A laboratory study on wave transmission over hexagonal artificial reef

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Abstract. Artificial reefs are commonly used to rehabilitate natural coral reef damage. Artificial reef serves as a new habitat for marine life and simultaneously protect the shoreline by reducing wave energy without reducing the aesthetics of the protected beach. As an artificial reef can serve as submerged breakwaters, the level of their effectiveness in reducing incoming wave need to be investigated. The new form hexagonal shape artificial reef is proposed then evaluated based on the transmission coefficient. The tests for various configurations of a hexagonal reef in a 1:10 scale were conducted in the wave flume of Department Ocean Engineering, Institut Teknologi Sepuluh Nopember, Surabaya. The result of tests was presented and showed that the new proposed hexagonal shape artificial reefs have better performance compared to cylindrical and cubical shape artificial reefs.

1. Introduction
Artificial reefs have been widely and traditionally used for years to attract fish and increase their productivity besides Fish Aggregating Devices [1]–[4]. The engineering properties of artificial reefs are like the submerged breakwaters. Concrete breakwater blocks such as tetrapod, tetrahedron, or tri-leg are commonly used as artificial reefs because they have large surface areas. Some breakwater blocks such as tetrapods may be more effective in growing seaweed than many substrate blocks [5]. Various shapes of artificial reefs have also been used to attract fish by producing coherent eddies with the upward flow as well as by providing hiding places for fish such as the “SAB Chamber Structure” model [5].

Studies on submerged breakwaters and their performance have been widely conducted in the past [6]–[9]. Most of the breakwaters evaluated in the previous studies were constructed using rocks or prefabricated concrete blocks specially design to dissipate wave energy. The use of hemispherical shape artificial reef as submerged breakwater was introduced in the Dominican Republic for habitat enhancement and shoreline erosion abatement [10]. The performance of hemispherical artificial reef has also been investigated numerically [11], [12], and physically [13]–[15]. The wave transmission on cylindrical and rectangular cube artificial reefs was also investigated physically in the wave flume of Department Ocean Engineering, Institut Teknologi Sepuluh Nopember, Surabaya [16]–[19]. Moreover, the performance of various shapes of the artificial reef has been evaluated numerically using finite volume methods [12]. The effect of porosity of rectangular hollow artificial reefs on wave attenuation has also...
been examined [20]. The porous test models were relatively less effective in dissipating wave energy against longer waves (lower kd values) compared to shorter waves (high kd values).

Figure 1. Typical Artificial Reef Breakwater.

In this paper, an array of hexagonal shape artificial reefs as typically shown in Figure 1 is proposed as coastal protection structures or submerged breakwater. The performance of the submerged structure was evaluated based on a non-dimensional parameter defined as wave transmission coefficient: a ratio between the transmitted wave (Ht) over the structures to the incoming waves (Hi). As the wave height is proportional to the square root of wave energy, the wave transmission is symbolized by KT and expressed as follows:

\[ KT = \frac{H_t}{H_i} = \left( \frac{E_t}{E_i} \right)^{1/2} \]  

Therefore, according to the equation above, the smaller the KT the better the structure in reducing wave energy. Various variables affecting the transmission coefficient. The investigation on the effect of freeboard on hollow cylinders artificial reefs revealed that the transmission coefficient was smaller with an increase in the relative depth (h/d) [18]. The investigation of porous concrete block submerged breakwater has found that parameters that affect reflection, transmission, and wave dissipation of the breakwater were the incoming wave height (Hi), wave period (Tp), relative width (B/L), and water depth (d) [21]. A series of experiments on hemispherical shape artificial reef, also found that KT is most influenced by relative depth (h/d), reef proportion (h/B), and incoming wave steepness (H/gT^2) [22].

2. Materials and methods

2.1. Experimental Set-Up

The hexagonal artificial reefs were physically tested in a 2 m wide, 2 m deep, and 25 m long wave flume equipped with a computer-controlled plunging wedge wave generator. The generator is capable to generate regular and irregular waves. A passive wave absorber is located at the end of the flume to minimized reflected wave energy. One side of the flume was made of glass where visual observations can be made. A passive wave absorber is located at the end of the flume to minimized reflected wave energy.

Two wave probes were installed in the front and behind the structures, to measure incoming and transmitted waves. Due to the limited number of hexagonal reef models, a divider wall was built to reduce the width of the testing area. A sloped platform was built to increase the level of the reef placement. Figure 2 gives the details of the wave probe placement and hexagonal artificial reef placement in the wave flume.
2.2. Model configuration and construction

The hexagonal reef models as shown were placed in the provided platform, and a series of wave height and wave period were introduced by the wave generator. The models were tested using irregular dan regular waves. However, due to the limited space, only irregular wave tests were presented in this paper. The arrangement was made to distinguish the effect of relative depth and the relative width of the structures on the transmission coefficient. Basically, there are two arrangements of the models in the physical model: A. one layer placement and B. two layers placement as seen in Figure 2. Index 1 and 2 represent the width of the first layer. A₁ and B₁ consist of four unit hexagonal artificial reefs for the first layer, while A₂ and B₂ consist of five unit hexagonal artificial reefs for the first layer. The A₁ and A₂ configurations have a freeboard of 0.23 m with a crest width of 1m and 1.25m respectively, while the B₁ and B₂ configurations have a freeboard of 0.13 m with a crest width of 0.75m and 1m, respectively.

Table 1 summarizes the reef placement and the wave conditions for the test groups and configurations indicated above. The wave heights were 0.04 m, 0.05 m, and 0.06 m with a period of 1.1, 1.3, and 1.5 seconds.

| Test No | Configuration | Wave Height [m] | Wave Period [second] |
|---------|----------------|-----------------|----------------------|
| 1       | A₁             | 0.04; 0.05; 0.06| 1.1; 1.3; 1.5        |
| 2       | A₂             | 0.04; 0.05; 0.06| 1.1; 1.3; 1.5        |
| 3       | B₁             | 0.04; 0.05; 0.06| 1.1; 1.3; 1.5        |
| 4       | B₂             | 0.04; 0.05; 0.06| 1.1; 1.3; 1.5        |
Figure 3 shows the size of hexagonal artificial reef models. The width of the model was 250 mm with a height of 100 mm. There are three holes on each side of the hexagon, providing water circulation inside of the reef, providing hiding places for fish, and facilitating vortices and turbulence in the vicinity of the reef.

The model was made of concrete, with the ratio of sand and cement composition were 2.5:1. A 3 mm plastic cardboard and PVC with a diameter of 2.2 cm pipe were used as the molding as seen in Figure 4. The average weight of the models was about 4.6 kg with a volume of 2,782 cm³.

3. Results and discussion

3.1. Dimensional Analysis

Dimensional analysis can guide how an experimental study should be conducted and how the results should be plotted. The analysis also provides the laws necessary to successfully model the system that has been analyzed [23]. Referring to Figure 1, the dimensional variables that influence the wave transmission KT can be expressed as follow:

$$H_t = f(h, T_p, H_i, g, d, B, \rho)$$

(2)

$\rho$, $\mu$, is the mass density and dynamic viscosity of water in the vicinity of reefs, while $g$ is the gravitational acceleration. Solving equation (1) by the matrix method [23] produces the following $\pi$ terms:

$$d \frac{B}{h^3} \frac{H_i}{h^3} \frac{H_t}{h} \frac{gT^2}{h} = \pi_1, \pi_2, \pi_3, \pi_4, \pi_5$$

(3)

After compounding $\pi$ terms, equation (3) becomes:

$$\left( \frac{h}{B} \right)^2 \frac{H_i}{H_t} \frac{H_t}{gT^2} \frac{B}{gT^2}$$

(4)

The first term is the depth submergence, the second is reef proportion, while the third and fourth terms explain the properties of the incoming and transmitted waves, namely wave steepness and wave steepness. The last term is the relative crest width of the reefs. The final form of the equation, therefore:

$$KT = \frac{H_t}{H_i} = f \left( \frac{h}{B} \frac{H_i}{gT^2} \frac{B}{gT^2} \right)$$
3.2. Parametric Analysis

A qualitative parametric analysis was performed to examine the effects of the external and dimensional variables on the wave transmission through hexagonal artificial reefs. The wave transmission coefficient, KT, was be plotted against wave steepness, relative crest width, and reef configuration to observe and identify if any relationship or trends were present.

3.2.1. Influence of Wave steepness. Figure 5 shows the relationship between the transmission coefficient and wave steepness for the same depth with different configurations. The transmission coefficient values in the range of 0.78 – 0.93 for A1 configurations; 0.79 – 0.88 for A2; 0.68 – 0.81 for B1 and 0.65 – 0.81 for B2. The entire configuration of the model indicates that the increment of wave steepness will result in lower transmission coefficient values. This suggests that the relationship between the transmission coefficient and wave steepness is inversely proportional. Linear regression analysis of configuration A1 shows a strong correlation between wave steepness and wave transmission coefficient with a value of $R^2 = 0.895$. The correlation in the A2 configuration is also quite high with a value of $R^2 = 0.773$. Meanwhile, B1 and B2 had correlations of 0.953 and 0.959, respectively. At a high value of wave steepness, the waves become unstable and break easily over the structure. Therefore, the transmission coefficients were decreasing with the increment of wave steepness.

![Figure 5. KT vs wave steepness.](image)

3.2.2. Influence of Relative Width. Figure 6 indicates a relationship between transmission coefficients with relative width at the same depth for various configurations. The transmission coefficients were in the range from 0.78 – 0.93 for h/d 0.3 m (A1 and A2) and in the range of 0.65 – 0.81 for h/d values of 0.6 (B1 and B2). For one-layer reef placement, the A2 configuration produces a smaller transmission coefficient than the A1 configuration. Similar trends were also observed at B1 and B2 configurations which consist of two layers of the hexagonal reef. The B2 configuration, which has a 1m crest width, produces a smaller transmission coefficient than the B1 configuration with a crest width of 0.75 m. All configurations show the same trend, that the greater the relative width value the smaller the transmission coefficient value.
The crest of the structures causes the friction of the passing waves. The increment of crest width caused the larger reduction of the passing waves. The wave passing through the structure will touch the upper side of the structure, trigger a breaking wave or creating turbulence and causing a reduction of incoming waves. The wider the breakwater crest (B), resulting in the greater the friction area, which in turn increases the reduction of waves. This was observed from the decrease of the KT at the wider hexagonal reef arrangement. The influence of crest width will be evident for high incoming wave height with small periods or large wave steepness.

3.2.3. Influence of depth submergence. Figure 7 shows the relationship between the transmission coefficient and the depth of submergence (h/d) for each configuration. Configuration A with a depth of submergence of 0.3 and 0.6 for configuration B. The transmission coefficient is slightly influenced by the depth of submergence as seen in the figures. The A1 and A2 configurations with an h/d value of 0.3 produce a transmission coefficient in a range of 0.77 – 0.89. For an h/d value of 0.6 from B1 and B2 configurations, the range of transmission coefficients was 0.63 to 0.8. It is observed that configurations A1 and A2 produce a larger transmission coefficient than configurations B1 and B2. In other words, the B1 and B2 configurations were better at reducing waves.

The increment of the depth of submergence (h/d) caused the larger reduction of the passing waves. This is due to the higher depth of submergence as a result of a smaller freeboard; a distance between
water level to the crest height of the structure. Therefore, the passing waves ‘feels’ the presence of the structures. As previously explained, the passing wave over structure triggers a breaking wave or creating turbulences and reduces the incoming waves.

3.2.4. Influence of reef proportion. The arrangements of hexagonal reefs with a larger reef proportion (h/B) lead to a decrease in the transmission coefficient. On the contrary, a decrease in the reef proportion (h/B) leads to an increase in the transmission coefficients. As displayed in Figure 8, the test results on A₁ configurations which have a similar crest width (1 m) with B₂ configurations, have the average transmission coefficients greater than the B₂ configuration. Since the reef proportion (h/B = 0.2) of B₂ was greater than A₁ with reef proportion (h/B) of 0.1, the average transmission coefficients of B₂ were lower than A₁.

In general, structures with a larger reef proportion lead to a decrease in the value of the transmission coefficient. On the contrary, a lower value of h/B leads to a high transmission coefficient. The lower reef proportion causes the amount of friction between the structure and the wave to increase and resulting in lower wave transmissions. For the case of A₁ and A₂, the influence of relative width to the transmission coefficients was higher than the reef proportion as each configuration has a similar depth of submergence.

In Figure 8, KT vs reef proportion.

3.3. Discussion

The performance of submerged breakwaters is measured based on their ability to produce small transmission coefficients. In this study, the hexagonal reef configuration that produced the least range of transmission coefficient was the B₂ configuration. This configuration has a depth of submergence (h/d), relative crest width (B/gT²), and reef proportion (h/B) values greater than other configurations.

In Figure 9, Performance of various artificial reef units as a submerged breakwater.
The tests results showed a similar trend between the cube model [17], the hollow cylindrical model [18] and the hexagonal model as shown in Figure 9. The coefficient of wave transmission tends to increase with reduced wave steepness and conversely the transmission coefficient decreases with increased wave steepness. Hexagonal artificial reefs perform better than cylindrical and cube shapes artificial reefs, as they have smaller KT for the same wave steepness value. The hexagonal shapes of artificial reefs are also having steeper regression lines compared to those cube and cylindrical shapes. For the wave steepness range of 0.003 – 0.005, the hexagonal reefs produce a KT coefficient in the range of 0.77 – 0.93 while for cube and cylinder shapes it produces KT values of 0.81 – 0.89 and 0.83 – 0.90, respectively.

Based on the parameter analysis above, the transmission coefficient is influenced by several parameters such as wave steepness (Hi/gT^2), relative crest width (B/gT^2), depth of submergence (h/d), and reef proportion (h/B). The transmission coefficient decreases as the wave steepness increases. This occurs because of the instabilities of the waves at high wave steepness values, resulting in breaking waves, thus reducing the wave energy. The relative crest width also affects the transmission coefficient. The transmission coefficient decreases as the relative width increases. The wider the crest of the structures, the better the performance of the structure in reducing the waves. The passing wave over the submerged structure tends to break at the structure and creating turbulences causing the reduction of incoming waves energy. The greater the width of the breakwater crest, providing greater the friction area, which in turn reduces the incoming wave.

The reef proportion also influences the transmission coefficient, where the transmission coefficient tends to decrease as the reef proportion increases. The higher the structure and the closer the distance to the water surface, the better its performance in reducing waves. When the structure is high, the wave energy was blocked, absorbed, reflected, and transmitted partially behind the structure. The hexagonal model test showed that the transmission coefficient tends to decrease as the reef proportion increases. The higher and wider a hexagonal reef structure arrangement, the better the structure at reducing waves.

4. **Concluding remarks**

The performance of a hexagonal artificial reef serving as submerged breakwater has been presented. The influence of water depth, incident wave height and period, also reef configuration on wave transmission were investigated. The incoming wave height reduction was found to be influenced by the wave steepness, depth of submergence, and reef geometry. About 74% of the incoming wave energy was reduced on average. The smallest transmission coefficient produced on hexagonal-shaped artificial reefs was 0.63. The parameters analysis showed that a higher value of wave steepness (H/gT^2), relative width (B/gT^2), depth of submergence (h/d), and reef proportion (h/B) result in better waves reduction. The B2 configuration has the best performance.

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