WAVE TRANSMISSION ON SUBMERGED BREAKWATERS MADE OF HOLLOW HEMISPHERICAL SHAPE ARTIFICIAL REEFS

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ABSTRACT

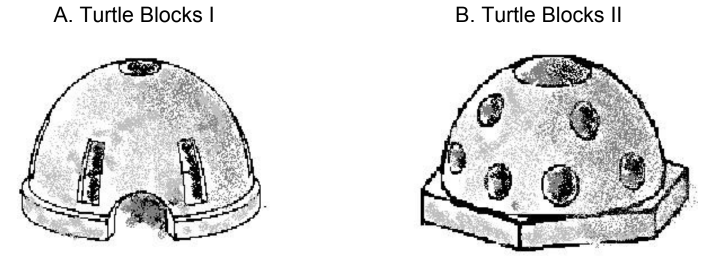
An array of perforated hollow hemispherical shaped artificial reefs (HSAR) can be used as a submerged breakwater to provide opportunities for environmental enhancement, aesthetics and wave protection in coastal areas due to their characteristics that are not found in conventional breakwaters. These characteristics include the ability to promote water circulation and provide a fish habitat enhancement capability. In this paper, a study of the parameters influencing wave transmission through the proposed submerged breakwater is presented based on two dimensional tests using regular and irregular water waves conducted at Queens University Coastal Engineering Research Laboratory (QUCERL). The influences of wave steepness (Hi/gT^2), reef proportion (h/B), submergence depth (h/d) and reef configurations on wave transmission was studied. Mathematical models for wave transmission were developed using Multiple Regression Analysis and can be used to predict the performance of the proposed submerged breakwater.

INTRODUCTION

In areas where environmental considerations must be evaluated, submerged type breakwaters are considered more frequently as a ‘soft’ solution in solving coastal engineering problems. These coastal structures can provide liited environmental benefits. Studies on submerged breakwaters and their performance have been widely conducted in the past (Seabrook, 1997 Tsujimoto et al, 1999; Hayakawa et al, 1998; Kawasaki and Iwata, 1998). Most of the breakwaters evaluated in the previous studies were constructed using rocks or prefabricated concrete blocks specially design to dissipate wave energy. Concrete breakwater blocks such as tetrapods, tetrahedrons, or trilegs are commonly used as artificial reefs. However, they are designed and developed from an engineering point of view and do not function as fish habitat or substrata for coral and seaweed. On the oherhand, artificial reefs have been widely and traditionally used for a number of years to attract fish and increase their productivity (Bohnsack et. al. 1991, Ino 1974).

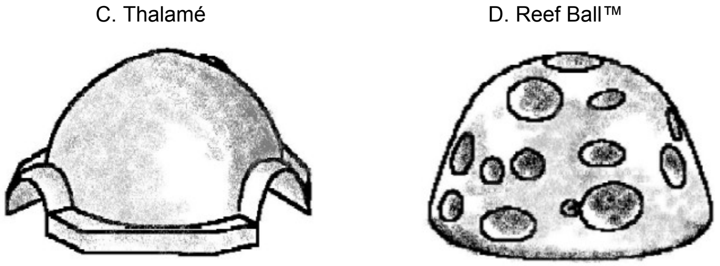
An array of perforated hollow hemispherical shape artificial reefs (HSAR) is proposed to be used as a submerged composite breakwater. Bottom-seated smooth-shaped, hollow HSAR’s were selected due to their hydraulic stability (Roehl, 1996), capability in reducing the tearing of fishing nets, producing coherent eddies with upward flow and providing hiding places for fish (Mottet, 1985, Armono, 1999).

The HSAR's can also generate beneficial vortices and turbulence, which is an attractive characteristic for habitat structures since fish abundance is influenced by current vortices (Lindquist and Pietrafiesa, 1989). Figure 1 below shows typical HSAR units. Since the engineering properties of HSAR's are similar to the submerged breakwaters materials, they can also be used as energy dissipating structures



A. Turtle Blocks I

B. Turtle Blocks II



C. Thalamé

D. Reef Ball™

Figure 1. Typical HSAR units (adapted from Mottet, 1985, Harris,2001, Alemand, et.al., 2000)

HSAR's have been deployed at the Gran Dominicus Resort, Dominican Republic for habitat enhancement and shoreline erosion abatement. Three rows of Reef Balls™ combined with small rocks in the landward area were directly laid on the ocean floor (Harris, 2001). Reef Balls™ are designed artificial reefs mainly used to restore ailing coral reefs and to create new habitat for fish and other marine or freshwater species (Barber, 2001). The results of a field survey shows that the Reef Ball™ is greatly assisting with reef stabilization and is also assisting with beach restoration at the Resort However, two problems have occured following the placement of breakwater: small rocks and sea urchins, hazardous in the swimming area between the shoreline and the breakwater, have accumulated.Additionally, the breakwater was placed too close to the shoreline eliminating much of the swimming area. Another problem may occur as the Reef Balls™ settle; a portion of the structures may be buried in the ocean floor. This condition could reduce the efficacy of the artificial reefs since the voids feature in the lower part of the Reef Balls™ which attracts crawling marine organism will be buried and covered with sediments. Therefore, it is necessary to construct the Reef Ball on a base or foundation instead of directly laying them on the ocean floor to give a better placement and stability.

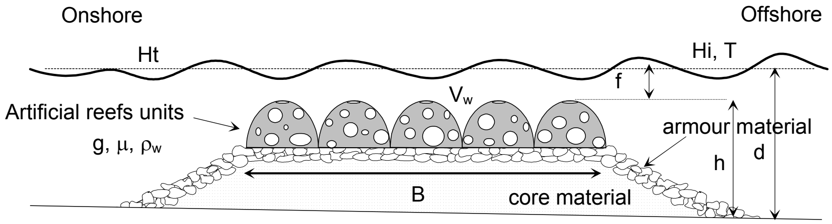


Figure 2. Proposed HSAR Breakwaters

Figure 2 shows a proposal for constructing a breakwater using a rubblemounf base in conjunction with HSAR units. With this arrangement, the HSAR units can be placed at deeper locations, which therefore will provide more recreation area between the shoreline this system will provide advantages over conventional offshore structures by providing additional environmental enhancement, esthetics, and protection in the coastal areas as a result of their special characteristics, including the ability to generate beneficial circulation and provide significant habitat. Since the engineering properties of artificial reefs are similar to the submerged breakwaters materials; they can also be used as energy dissipating structures.

Since no previous study or data is available regarding the transmission of wave energy through HSAR breakwaters, two and three-dimensional tests of HSAR breakwaters were conducted at Queens University Coastal Engineering Research Laboratory (QUCERL) to investigate their hydraulic performance. The goal of the study was to provide an efficient and satisfactory design of the reef placement and arangement..

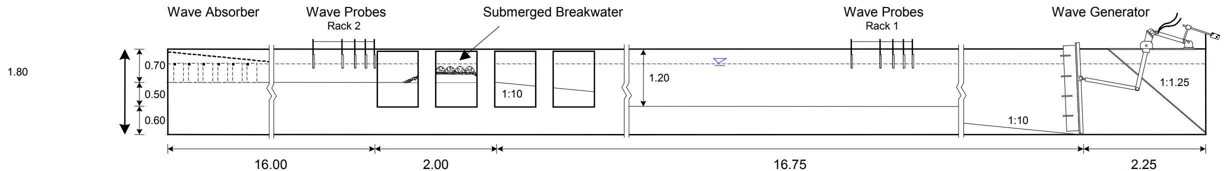
In general, the performance of submerged breakwaters is influenced by the local wave characteristics, local bathymetry, design and placement pattern of the breakwater units and the relative submergence (Herbich, 2000). In particular, previous researchers have identified the submerged depth (f/d or h/d) and crest width (B) as the critical and important factors influencing the transmission process (Dick and Brebner, 1968, Dattatri et al, 1978, Seabrook, 1999) while others have reported that the relative water depth (d/Hi) (Bleck and Oumeraci, 2002, Saito, et al, 2002), thickness-depth ratio (h/d) (Twu et al, 2001) and relative freeboard (f/Hi)(Goda in Silvester, 1974) also contribute to wave transmission.

The intention of this study is to develop a model for wave transmission past a submerged breakwater made of multiple HSAR units and to determine the optimum configuration of the reef that will minimize the incoming wave energy. The transmission coefficient, Kt, which is the ratio between transmitted and incoming wave (Ht/Hi), will be expressed as a function of depth submergence, wave height, wave period, reef crest width and reef configuration to observe and identify if any relationships or trends were present. Due to limited space, only two configuration tested in QUCERL's flume tank will be discussed in this paper. The complete data set for all of the 2 and 3-dimensional tests is provided in Armono (2002).

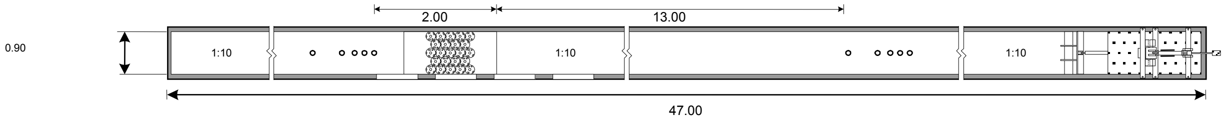
HYDRAULIC MODEL TEST

Experimental Setup

Two-dimensional tests of the hemispherical artificial reefs was carried out in a 0.9m wide, 1.2m deep, 47m long wave flume tank is equipped with computer controlled wave generator capable to generate regular and irregular wave. Figure 3 shows details of the wave flume. There are 4 glass windows (1.2 m x 0.8 m each) along one side of the flume where visual observations can be made. A passive wave absorber is located at the end of the flume to minimized reflected wave energy.



a. Side View



b. Plan View

Figure 3. QUCERL Wave Flume

Two arrays of five capacitance wave gauges were used to measure the water surface fluctuation time series both in front of and behind the reefs. The first aray was located 13m from the toe of the reef and the second array was located 2m behind the reefs. Figure 3 gives the details of the wave gauge placement and HSAR breakwater placement in the wave flume.

Reef Ball™ model units were used for the HSAR units. The HSAR breakwater was constructed by arranging and stacking the Reef Ball™ units on a platform located approximately 17m from the wave paddle as shown in figure 3 above. The porosity of Reef Balls™ varied between 10 to 40% as the number of the holes, as well as their diameters were varied. However, in this study, the influence of porosity on wave transmission was not investigated since the Reef Balls™ provided were precast with specific molds and the average porosity of the avalaible Reef Ball™ model was about 20%.

Breakwater Model Configuration and Construction

There were 5 reef configurations tested for various wave conditions and water depths to assess their effect on wave transmission. Figure 4 shows the HSAR breakwater configuration used in flume tests. In general there were two main groups of breakwater configurations to be tested. The first group was HSAR's without a base, namely Tests 2 and 3. Test 2 utilized three levels of Reef Balls. The second layer for this configuration was arranged upside down to give good interlocking with the first layer and to provide a base for the top layer. The second configuration was refered to as Test 3. This is the reduced version of Test 2 with only two layers used. The arrangement and stacking of the first and second layers was identical to the first and second layer of Test 2.

The second group of configurations utilized units with a base attached to the reefs. There are three configurations used in this group, referred to as Tests 4, 5, and 7 as shown in Figures 4c, 4d, and 4f, respectively. The base was constructed using a 1.0 m wide base of 4.0 mm (D_{50}) core covered with 36.6 mm D_{50} armour stone. The slope of the base is 1:2 and has a total height of 22 cm. The rock armour material for the base was selected based on availability in the laboratory and did not consider hydraulic stability.. However, there was no significant damage to the armour during the test, since its located relatively far below the water level.

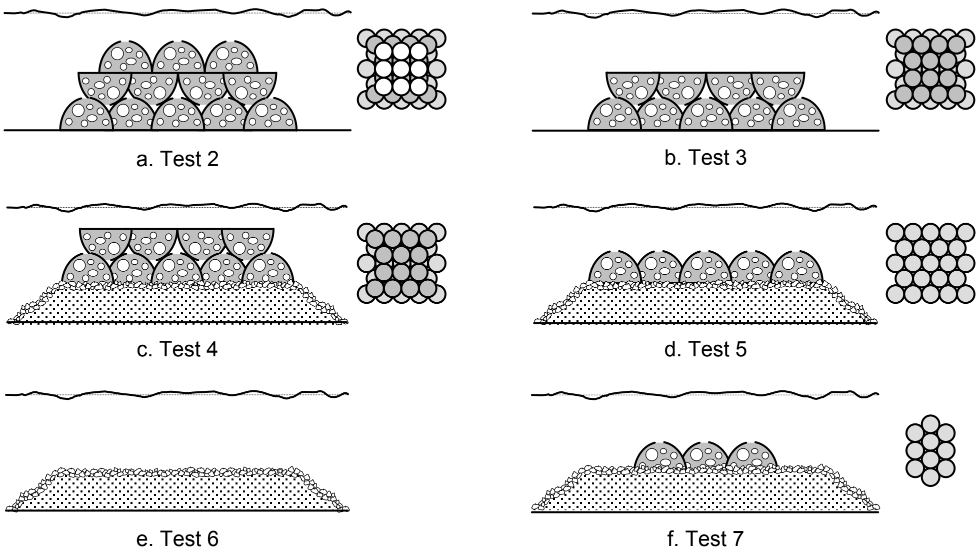


Figure 4. Submerged Breakwater Confgurations Tested

Test 1 was a wave paddle calibration and flume reflection test to quantify the reflection and characteristic of the flume tank and is not reported in this paper. Test 6 is a limited test of a conventional submerged breakwater (test without any Reef Ball™ units). Table 1 summarizes the reef placement and the test conditions for the test groups and configurations indicated above. Only configuration test numbers 5 and 7 are discussed in this paper.

Table 1. Wave Test Condition in Flume Tank

Test No.	Reef Ball™ Model	Base	Water depth (mm)	Wave height (cm)	Period (sec)
Irregular Wave					
1	No	No	144, 150,163,186, 200, 250,300,350, 400,433	5, 10, 15, 20	1, 1.5, 2, 2.5
2	Yes	No	210, 230, 263,295	5, 10, 15, 20	1, 1.5, 2, 2.5
3	Yes	No	210, 230, 263,295	5, 10, 15, 20	1, 1.5, 2, 2.5
4	Yes	Yes	430, 467, 525, 600	5, 10, 15, 20	1, 1.5, 2, 2.5
5	Yes	Yes	350. 389, 438, 500	5, 10, 15, 20	1, 1.5, 2, 2.5
6	No	Yes	350. 389, 438, 500	5, 10, 15, 20	1, 1.5, 2, 2.5
7	Yes	Yes	350. 389, 438, 500	5, 10, 15, 20	1, 1.5, 2, 2.5
Regular Wave					
4	Yes	Yes	430, 467, 525, 600	5, 10, 15, 20	1, 1.5, 2, 2.5
5	Yes	Yes	350. 389, 438, 500	5, 10, 15, 20	1, 1.5, 2, 2.5
7	Yes	Yes	350. 389, 438, 500	5, 10, 15, 20	1.5

Note: Test 1 is Flume Reflection test and calibration test

RESULTS and DISCUSSION

Dimensional Analysis

Dimensional analysis can guide the way in which 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 (Sharp, 1981). Referring to figure 2 above, the dimensional variables that influence the wave transmission Kt can be expressed as follow.

$$[1] \qquad K_t = \frac{H_t}{H_i} = f\left[h, T, \rho_w, H_i, H_t, d, B, V_w, \mu, g\right]$$

ρ_w, μ, and V_w is the mass density, dynamic viscosity and typical velocity of water in the vicinity of reefs, while g is the gravitational acceleration. Solving equation [1] by the matrix method (Sharp, 1981) produces the following π terms:

$$[2] \qquad \frac{Hi}{h}, \frac{Ht}{h}, \frac{d}{h}, \frac{B}{h}, \frac{VwT}{h}, \frac{\mu T}{h^2 \rho_w}, \frac{gT^2}{h} = \pi_1, \quad \pi_2, \quad \pi_3, \quad \pi_4, \quad \pi_5, \quad \pi_6, \quad \pi_7$$

by compounding the π terms

$$[3] \qquad \frac{Hi}{gT^2}, \frac{Ht}{Hi}, \frac{h}{d}, \frac{h}{B}, \frac{V_w T}{h}, \frac{V_w h}{\mu / \rho_w}, \frac{V_w^{\,2}}{gh} = \frac{\pi_1}{\pi_7}, \quad \frac{\pi_2}{\pi_1}, \quad \pi_3^{-1}, \quad \pi_4^{-1} \quad \pi_5, \quad \frac{\pi_5,}{\pi_6} \quad \frac{\pi_5^{\,2}}{\pi_7}$$

The first four terms explains the properties of the incoming and transmitted waves, structure placement and geometry, namely: wave steepness, wave transmission, depth submergence, and reef proportion. The last three parameters are the Keulegan-Carpenter (KC) number, Reynolds number and Froude number which are important in similitude analysis of hydraulic and turbulent modeling (Hughes, 1993). When the last three terms is considered constant, equation [1] can be expressed as follows:

$$[4] \qquad K_t = \frac{H_t}{H_i} = f\left[\frac{Hi}{gT^2}, \frac{h}{d}, \frac{h}{B}\right]$$

Parametric Analysis

A qualitative parametric analysis was performed to examine the effects of the external and dimensional variables on the wave transmission through HSAR breakwaters. The wave transmission coefficient, Kt, was be plotted against depth submergence, wave height, wave period, reef crest width, and reef configuration to observe and identify if any relationship or trends were present. When plotting Kt against the specific independent variables above, all other variables were held constant. Figure 5 shows the relationship between wave transmission and wave steepness (Hi/gT^2) differentiated by relative depth submergence (h/d), and reef proportion (h/B) in Tests 5 (Figure 5.a) and 7 (Figure 5b). The variation of transmission with Reef Ball™ configuration is given in Figure 6, while in Figure 7, a comparison of regular wave and irregular wave results are presented. The influence of other variables along with a discussion of the three-dimensional tests results are provided in Armono (2002).

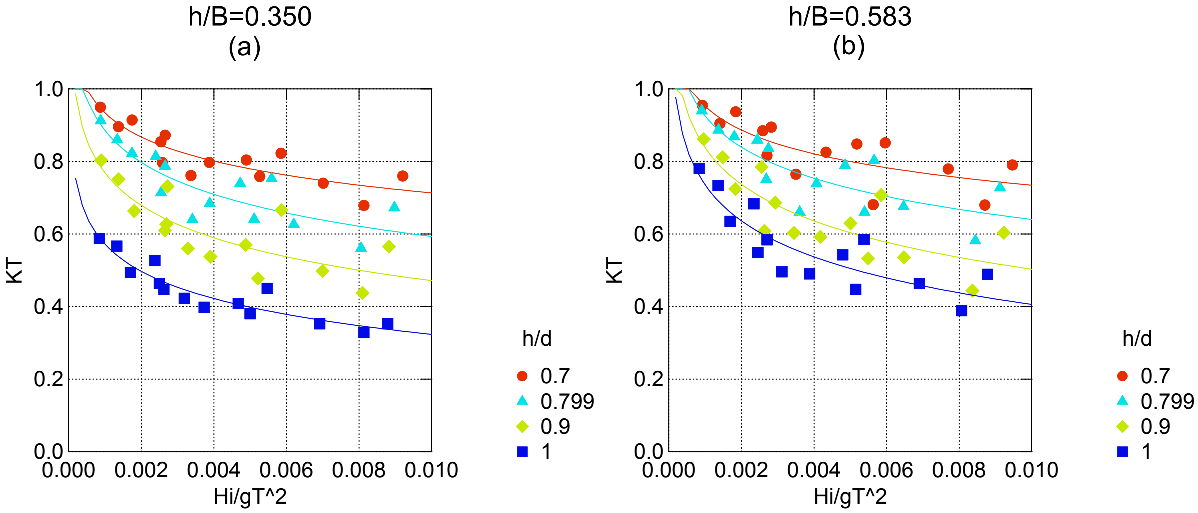


Figure 5. Typical Plots of Parametric Analysis in Irregular Wave Tests: (a) Test 5 and (b) Test 7

From the experimental observations made in the wave flume and examining Figure 5, 6 and 7, the following remarks can be drawn:

- Tests at low water depth (h/d = 1) had the lowest values of Kt while those at higher depths (h/d = 0.7) had the highest average value of Kt for a given wave height.
- Incoming waves with a high wave steepness (Hi/gT^2) in low water depth had the lowest values of Kt while those at higher depth and lower wave steepness had the highest value of Kt.
- For low submerged depths, (i.e., the breakwater height is more than 70% of water depth) the effect of breakwater width (or reef proportion) is noticeable. However, this effect becomes insignificant as the water depth increases. This is due to the fact that the incoming waves do not ‘touch’ the reef surface resulting in ineffective wave attenuation.
- Test 5 had the lowest transmission at all depths of submergence (h/d) except for h/d =1 where Test 3 results exhibited the lowest transmission. In general Test 5, 3 and 4 had better performance than the other tests. However, when waves attacked the top layer of Reef Balls™ in Test 3 and 4 is unstable comparing to those at Test 5. The highest transmission occurred in Test No. 2.
- The difference between wave transmission obtained from regular and irregular wave tests was not significant.

A comparison of wave transmission through the various Reef Ball™ configurations is given in Figure 6, while in Figure 7 provides a comparison of regular and irregular wave reults.

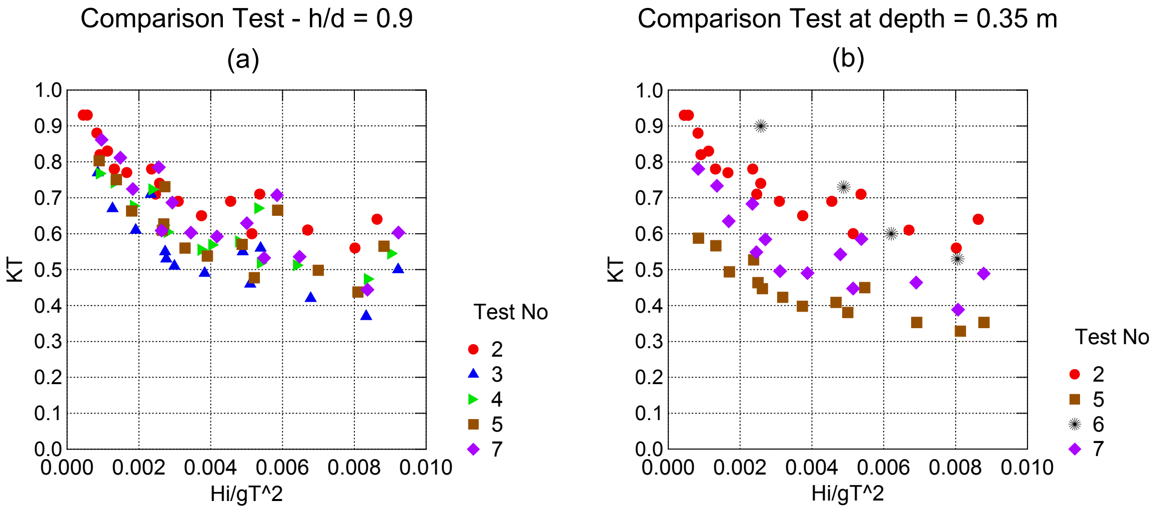


Figure 6. Wave transmission as a Function of Test Configuration at (a) h/d = 0.9 and (b) water depth = 0.35 m

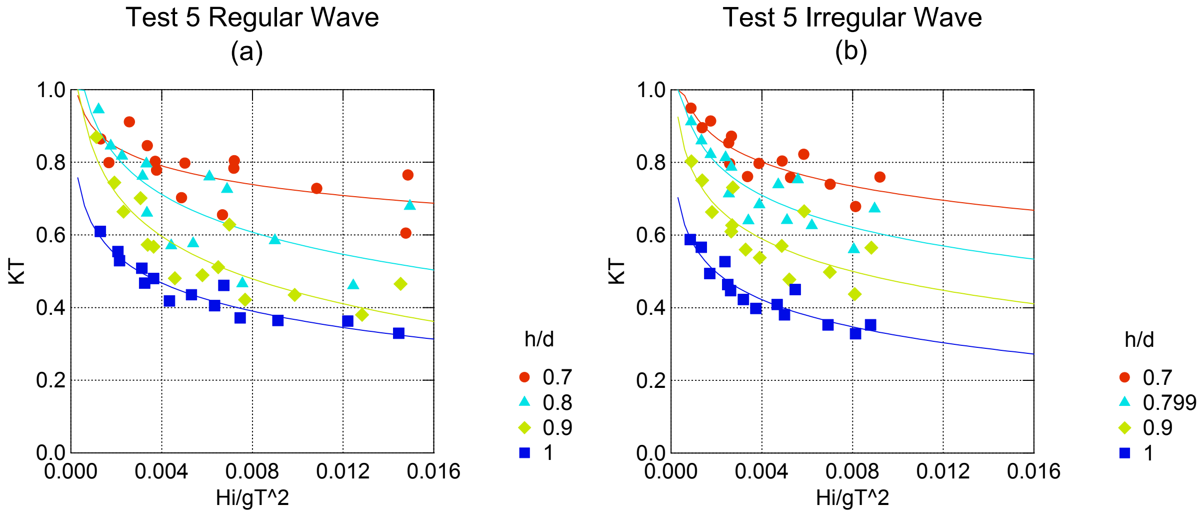


Figure 7. Comparison of Wave Transmission – Irregular and Regular Waves

Multiple Regression Analysis

Data from the wave flume experiments were analyzed using a multiple regression analysis. The analysis was performed to determine the relationship between wave transmission and the independent variables and to develop an equation for estimating wave transmission through HSAR breakwaters. The proposed wave transmission equation was a proportional estimation between statistical validity and practical implication, as some parameters, especially combined variables, may have statistical significance but no physical basis. As each parameter in equation [4] has a physical meanings, statistical analyses were performed to produce the best, simplest, and most feasible equation to assist with practical HSAR breakwater design and evaluation.

Only 95% of data collected from 112 observations in Irregular Wave Test 5 and 7 were used in analysis. The remaining 5% of the data were removed randomly for validation purposes. Observation data from the Regular Wave Tests were used to evaluate the proposed equation by examining the percentage of prediction errors, index of fit R^2, standard error of the estimate, residual normality and F statistics. A commercial statistical sofware package SYSTAT® v8.0 (SPSS, 1998) was employed to accelerate the analytical process. The following equation for wave transmission was found to provide a good representation of the wave transmission through HSAR breakwaters.

$$[5] \qquad K_t = 1.616 - 31.322\frac{Hi}{gT^2} - 1.099\frac{h}{d} + 0.265\frac{h}{B}$$

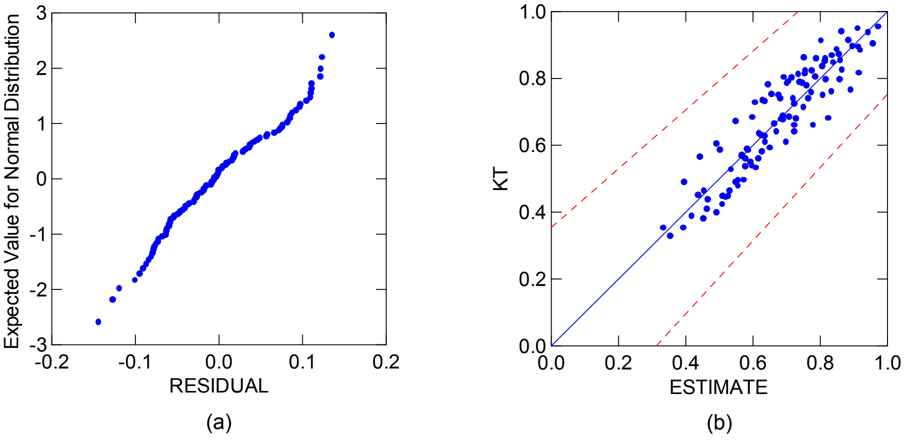


Figure 8. (a) Residual Plot (b) Comparison Plot Between Measured and Estimated Kt (b)

The standar error estimate for the above equation was 0.065 and the index of fit value (R^2) was 0.841. This means that 84.1% of the variability in Kt can be explained by the wave steepness (Hi/gT^2), depth of submergence (h/d) and reef proportion (h/B). An F ratio of 179.856 ws achieved which exceeded F(0.001; 3; 102). Therefore, the p value is highly significant (P) < 0.001. Accordingly, the wave steepness, depth submergence and reef proportion, when considered together, are significant predictors of wave transmission. Figure 9 shows the normal distribution of residuals and a comparison between measured and estimated Kt for Tests 5 and 7. The predicted Kt was within the 95% confidence interval as shown in Figure 8.(b).

To validate the proposed equation, the data obtained from the regular wave experiments and the 5% of the irregular wave data previously isolated data, were compared to predictions provided by the model in Figure 9 .The average absolute error from the irregular wave data was 7.35% while the average absolute error from the regular wave data was 8.25%. Figure 9 shows that the irregular wave data were within the range of the 95% confidence interval of equation [5] and only 2 data points from the regular wave tests were outside of this range. Based on Figures 8 and 9, the equation provides good agreement with the results of experimental program.

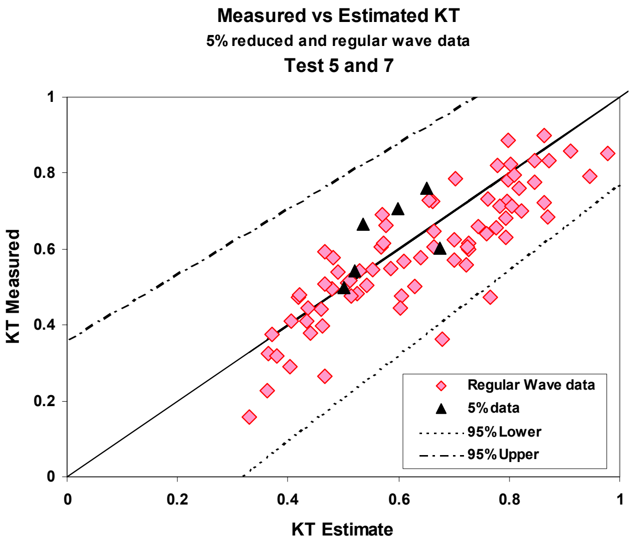


Figure 9. Measured vs Estimated Kt for Irregular and Regular Wave Data.

CONCLUSIONS

Quantification of wave attenuation by a hemispherical artificial reef (HSAR) submerged breakwater has been presented. The influence of water depth, incident wave height and period and reef configuration on wave transmission were investigated. Wave height reduction was found to be influenced by the wave steepness, depth of submergence, and reef geometry. About 60% of the incoming wave energy was reduced on average.

An equation to predict the transmission has been proposed. The emprically based equation developed has been shown to provide a good estimate of Kt for the type of structure tested within the following range of parameters: $Hi/gT^2 = 0.001 \sim 0.015$, $h/B = 0.35 \sim 0.583$, and $h/d = 0.7 \sim 1$. The equation provides good agreement with the results of 2-D tests with a correlation coefficent, $R^{2,}$ of 0.841 and standar error estimate 0.065. The equations can be used for initial estimates of wave transmission, while physical model test are suggested to confirm the final design parameters for the breakwater construction project.

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