from Armono and Hall.

5. Conclusion

The reflection coefficient (Cr) on the sloping hollow breakwater increases if the parameter values of Hi/L, d/L, Vr/Vl, Vr/Vs increase, with the conditions of use of the value Hi/L = 0.018 – 0.043, d/L = 0.128 – 0.235, Vr/Vl = 2.0 – 3.1 and Vr/Vs = 0.11 – 0.17 will give the value Cr = 0.101 – 0.280 or an increase of 0.179.

The transmission coefficient (Ct) on the sloping hollow breakwater decreases if the parameter values of Hi/L, d/L, Vr/Vl, Vr/Vs increase, with the conditions of use of hi/L values = 0.018 – 0.043, d/L = 0.128 – 0.235, Vr/Vl = 2.0 – 3.1 and Vr/Vs = 0.11 – 0.17 will give a value of Ct = 0.389 – 0.191 or decrease by 0.199.

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