CHAPTER 84

MODEL TESTING OF WAVE TRANSMISSION PAST LOW-CRESTED BREAKWATERS

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Abstract

Small-scale model tests were conducted to assess the wave transmission characteristics of low-crested breakwaters. The goals of this study are to quantify the wave transmission characteristics of these breakwaters for various structure heights, water depths, and wave conditions. The tests were conducted on cross-sections of solid and rubble breakwater models using both regular and irregular waves. A new parameter, $(F\text{-}Ru)/H_i$, is then proposed to represent transmission past a breakwater for all values of breakwater freeboard.

Introduction

Several recent studies have considered the wave transmission characteristics of low-crested breakwaters in which the armor stones were small enough to be remolded by the incident wave action, e.g. Ahrens (1987a) and van der Meer (1990). For such cases, Ahrens (1987a) has proposed that the breakwater porosity can be characterized by the Bulk Number, which represents the number of stones in the breakwater cross-section. These studies then provide wave transmission data for breakwaters with high Bulk Numbers, in the range of 200 to 600, and sometimes more.

In the United States, however, most low-crested breakwaters are not built with such small armor stones and Bulk Numbers in the range of 10 to 50 are most common. As a result, some of the recent data on wave transmission may not be applicable to realistic breakwater design conditions. In the present study, wave

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transmission results from physical model tests are presented for low-crested breakwaters with Bulk Numbers in the range of 12 to 36. The breakwaters considered here are so-called statically-stable homogeneous breakwaters, e.g. van der Meer (1991), which contain a single uniform stone size selected in the traditional way according to the Hudson Formula to be stable under wave attack.

The overall objective of this study is to expand the existing database on wave transmission past low-crested breakwaters for conditions that would normally be encountered in design. Toward this goal, more than 250 small-scale physical model tests were carried out on two-dimensional solid and rubble breakwater cross-sections in the Coastal Engineering Wave Basin at the United States Naval Academy. This study was similar in scope to that of Seelig (1980). The primary goal was to investigate the parameters which affect the transmission of waves past the types of low-crested or reef breakwaters currently being constructed in the United States. Figure 1 illustrates the variables of interest.

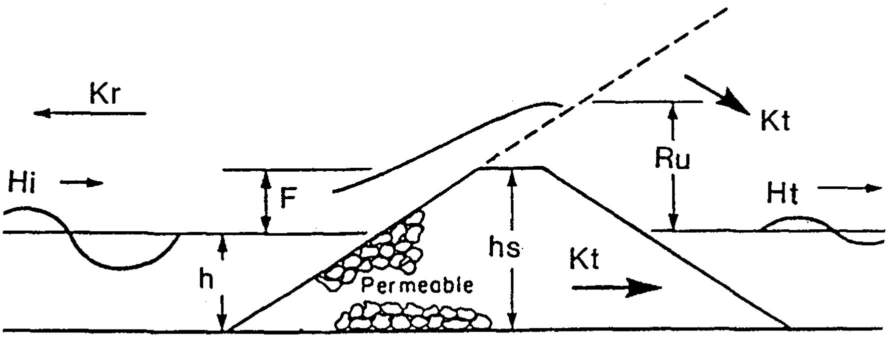

Figure 1. Reef Breakwater Definitions

Experimental Setup

Laboratory tests were performed in the United States Naval Academy's Coastal Engineering wave basin. Figure 2 shows the side view of the test setup. The wave basin measured 16.61 meters long, and has a piston-type wavemaker that can generate either regular or irregular waves. The basin was then sub-divided by 2 plexiglass walls to form a test channel with a width of 0.61 meters. The test channel consisted of 3 segments. The first segment, 2.44 meters long, consisted of a 1:15 slope. The second segment, 4.88 meters long, was comprised of a level false bottom. In the final segment, 1.22 meters long, the false bottom was replaced by a wave absorbing gravel beach. Between the end of the channel and the back wall of the wave basin, there existed a 1.30 m wide space which prevented the ponding of water behind the breakwater test sections. A second wave absorbing

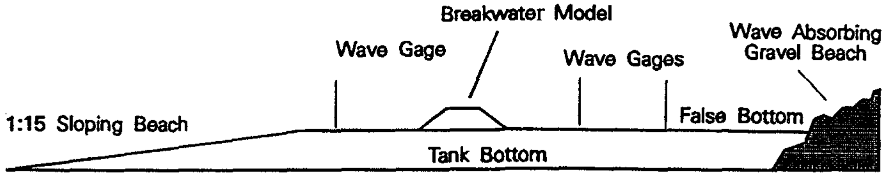

Figure 2. Side View of the Test Channel

beach was placed in front of the back wall of the tank. Numerous tests were conducted to document the effectiveness of the wave absorption system. In all cases studied, the value of wave reflection did not exceed 10%.

Capacitance wave gages were used to measure wave heights in front of and behind the breakwater. For the regular wave tests, three wave gages were generally used. Gages were placed 0.91 and 1.52 meters behind the breakwater and the results were averaged to yield the height of the transmitted wave, in a manner similar to Ahrens (1987b). The incident wave height was measured through the use of a single wave gage which was moved in front of the model from the base of the model to the top of the sloping beach. Through the movement of the gage, the incident and reflected wave heights were obtained from the partial standing wave envelope. The irregular wave tests utilized four wave gages, two in front of the model and two in the lee of the structure. Both pairs of these gages constituted a so-called Goda array, e.g. Goda and Suzuki (1976), which when analyzed has the capability of yielding the incident and reflected significant wave heights in front of and behind the breakwater at all frequencies in a random sea. The separation distance between these gages was 15.24 cm. The first pair of gages were located 76 cm in front of the breakwater while the lee pair were located 91 cm behind the model.

The breakwaters studied were two dimensional models, for which the transmission characteristics of different wave conditions and breakwater freeboards were of most interest. As a result, several design variables were held constant. The side slopes of the breakwater were built with a standard slope of 1:1.5, based on study of several recent reef breakwater projects in the United States. The weight of the armor stone was obtained through use of the Hudson (1959) equation. Despite the recent availability of alternate methods of sizing armor stone, the Hudson equation is still used to determine the size of the rock used in almost all current reef breakwater projects in the United States. For this model study, where limestone with a specific weight of 2659 kg/m^3 was used, the Hudson equation yielded an armor stone weight of 0.18 kg and a diameter of approximately 5.1 cm, based on a maximum wave height of 10.2 cm in the test channel. Following this analysis, the available stones were sieved and only rock that fell between the limits of 3.8 to 6.4 cm in diameter and 0.13 to 0.23 kg was accepted. Finally, the crest width was established from recommendations in the Shore Protection Manual of the U.S. Army Corps of Engineers (1984). The crest width used in this study was taken as 3 times the median stone diameter or 15.2 cm.

One unique aspect of these tests is that this design process yielded an order of magnitude smaller Bulk Numbers than the previous tests of Ahrens (1987a) or van der Meer (1990). Bulk Number is defined as:

$$B_n = \frac{A_t}{d_{50}^2}, \qquad (1)$$

where A_t is the area of the breakwater cross section and where d_{50} is the median diameter of armor stone. The Bulk Number is therefore proportional to the number of stones in the cross-section. Based on the characteristics of the breakwater discussed above, the values of Bulk Number tested in this study ranged between 12 and 36, depending upon the breakwater crest height. Typical values for breakwaters built in the U.S. range from 10 to 50, e.g. Fulford (1985), so that values tested were within the range of recent prototype conditions.

Solid and rubble breakwaters were both tested during the course of this study. The solid models, which served as the limiting condition of zero permeability, were constructed of PVC to the same geometry specifications as the rubble structures. The crest heights tested for both types of models were 10.2, 15.2, and 20.3 cm tested in water depths of 10.2, 15.2, and 20.3 cm of water above the false bottom in the test channel. This produced a 3x3 test matrix. However, the two extreme cases were not tested, so that a 10.2 cm breakwater was not tested in 20.3 cm of water and likewise, a 20.3 cm breakwater was not tested in 10.2 cm of water. The purpose of this investigation was to study wave transmission past breakwaters at or near the still water line, with freeboards of +5.1 cm, 0.0 cm, and -5.1 cm.

The solid breakwater tests were conducted using regular waves only. Four frequencies were tested at each crest height and water depth combination. These frequencies were 0.55, 0.7, 0.9, and 1.1 Hz. In turn, at each of these frequencies four wave heights were generated. These wave heights extended up to heights which were close to breaking. The regular wave tests for the rubble breakwaters were run in exactly the same manner. The irregular wave tests were only conducted using the rubble models. These tests utilized the same combinations of crest height and water depth as did the regular wave study. With the irregular waves, JONSWAP spectral peak frequencies of 0.7 and 0.9 Hz were tested, and at each peak frequency, two significant heights were tested.

Results--Regular Waves

Results for solid and rubble breakwaters subjected to regular waves are presented in Figures 3-6. Figures 3 and 4 illustrate the change in the wave transmission coefficient, K_t, or H_t/H_i for various wave steepness conditions, H_i/gT^2, breakwater geometries, h/h_s, (see Figure 1), and relative water depths, h/gT^2. These figures illustrate the dependence of wave transmission on wave steepness and relative water depth. They are especially valuable in illustrating the trends associated with various wave steepness conditions and breakwater freeboards where freeboard is defined as $F = h_s - h$.

Breakwaters with a high water depth to structure height ratio, $h/h_s = 1.5$, as shown in Figures 3a and 4a for solid and rubble breakwaters respectively, exhibit a trend of very high transmission for very low wave steepness, with diminishing values of K_t for very high steepness waves. This can be attributed to the fact that the breakwater, being below the still water level, allows waves of very low steepness to pass directly overhead with very little attenuation of the incident wave energy. Incident waves with very high steepness, on the other hand, are closer to breaking and the breakwater will succeed in "tripping" the wave, leading to energy dissipation. This situation is seen for both the solid and rubble breakwaters and K_t values are seen to approach about 0.5 for higher values of wave steepness.

The next conditions considered, in Figures 3c and 4c, are for breakwaters with a positive freeboard, where h/h_s 0.75. The trend shown for this situation is different from that shown above for a breakwater with a negative freeboard and yields very different trends for the rubble and solid breakwaters. Figure 3c shows the case for the solid breakwaters studied. In this case, considering that the structure is impermeable, no wave energy will overtop the breakwater for very low steepness waves so that values of K_t are equal to zero in this portion of the graph. As the steepness of the waves increase, the wave runup will begin to overtop the breakwater and nonzero values of K_t are witnessed. As the wave steepness continually increases, the values for the transmission coefficient seem to approach a value between 0.4 to 0.5.

Rubble breakwaters, as shown in Figure 4c, illustrate a much different trend due to their porosity. Initially, even for very low steepness waves, there is transmission due to the flow through the permeable structure. The most interesting trend, however, is the fact that as wave steepness increases, K_t decreases, so that the breakwater is more effective in dissipating the energy of the steeper waves. In these cases, the waves are not able to run up the surface of the rubble structure to the same degree that they were able to run up the smooth surface of the solid breakwater. Thus, much less of the incident wave is able to overtop the structure, and instead must pass through the pores of the structure. In the process of passing through the structure, the higher steepness waves are not able to pass through the

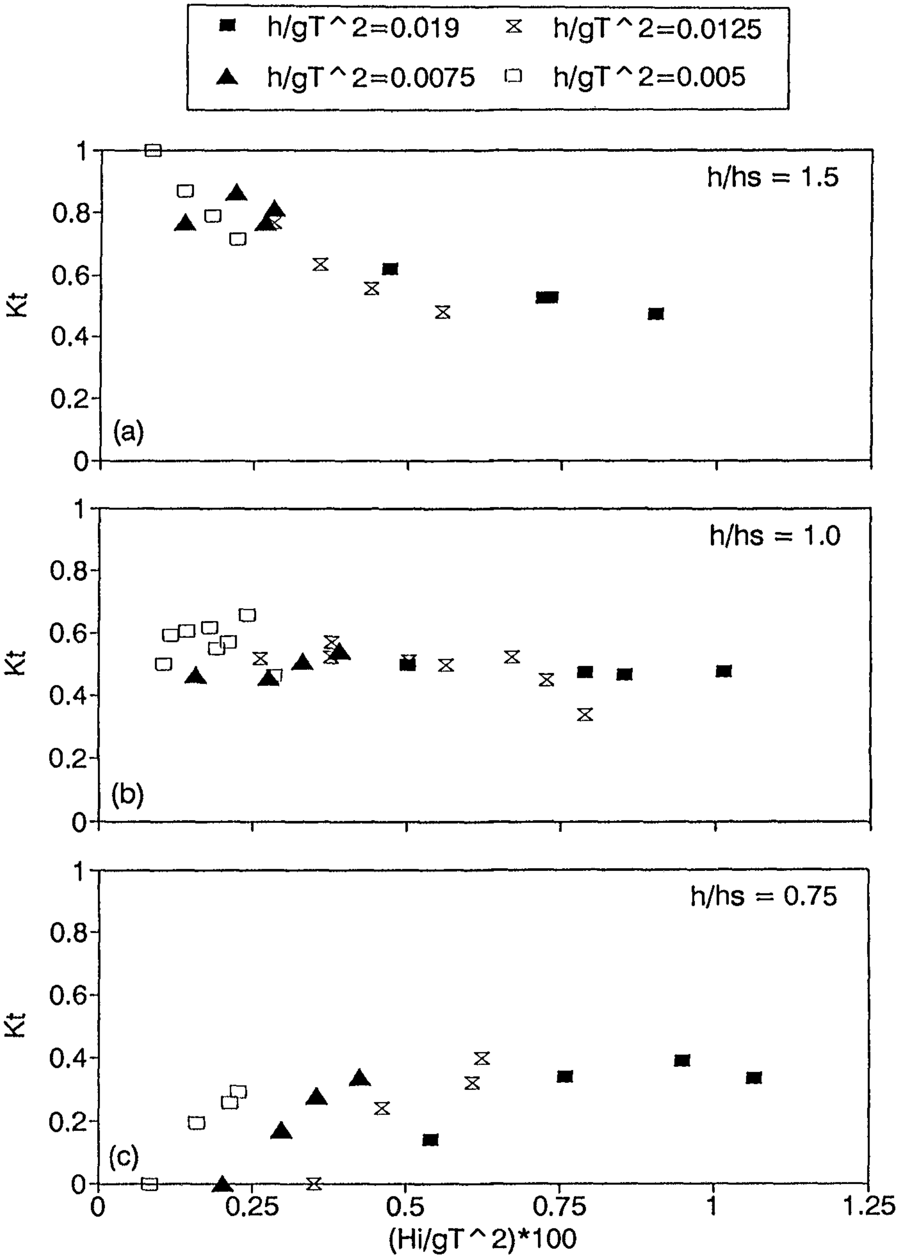

Figure 3. K_t as a function of wave steepness for several structure geometries for solid breakwaters.

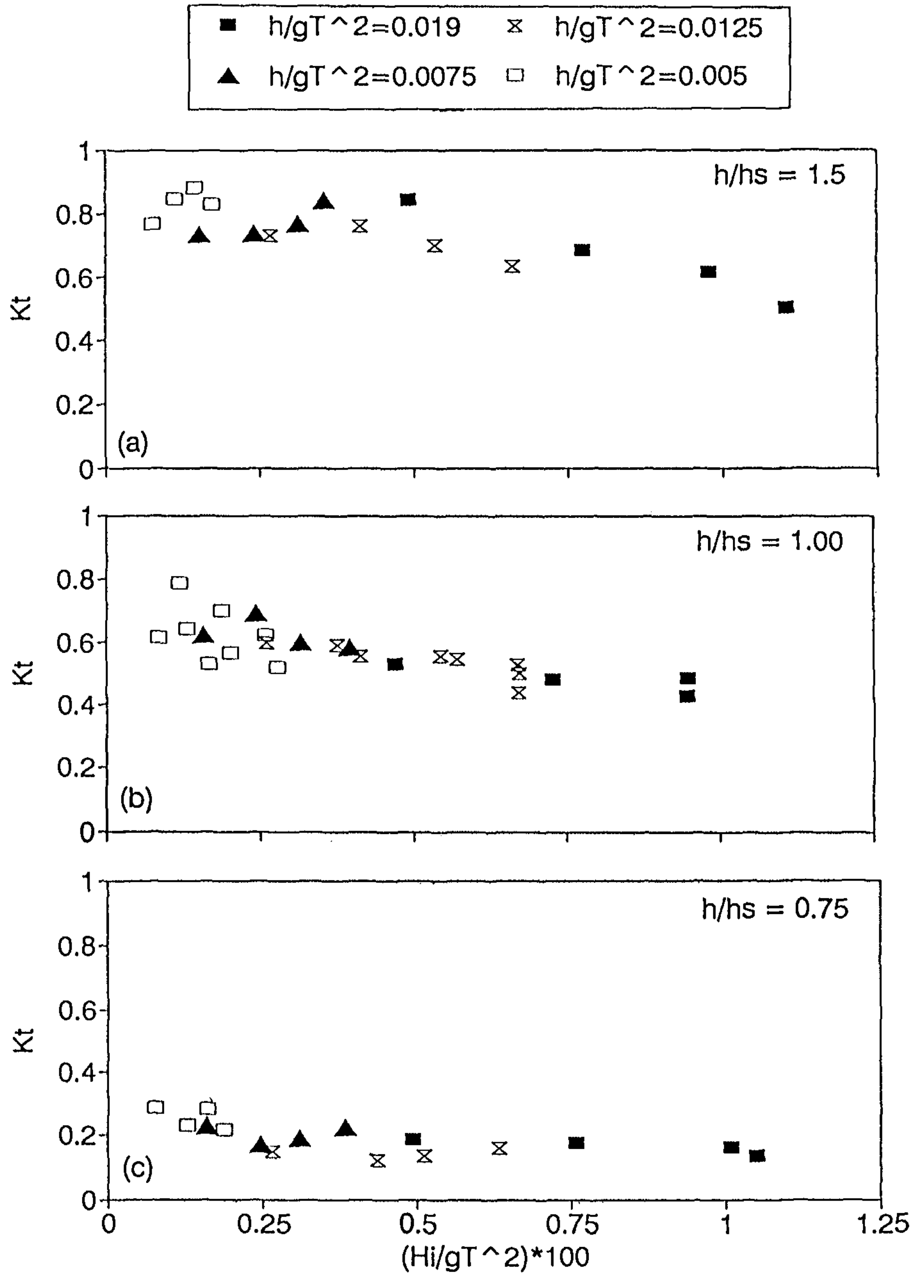

Figure 4. K_t as a function of wave steepness for several structure geometries for rubble-mound breakwaters.

breakwater as "cleanly" as are the low steepness waves. Within the breakwater, energy dissipation is likely related to the water particle velocities squared, much like head loss in turbulent fluid flow through pipes. Due to this, high steepness waves dissipate a greater percentage of their energy within the pores of the breakwater accounting for the downward trend in the data for steeper waves.

The final category of breakwaters considered are those with a zero freeboard, whose water depth to structure height ratio is equal to one. Figures 3b and 4b illustrate this case for solid and rubble breakwaters respectively. The trends shown in these figures are once again very similar for both solid and rubble breakwaters. As the wave steepness parameter increases, K_t seems to approach a limiting value of about 0.5. This limiting value appears to fit well within the trends established by Figures 3a, 3c, 4a, and 4c. Figures 3b and 4b also illustrate a weak transmission dependence upon relative water depth. For low values of relative water depth and low steepness waves, the transmission is greater than 0.5. As the steepness and relative water depth increase, however, there is less dependence upon relative water depth. In conclusion, Figures 3 and 4 show that values of K_t depend heavily upon wave steepness and breakwater geometry, and to a more limited degree on the relative water depth parameter, h/gT^2.

In addition to wave steepness, the relative freeboard parameter, F/H_i, was investigated as a controlling parameter for wave transmission. Figure 5 shows the values of K_t as a function of the relative freeboard parameter for both solid and rubble structures. The prediction equation of van der Meer (1991) is also superimposed along with its corresponding 90% confidence bands. Van der Meer's equation is defined as:

Range of validity	*Equation*	
$-2.00 < F/H_i < -1.13$	$K_t = 0.80$	
$-1.13 < F/H_i < 1.2$	$K_t = 0.46 - 0.3(F/H_i)$	**(2)**
$1.2 < F/H_i < 2.0$	$K_t = 0.10$,	

and was meant originally for application to random wave transmission. The relative freeboard parameter has been the most widely studied of all parameters relating to wave transmission. Goda (1969), Seelig (1980), and Ahrens (1987a, 1987b) are just a few of the authors who correlate transmission past a breakwater to this parameter.

As illustrated by the data in Figure 5, when the relative freeboard of either a rubble or solid structure is negative, the transmission coefficient is relatively high. In these cases, the incident waves are able to pass over top of the structure with little interaction from the structure, especially for the lower steepness waves (small H_i) as was illustrated above in Figures 3 and 4. In some cases for the solid breakwaters, K_t actually reaches a value of 1 for various cases of large negative relative freeboard. On the other hand, when the relative freeboard of the structure

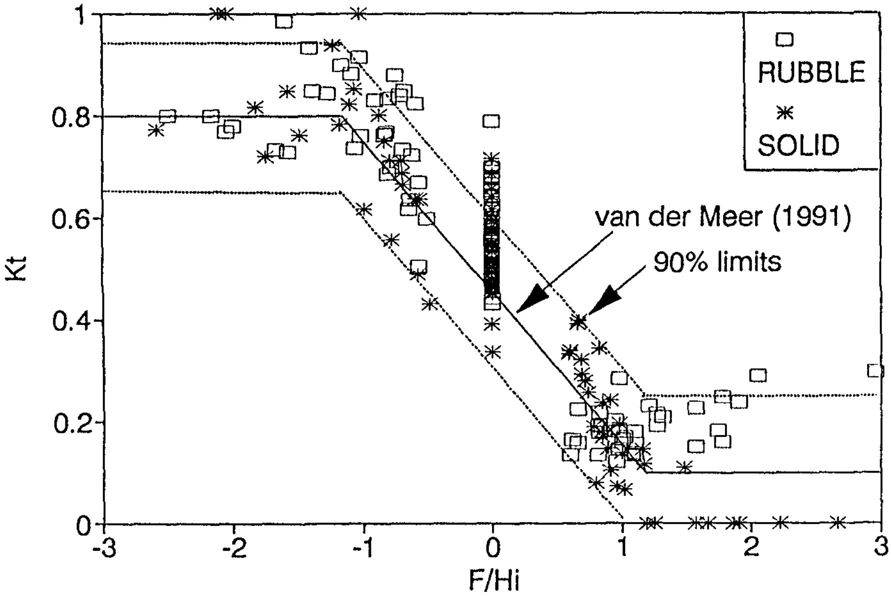

Figure 5. Transmission of regular waves past solid and rubble breakwaters using traditional freeboard parameter.

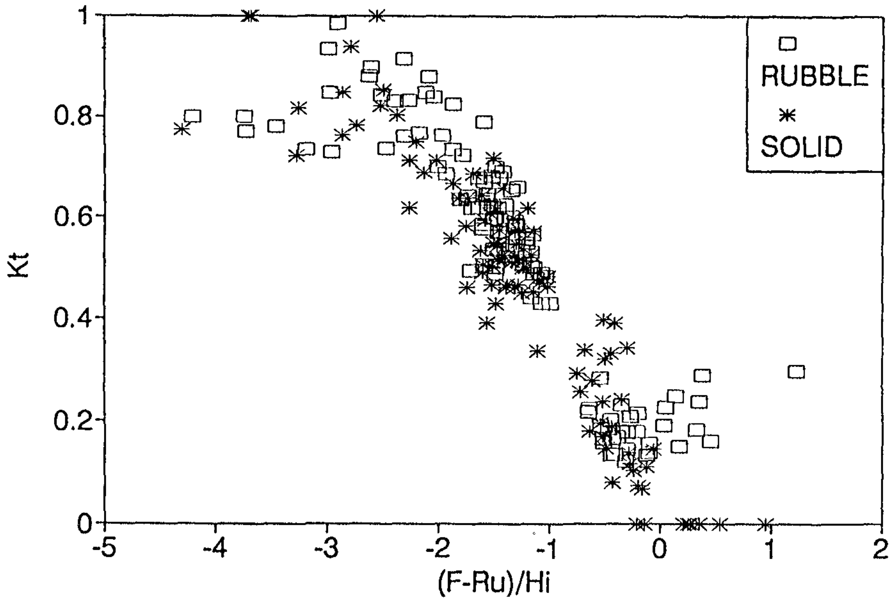

Figure 6. Transmission of regular waves past solid and rubble breakwaters using new freeboard parameter.

is positive, the transmission coefficient is relatively low in both cases. In this extreme, however, the solid breakwater differs greatly from the rubble breakwater due to the latter's porous nature.

The solid breakwater in the positive extreme of the relative freeboard actually reaches a limiting value of zero since the structure only allows transmission once wave run up overtops the structure. The rubble breakwater, on the other hand, gives a minimum value of K_t at a relative freeboard value of about one. As the relative freeboard approaches higher positive values, the trend is once again back toward a larger K_t value due to flow through the structure. Since the highest value of freeboard was set at 5.1 cm, the controlling factor in these high values of F/H_i is the wave height. As a result, this parameter illustrates that the breakwater will allow significant transmission through the structure for very small waves even if the freeboard is much higher than the incident wave.

Relative freeboard is a good parameter for describing the transmission past breakwaters with either positive or negative freeboard, but for breakwaters with zero freeboard, it has some disadvantages. This is illustrated in Figure 5 where this parameter is unable to discriminate values of K_t for the cases of zero freeboard. For these cases, this parameter yields K_t values anywhere from 0.4 to 0.8 and lacks any dependence on the incident wave height. Despite this drawback, it is apparent that the predictive equation given by van der Meer for random waves does a reasonable job in predicting the trends in the data for regular waves, and a majority of the data taken in this study falls within the error boundaries established by van der Meer.

Because the relative freeboard parameter is not effective at zero values of freeboard, a new parameter is proposed in Figure 6 to describe the transmission past a reef breakwater at all values of freeboard. This new parameter, $(F\text{-}Ru)/H_i$, incorporates the potential vertical wave run up, Ru, (see Figure 1), based upon the Irribarren Number, ξ, and therefore contains an influence of wave steepness in a way similar to that proposed by Allsop (1983). This parameter is also similar to the overtopping parameter suggested by de Waal and van der Meer (1992). The potential wave run up used in this parameter was first proposed by Ahrens and McCartney (1975) in the form:

$$\frac{Ru}{H_i} = \frac{a\xi}{1 + b\xi}; \quad \xi = \frac{\tan\theta}{\sqrt{H_i / L_o}} \tag{3}$$

where L_o is the deep water wavelength and a and b are empirical coefficients which have the values of a = 0.775 and b = 0.361, as proposed by Gunbak (1979).

As can be seen by Figure 6, this parameter does a better job in representing the data under all conditions of freeboard. Note that transmission past solid breakwaters is essentially zero when $(F\text{-}Ru)/H_i$ equals zero, as is to be expected.

Transmission past rubble-mound structures is then minimized when (F-Ru)/H_i is approximately equal to zero, that is when the potential run up just equals the crest height. In the case of large positive values of the parameter, somewhat larger transmission is indicated. In general, these larger transmission values are again associated with the smallest incident wave heights tested at the lowest frequencies.

In conclusion, Figures 5 and 6 show that wave transmission does not significantly differ between the solid and rubble-mound structures, despite the low Bulk Numbers tested. Only for conditions where the breakwater crest is higher than the run up limit were results dramatically different, due to wave propagation through the porous rubble cross-section. Figure 6 illustrates that this transition will occur, for the conditions tested in this study, at a (F-Ru)/H_i value of approximately -0.4. Thus, below this value, solid breakwaters are shown to be a reasonable approximation of porous reef breakwaters when modelling wave transmission. In addition, these findings also show that the Bulk Number does not seem to be a primary parameter in determining wave transmission since impermeable structures yield similar transmission results as do extremely porous breakwaters.

Results--Irregular Waves

Figures 7 and 8 present results obtained for rubble-mound breakwaters subjected to irregular waves, along with the earlier results for regular waves. For irregular waves, both the incident and transmitted wave heights are defined in terms of the significant height, H_s. Correlations were also performed using the root-mean-square wave height, but these results did not agree as well with the regular wave data. A possible reason behind this is that the energy dissipation and head losses in the porous structures are better modeled by H_s. Because the significant wave height represents the higher incident wave heights in random waves, it is more representative of the waves most affected by losses within the breakwater.

Both Figures 7 and 8 illustrate that the irregular waves tested followed the same trend and correlated well with the regular waves. Van der Meer's predictive equation for describing transmission as a function of F/H_i, again predicts the trend well and most of the random wave results fall within the suggested error bands. Once again, however the new (F-Ru)/H_i parameter is better able to discriminate K_t values for conditions with a zero freeboard, and the minimum wave transmission again occurs when this parameter is approximately equal to zero. This is shown to be the same for regular and irregular waves. Again, as was shown in Figure 6, the higher transmission for extreme positive and negative values of the new parameter are in all cases the result of very small waves of low frequency. Although the number of experiments performed with random waves was limited, the initial results indicate that regular wave results are useful for approximating the transmission of random waves defined by the significant height and peak frequency.

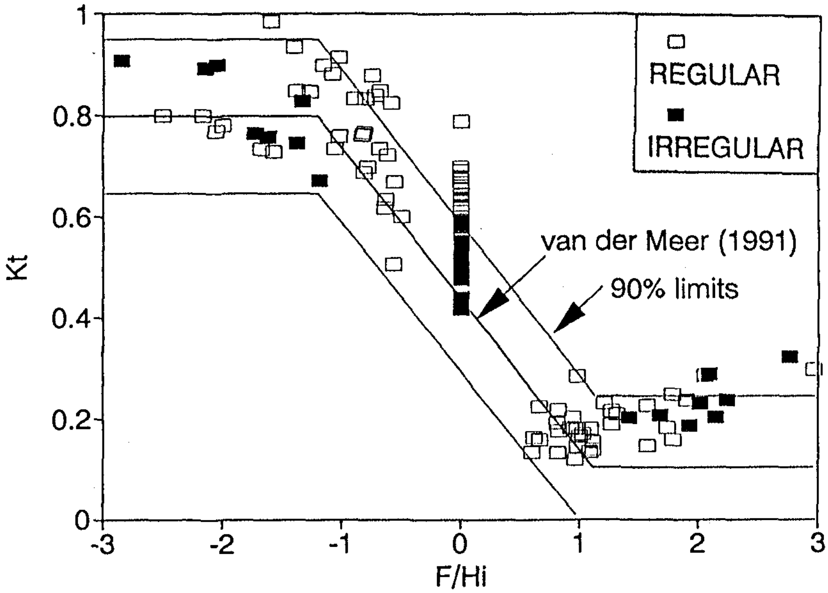

Figure 7. Transmission of regular and random seas past a rubble breakwater using traditional freeboard parameter.

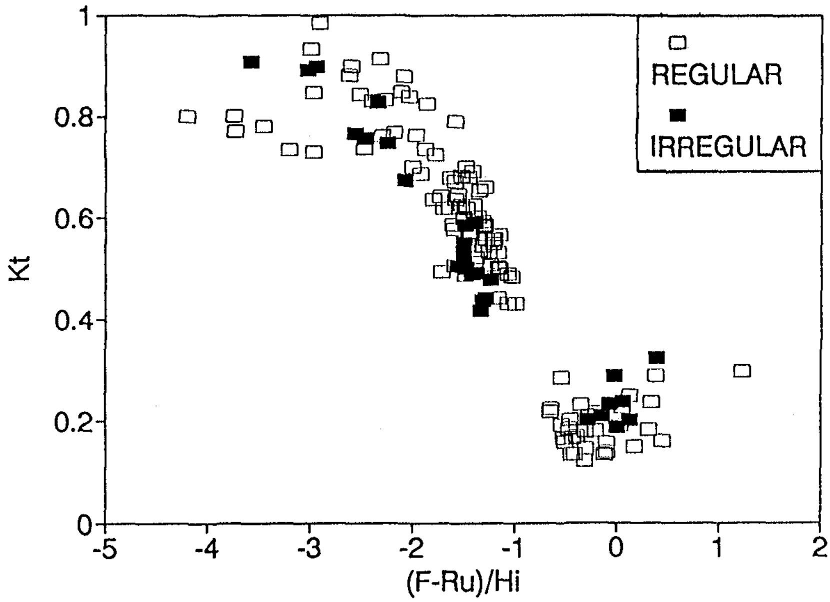

Figure 8. Transmission of regular and random seas past a rubble breakwater using new freeboard parameter.

Conclusions

In general, this study found that breakwater freeboard, incident wave height, and wave run up, as a measure of wave steepness and potential overtopping, are the primary parameters determining transmission past low-crested breakwaters. A new parameter, $(F-Ru)/H_i$ is proposed to describe the transmission characteristics of these structures. This parameter is able to spread the data for zero freeboard conditions, unlike the commonly used F/H_i parameter. In addition, solid breakwaters are shown to be a suitable approximation for transmission studies of rubble structures of values for $(F-Ru)/H_i < -0.4$; and, regular wave results are shown to be a suitable approximation of irregular waves of similar significant height and peak frequency. Finally, comparisons of solid impermeable breakwaters to very porous rubble-mound structures shows that there are observable differences in transmission, but that the Bulk Number does not seem to exert a large influence on the wave transmission characteristics.

Acknowledgments

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