ENERGY DISSIPATION CHARACTERISTICS OF ROCK ARMOURED RUBBLE MOUND BREAKWATERS

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ABSTRACT

The paper presents the results of large scale physical model investigations on the hydraulic performance of rock armoured rubble mound breakwaters. The energy dissipation characteristics of conventional trapezoidal layered breakwaters and berm breakwaters, both statically and dynamically stable are presented. The hydraulic performance of the structures are evaluated as a function of the incident wave parameters.

1. Introduction and objective of the paper

The failure, in the last two decades, of many large rubble mound breakwaters led to the careful examination of physical processes of wave-structure interaction. It is established that the interaction of waves with a rubble mound breakwater results in a complex flow pattern involving unsteady, two phase flow. Such flow generates equally complex force fields. Basic research findings have highlighted some of the related factors, which have contributed to the failures of rubble mounds. Such findings have led to the review of design procedures, development of new concepts and further examination of alternative design practices. This paper presents selected results of a detailed investigation on the hydraulic performance of a range of rock armoured breakwaters used in the design of harbours. The experimental programme, conducted using large scale physical models, was designed to investigate important aspects of the hydraulics of wave structure interaction of rubble mound breakwaters.

2. Classification of rock armoured rubble mound breakwaters

Rock armoured rubble mound breakwaters can be classified with respect to geometric configuration and stability of the principal armour. On the basis of geometric configuration are trapezoidal and berm structures. On the basis of stability are statically and dynamically stable structures.

The conventional sloping rubble mound breakwater generally consists of at least three main elements, namely, an armour layer of large stones, a core of small stones and one or more intermediate layers (under layers) which separate the core from the armour. This prevents finer material being washed out, an important requirement for stability and for restriction of wave transmission through the structure. The main armour is designed for limited damage and is statically stable (Figure 1a).

Sloping rubble mound breakwaters are very efficient with respect to wave energy dissipation. Two extremely effective mechanisms of wave energy dissipation are wave breaking and turbulent flow inside a porous medium. A porous sloping structure will cause most wind generated waves to break because of the decreasing water depth and the presence of a porous armour layer will contribute towards increased dissipation. However, this will result in certain levels of wave penetration into the structure.

Conventional multi-layered breakwaters designed to be statically stable may incorporate a berm or given a S-shaped profile in order to reduce wave forces, run-up and overtopping (Figure 1b). In effect it makes use of the hydraulic efficiency of a berm incorporated in a sloping structure. The presence of a berm in the form of a porous armour layer having a large bulk flow area will contribute towards increased energy dissipation. These structures are statically fully stable, designed to stay in place as built. The profile remains unchanged with only minor displacements of armour units.

A more recent development is the application of naturally reshaping mass armoured breakwaters which work in harmony with the flow field. This in practice is to construct a structure with a geometry and armour stone weight gradation which results in natural profile adjustment and subsequent minimisation of the applied hydrodynamic loadings. These structures are often called berm breakwaters due to the presence of a large berm of armour stones.

The design of a naturally reshaping berm breakwater is based on the concept that if the armour layers are built to significantly greater thickness than that of two stones used in the conventional design, much smaller stones are required to provide stable protection against wave action. The design also incorporates, to a certain degree, natural reshaping of the seaward profile during wave action (self adjusted profile). This provides the opportunity of using relatively smaller rocks because wave action will naturally optimize the profile to be the most resistant to wave action. If the mound is large enough to ensure stability and prevent erosion of the crest, then an S-shaped profile will develop as indicated in Figure 1c. This type of structure is classified as a dynamically stable structure. The 'built profile' becomes dynamically stable under wave attack and reshapes into a more statically stable profile. These structures are usually designed for non-overtopping.

If the stone size of the armour layer is gradually increased and if the thickness of the armour layer is still maintained significantly greater than that of the conventional design, the 'built profile' becomes statically stable from the very inception and its dynamic characteristics would be obviously less (Figure 1d).

Berm breakwaters have also been designed as statically stable structures of several stone classes with the aim to minimise stone movement, in contrast to the more frequently used dynamically stable design using only two classes of stone. The design is specifically aimed at optimising the structure with respect to wave load and possible yield from an armour stone quarry. Such breakwaters have been used in Iceland (Sigurdarson et al. 1998) and have been classified as 'Tailor made size graded berm breakwaters' (Figure 1e). It is clearly evident that the design focuses very heavily on optimisation of the estimated yield from the quarry.

3. Approach to the investigation

A breakwater is designed to dissipate wave energy with due attention focused on hydraulic, geotechnical and structural stability. The primary armour layer is designed to withstand the incident wave climate and extreme events without significant damage but with permissible levels of reshaping provided it is designed to accommodate such change of shape. The armour layer is expected to dissipate a significant proportion of the wave energy and in that process its voids matrix plays a vital role. The underlayers have to satisfy a number of specific demands including energy dissipation, the provision of a satisfactory foundation for the armour layer and the ability to act as filters to prevent core material from washing out through the voids in the armour layer. Included amongst the demands in the core is the provision of a satisfactory foundation for the underlayers and the primary armour and the ability to act as a relatively impermeable barrier to the transmission of wave energy.

When investigating the hydraulic performance of a breakwater with the view for improved design, the study of energy dissipation along the structure for varying incident wave climates provides important information of its effectiveness and efficiency. Such information could then be used to develop economical designs with due consideration given to hydro-geotechnical and structural stability as well as practical issues relating to construction and maintenance. Such information if available for a range of structures would also permit a very useful comparison leading to the identification of merits and demerits of different types of structures.

The use of physical models is the principal method for investigating experimentally the performance of breakwaters. Arising from the above discussion it is identified that, for a given structure, the most appropriate approach would be to study the wave energy dissipation at different sections, along its length, by obtaining information of the complete profile of the hydraulic performance for varying incident wave conditions. In this context it is necessary to obtain information of waves which are reflected and transmitted from the structure for the evaluation of the hydraulic profile and energy dissipation. Therefore attention has to be focused on achieving reliable estimates of wave reflection and direct measurements of wave transmission.

4. Relevance of large scale hydraulic models

The scale ratios which are usually adopted in investigating the stability of large rubble mound breakwaters are of the order of 1:30 to 1:60. These scale ratios, particular the smaller values lead to scale effects with respect to the flow field inside the breakwater. Therefore it is evident that the use of large scale physical models is essential to obtain reliable information. The fact that the actual permeability of the prototype rubble mound fill cannot be predicted due to factors such as segregation, settlement, variation in grading, supports the use of large scale physical models for these types of investigations.

5. Experimental Investigation

In order to achieve the objectives of the study two dimensional hydraulic model investigations were conducted on the following rock armoured structures.

1. Trapezoidal Layered Breakwater
   (statically stable) at scale 1 : 20

2. Trapezoidal Layered Breakwater with a Berm
   (statically stable) at scale 1 : 20

3. Reshaping Berm Breakwater
   (dynamically stable) at scale 1 : 36

4. Reshaping Berm Breakwater
   (dynamically stable) at scale 1 : 36
   This structure is of the same scale and shape to that of the third structure but with a correction factor applied to the weight of model primary armour to account for the use of fresh water in experiments.

Figure 2 illustrates the prototype breakwater cross-sections of the structures investigated.

Both regular and random waves were used for the studies for different still water depths. The still water depth has a notable influence on the hydraulic performance of structures which have a berm. The investigation was designed to obtain a complete profile of the hydraulic performance of the structures including the energy dissipation characteristics along its length with emphasis on the berm where applicable. Measurements of reflection (C_r), external transmission (C_{te}), internal transmission (C_{t1}, C_{t2} and C_{t3}), run-up (C_{ru}), run-down (C_{rd}) coefficients and observations on stability and overtopping were carried out for a range of incident wave conditions. Tables 1a, 2a, 3a and 4a summarise the incident wave conditions used for the different structures investigated. They illustrate the wide range of incident parameters with repect to wave period, wave height and water depth used for the study. Figure 3 illustrates the typical experimental set up adopted for the investigation. The tests were carried out by the authors in the wave flume at Lanka Hydraulic Institute (LHI), Moratuwa, Sri Lanka. The use of a relatively large scale ratio minimized the influence of scale effects with respect to flow inside the breakwater.

6. Discussion of results

Results presented in this paper in the form of figures and tables refer to the prototype structure. Where necessary, specific references are made to model dimensions and other parameters of the model. Tables 1b, 2b, 3b and 4b illustrate a summary of the energy dissipation characteristics corresponding to the sections at which wave transmission was measured by using probes inserted in highly porous tubes. The ratio E_d/E_i is presented as a percentage and gives a clear indication of the magnitude of energy dissipation at the respective sections.

Trapezoidal Layered Breakwater
(refer Tables 1a and 1b)

In the case of the rock armoured trapezoidal layered breakwater, three probes were used for transmission measurements. The first and second are within the structure and the third behind the structure. It is observed that for 6 sec waves, 79% - 92% of the energy is dissipated by the time the waves reach the first probe. This percentage reduces as the period increases, an observation which is of significance in understanding the response of structures to long period waves.

It is noted that when the still water depth is reduced the energy dissipation is higher which is mainly due to the increase in the effective length of the porous structure corresponding to the still water depth. In comparison at the shallower depth of 7 m the length of the structure at still water depth is longer by a distance of 4 m. Since significant wave action and thereby energy dissipation takes place in the vicinity of the mean water level, the increase in the length of the structure has a notable influence on the degree of energy dissipation.

Figures 4 and 5 illustrate the variation of transmission coefficients, (C_{t1}, C_{t2} and C_{te}) with steepness for regular waves. As the steepness increases, frictional losses which depend on velocity and as a consequence on wave height and wave period, increase resulting in lower amplitudes for the transmitted wave. Therefore the transmission coefficients decrease with increasing steepness. It is clearly evident that as the wave period increases the transmission coefficients increase. A detailed analysis also indicates that for a given wave height as the wave period increases, more wave energy is transmitted through the porous medium. A similar trend to that of regular waves is observed for random waves.

Reflection coefficients of the structure decreased with increasing steepness. There is a clear increase in the reflection coefficients with increasing period. In comparison, transmission coefficients display a more definite reliance on wave steepness. Reflection coefficients also display more scatter compared with transmission coefficients. This scatter may also be due to the rather complex technique which has to be used for the measurement of wave reflection, and this problem has been encountered by all researchers who have undertaken reflection measurements.

Further details of the investigation on the Trapezoidal Layered Breakwater are presented by Hettiarachchi and Mirihagalla (1999a).

<u>Trapezoidal Layered Breakwater with a Berm</u>
<u>(refer Table 2a and 2b)</u>

In the case of the rock armoured trapezoidal layered breakwater with a berm, four probes were used for transmission measurements. This was necessary to evaluate the performance of the berm. The first and second are at the beginning and at the end of the berm and the third is at the crest. The fourth is behind the structure, corresponding to external transmission. In the case of regular waves it is observed that for 6 and 8 second waves and for water depths of 7 m, 8 m and 9 m, the percentage energy dissipated by the time the waves reach the third probe at the crest is between 79% - 94%. This percentage reduces when the period increases to 12 seconds. For this period the percentage lies between 51%-83%. The energy dissipation is also lower when the water depth is 10 m. For this depth the still water level is 2 m above that of the berm and therefore the hydraulic efficiency of the berm is certainly at a lower level. It is observed from the results that the performance of the structure under random waves is very similar to that of under regular waves.

In comparing the performance of the structure at depths of 7 m and 8 m it is noted that transmission coefficients are lower for the latter indicating very clearly the influence of the berm, in particular the action of wave breaking and energy absorption on the berm. As the water depth was increased to 9 m and 10 m the internal transmission coefficients futher increased. It is important to note that at these two depths a partial standing wave, arising from reflections from the upper slope, is formed on top of the berm. In fact for the tests pertaining to 10 m depth, a crest wall too was installed and the wave envelope was influenced by the reflections from that wall. In all test conditions the external transmission coefficients were very low of the order of 10^{-4}. This indicates that a greater percentage of wave energy is dissipated inside the structure and the remainder is reflected.

Wave reflections for both regular and random waves displayed considerable scatter. This is mainly due to the fact that results represent widely varying incident wave conditions and varying geometry relating to wave structure interaction. The mechanics of energy dissipation is considerably different for the different water depths, thus leading to scatter. In general high reflection coefficients are observed for higher wave periods.

For both regular and random waves the influence of long period waves on energy absorption is very evident. The designers should be aware that energy dissipation can be considerably lower for long period waves for which condition wave transmission levels would be very high. From the results it is observed that the hydraulic efficiency of the structure is high corresponding to 8 m water depth which is equal to the height of the berm. For still water levels corresponding to the berm height or to a value which is marginally higher, it can be expected that the structure will perform at a high hydraulic efficiency.

It was observed that a high level of energy dissipation takes place by the time waves reach the third probe, by which stage the transmission coefficients are greatly reduced. Thereafter, these waves having a comparatively smaller height propagate through the remaining portion of the structure with marginal dissipation of wave energy. It is observed that since the transmission coefficients are smaller by the time the wave reaches the third probe, the portion of the structure beyond this probe is not fully utilised for energy dissipation. On the other hand, if waves of greater height reached the third probe, the remaining portion would be effectively utilised for energy dissipation. This aspect is evident to a certain extent in Figure 6, which illustrates the wave transmission along the structure plotted against the relative distance for still water depth of 7 m. The transmitted wave height range at the third probe for different wave periods are, 0.31 m to 0.66 m for T =12 secs, 0.23 m to 0.33 m for T=8 secs and below 0.13 for T = 6 secs. Figure 6 clearly shows effective dissipation for the highest wave height range which in this case corresponds to 12 sec wave period. In interpreting this figure it should be noted that energy dissipation is also dependent on the reflection coefficient for the given experimental condition.

The study of the energy dissipation characteristics along the structure identifies that the length of the structure could be reduced leading to the development of a more economical design with a shorter berm but having a hydraulic efficiency of the same order. By reducing the berm length it could be expected that waves having a higher transmission coefficient would reach the third probe. But the energy of such waves will be dissipated effectively by the portion of the structure beyond the third probe, as observed in Figure 6. The improved design would make use of the advantages of a berm in an economical manner while maintaining a high hydraulic efficiency.

Further details of the investigation on the Trapezoidal Layered Breakwater with a Berm are presented by Hettiarachchi and Mirihagalla (1999b).

Reshaping Berm Breakwater
(refer Tables 3a, 3b and 4a and 4b)

In the case of the reshaping berm breakwater, three probes were used for transmission measurements. The first is located on the slope above the berm, closer to the crest. The second is located at the rear end of the crest and the third is behind the structure, corresponding to external transmission. Tables 3a and 3b refer to the structure in which the linear scale ratio was used to scale the primary armour, the underlayers and the core.

A second structure of the same scale and shape but with a correction factor applied to the weight of the model primary armour, to account for the use of fresh water in experiments was also investigated. The correction factor demands the use of stones of smaller weight for the primary armour. Tables 4a and 4b refer to the second structure. The main purpose of this exercise was to study the influence of using a smaller primary armour on the stability and the hydraulics of wave-structure interaction, giving due consideration to the use of freshwater in the model.

In comparing the results of both structures it is evident that their performance was similar with respect to the measured hydraulic parameters and stability.

Figures 7 and 8 illustrate the variation of transmission coefficients with steepness for regular and random waves for the first reshaping structure. In the case of regular waves as the wave steepness increases transmission coefficients decrease and it is also observed that waves of high periods display high transmission coefficients. Although the external transmission coefficients are of the same order of magnitude for all conditions, the energy dissipation along the structure vary with steepness. For waves having a high steepness a significant amount of energy is dissipated by the time the wave reaches the first probe.

Figure 8 illustrate an important observation relating to the performance of long period waves of high magnitude. Attention is focused on the three points identified by T_p & H_s values of 15.1 sec & 2.61 m, 10.1 sec & 4.96 m and 12 sec & 7.29 m respectively. Although the third point is of high steepness the coefficient of transmission (C_{t1}) is very high. This indicates that for waves of high steepness arising from long period waves having a high amplitude the wave transmission coefficients are very high. The high steepness alone is not sufficient to reduce the transmission coefficient.

7. Conclusions

The paper has presented the results of three detailed model investigations on the hydraulic performance of rock armoured breakwaters. The structures included a conventional sloping layered breakwater and two berm breakwaters. Results from this investigation illustrate the wave decaying characteristics for a wide range of incident wave conditions using both regular and random waves.

Results indicate that by the time the waves reach the section corresponding to the crest, a significant component of energy is dissipated, in particular for waves having a small period. Energy dissipation decreases as the period increases with increasing external transmission coefficients. In general the transmission coefficients decrease with increasing steepness. However, it was observed that in the case of the reshaping breakwater, waves of high steepness arising from long period waves and having a high amplitude produced high transmission coefficients (C_{tl}) near the crest. This observation is of significance in understanding the response of the structure to long period waves. The comparison of results have identified the important function of a berm with respect to increased energy dissipation. It has also identified the importance of berm breakwaters as an alternative design to the conventional breakwater.

Results from this investigation indicate the effectiveness of both statically stable and dynamically stable (reshaping) berm breakwaters. For still water levels corresponding to the berm height or to a value which is marginally higher or lower, the structures perform at a high hydraulic efficiency making full use of the berm for energy dissipation. The fact that the design of naturally reshaping berm breakwaters are aimed at optimising the structure with respect to wave load and possible yield from an armour stone quarry is a very important advantage.

References

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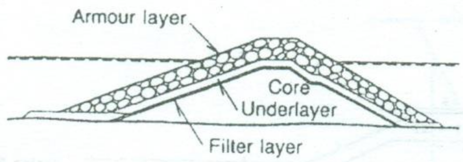


Fig. 1a Conventional multi-layered rubble mound breakwater (statically stable)

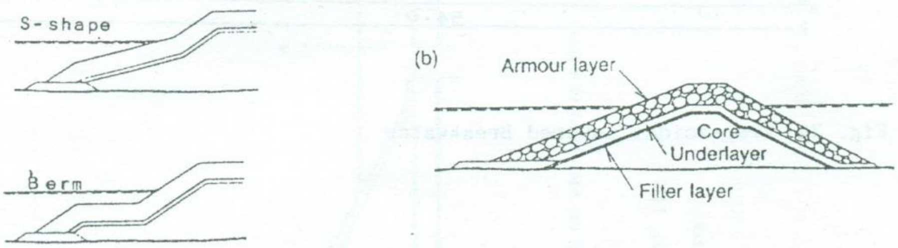


Fig. 1b Use of berm/S-shaped profile in a conventional multi-layered breakwater (statically stable)

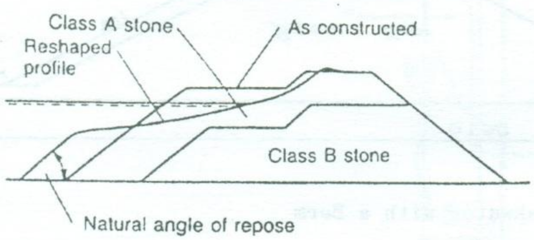


Fig. 1c Dynamically stable berm breakwater (two classes of stone)

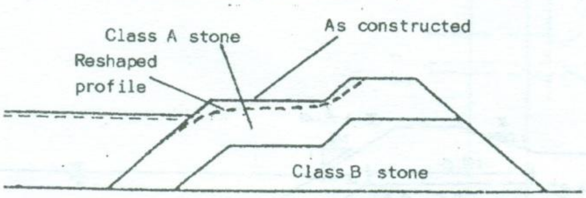


Fig. 1d Statically stable berm breakwater (two classes of stone)

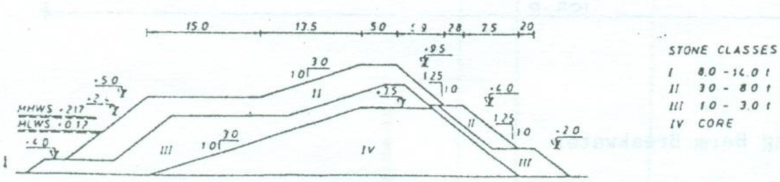


Fig. 1e Statically stable berm breakwater (several classes of stone)

FIGURE 1 Types of rock armoured rubble mound breakwaters

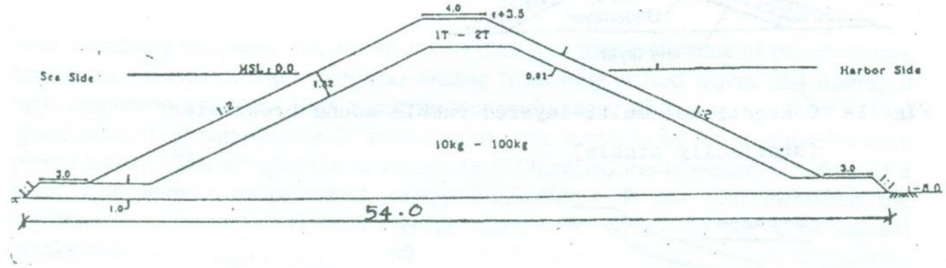


Fig. 2a Trapezoidal Layered Breakwater

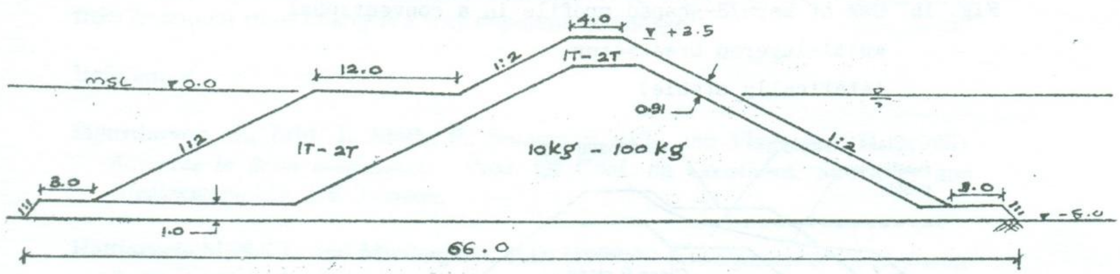


Fig. 2b Trapezoidal Layered Breakwater with a Berm

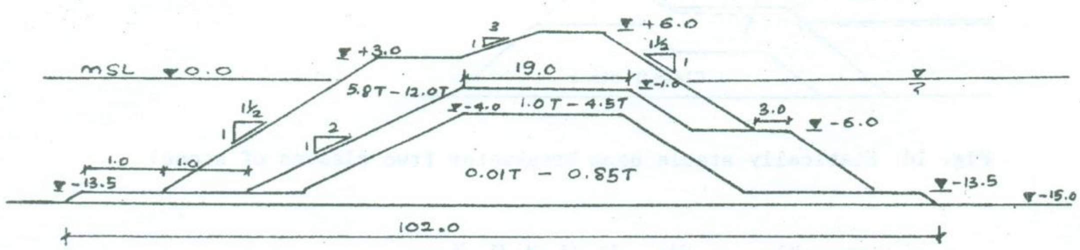


Fig. 2c Reshaping Berm Breakwater

FIGURE 2 Prototype breakwater across-sections of the structures investigated

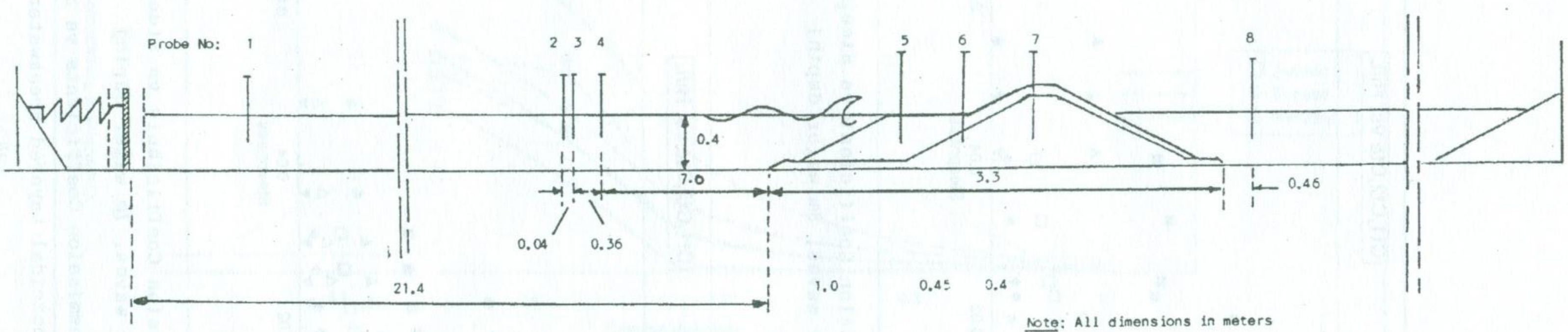


FIGURE 3 Experimental setup for 1:20 scale model of the Trapezoidal Layered Breakwater with a Berm

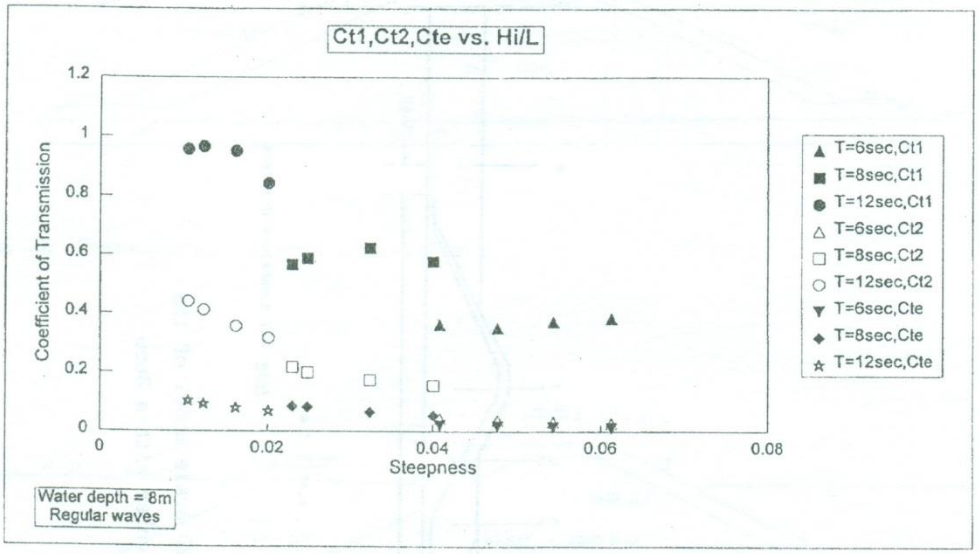


FIGURE 4 Transmission Coefficients vs Steepness (Regular waves, 8m water depth)

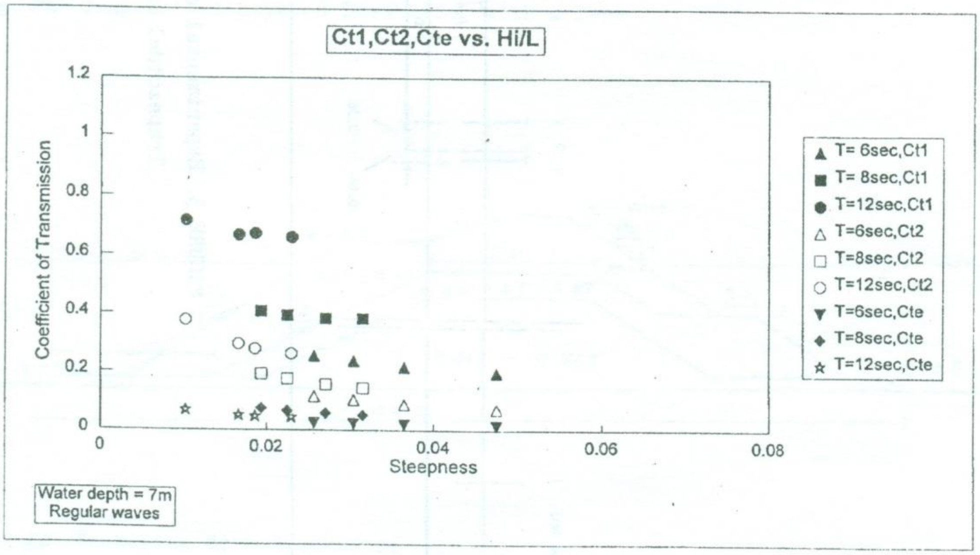


FIGURE 5 Transmission Coefficients vs Steepness (Regular waves, 7m water depth)

FIGURE 4 and 5 Transmission Coefficients vs Steepness for Trapezoidal Layered Breakwater

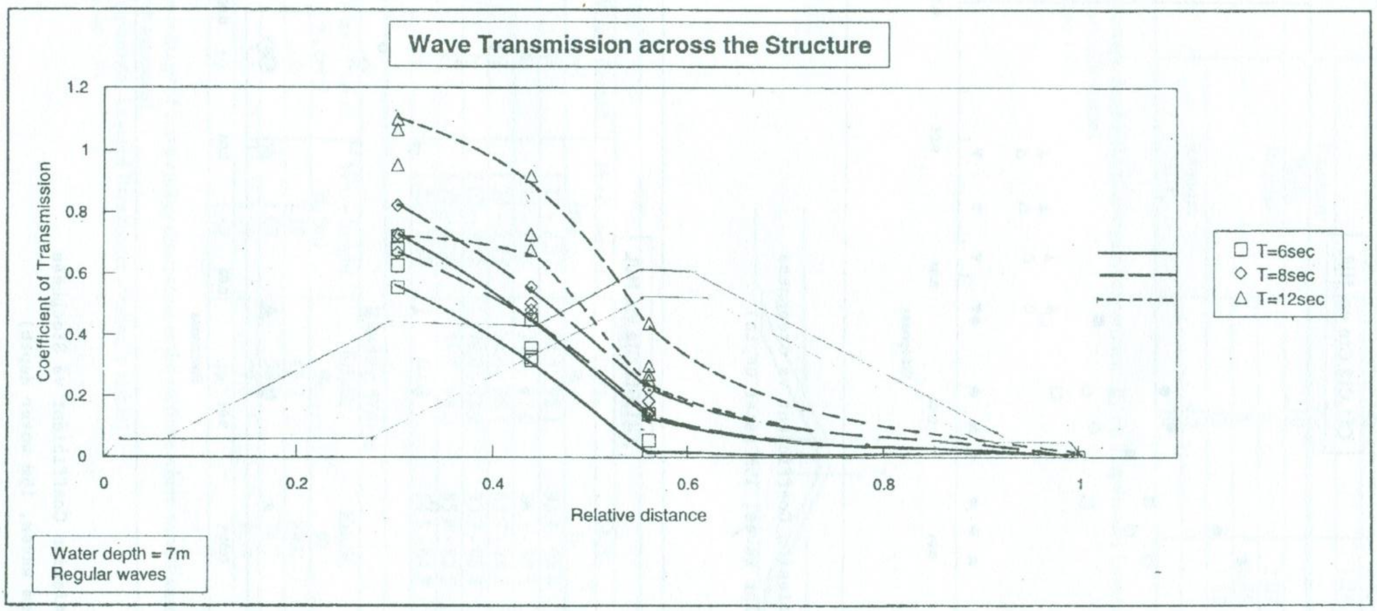


FIGURE 6 Wave Transmission across the Structure vs Relative distance for Trapezoidal Layered Breakwater with a Berm

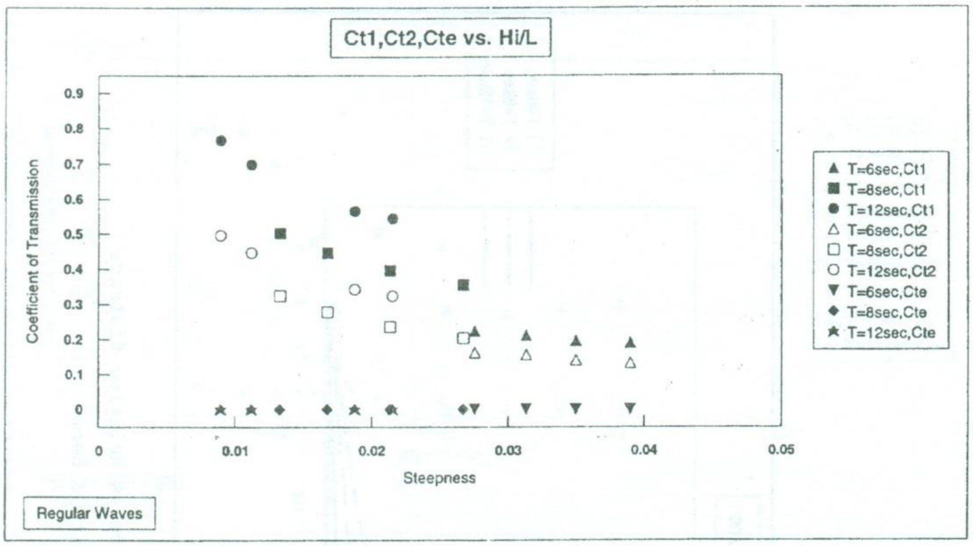


FIGURE 7 Transmission Coefficient vs Steepness
(Regular waves, 15m water depth)

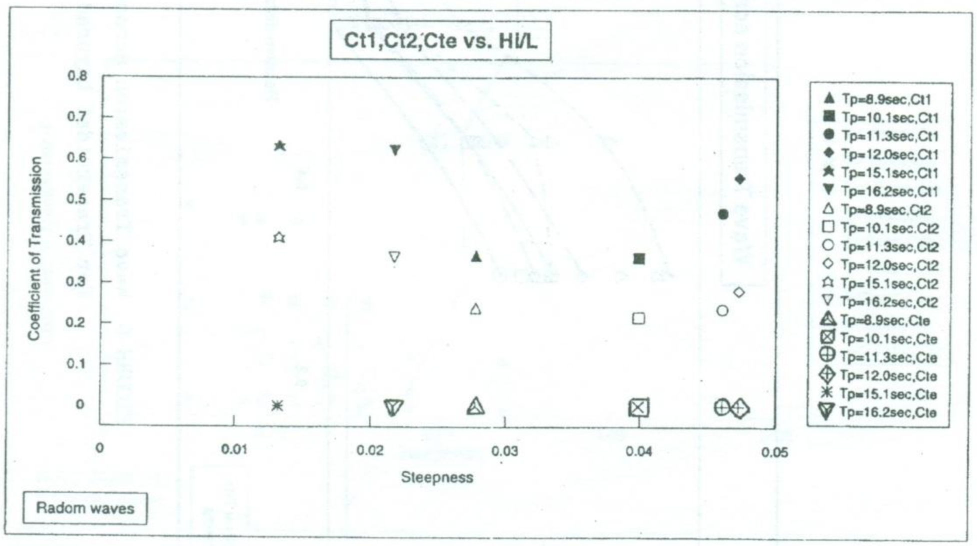
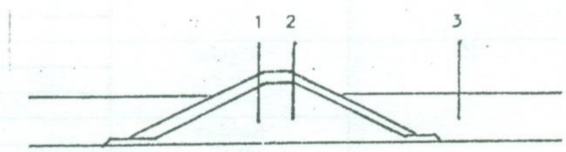


FIGURE 8 Transmission Coefficient vs Steepness
(Random waves, 15m water depth)

FIGURES 7 and 8 Transmission Coefficients vs Steepness
for Reshaping Berm Breakwater

Water Depth (m)	Type of Wave	Wave Period (sec)	Wave Height (m)
7	Regular	6	1.27, 1.51, 1.82, 2.37
		8	1.43, 1.65, 1.99, 2.33
		12	1.24, 2.00, 2.24, 2.75
	Random	6.5	2.19
	H_s ,T_p	10	1.68
8	Regular	6	2.07, 2.42, 2.76, 3.12
		8	1.75, 1.88, 2.46, 3.06
		12	1.32, 1.55, 2.02, 2.49
	Random	6.5	2.29
	H_s ,T_p	10	1.67

TABLE 1a : Prototype conditions investigated experimentally on Trapezoidal Layered Breakwater (Statically stable)
Scale 1:20



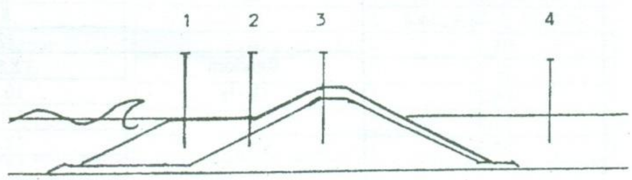
Water depth (m)	Regular Waves				
	Wave Period (sec)	**Wave height (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
7	6	1.27 – 2.37	88.3 - 92.1	93.4 - 95.6	94.6 - 96.4
	8	1.43 – 2.33	74.4 - 77.0	87.3 - 89.5	90.0 - 91.3
	12	1.24 – 2.75	26.6 - 38.1	63.7 - 74.7	77.4 - 81.3
8	6	2.07 – 3.12	79.0 - 83.2	93.7 - 95.4	93.7 - 95.6
	8	1.75 – 3.06	51.5 - 58.2	85.6 - 88.5	89.1 - 90.7
	12	1.32 – 2.49	0.68	54.5 - 61.8	69.1 - 72.9

Water depth (m)	Random Waves				
	Wave Period T_p (sec)	**Wave height H_s (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
7	6.5	2.19	83.7	89.0	90.3
	10	1.68	58.2	74.7	80.4
8	6.5	2.29	77.0	90.9	92.5
	10	1.67	49.7	79.5	86.6

TABLE 1b : Percentage of wave energy dissipation at the sections where wave transmission was measured.
Trapezoidal Layered Breakwater (Statically stable)
Scale 1:20

Water Depth (m)	Type of Wave	Wave Period (sec)	Wave Height (m)
7	Regular	6	0.89, 1.38, 1.96, 2.37
		8	1.04, 1.40, 2.11, 2.39
		12	0.71, 1.46, 1.90, 2.60
	Random H_s, T_p	4	1.39
		6	1.64
		8	1.86
		10	1.94
8	Regular	6	0.92, 1.15, 1.76, 2.26
		8	1.22, 1.59, 2.11, 2.91
		12	0.86, 1.49, 1.79, 2.59
	Random H_s, T_p	4	1.23
		6	1.65
		8	1.83
		10	1.92
9	Regular	6	1.00, 1.54, 2.01, 2.53
		8	0.96, 1.93, 2.39, 2.94
		12	1.04, 1.22, 1.60, 2.11
	Random H_s, T_p	4	1.25
		6	1.65
		8	1.85
		10	1.94
10	Regular	6	0.89, 1.86, 2.79, 3.88
		8	1.11, 2.26, 3.18, 3.93
		12	0.71, 1.51, 2.00, 2.81
	Random H_s, T_p	4	1.40
		6	1.77
		8	1.90
		10	1.95

TABLE 2a : Prototype conditions investigated experimentally on Trapezoidal Layered Breakwater with a Berm.
(Statically stable)
Scale 1:20



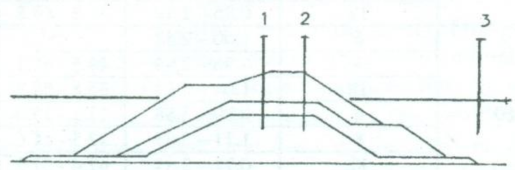
Water depth (m)	Regular Waves					
	Wave Period (sec)	Wave height (m)	Ed_1/E_i %	Ed_2/E_i %	Ed_3/E_i %	Ed/E_i %
7	6	0.89 – 2.37	39.5 - 63.4	71.3 - 85.0	89.6 - 94.8	91.6 - 95.1
	8	1.04 – 2.39	22.3 - 48.1	58.8 - 71.3	84.8 - 90.7	89.7 - 92.7
	12	0.71 – 2.60	37.74	31.3 - 44.7	63.9 - 83.9	83.2 - 90.4
8	6	0.92 – 2.26	42.2 - 74.1	77.6 - 83.8	93.4 - 94.7	95.2 - 97.4
	8	1.22 – 2.91	42.9 - 75.3	62.9 - 75.9	87.0 - 93.4	93.7 - 96.0
	12	0.86 – 2.59	42.2 - 69.8	3.4 - 50.6	56.1 - 62.9	87.0 - 89.7
9	6	1.00 – 2.53	3.3 - 51.0	61.2 - 80.6	88.8 - 91.2	97.1 - 98.0
	8	0.96 – 2.94	19.5 - 65.1	22.2 - 71.5	79.7 - 85.2	96.0 - 97.1
	12	1.04 – 2.11	36.8 - 59.3	8.7	51.7 - 57.3	91.0 - 93.2
10	6	0.89 – 3.88	13.4 - 17.0	53.2 - 86.4	68.6 - 87.6	93.7 - 98.0
	8	1.11 – 3.93	32.3 - 65.6	22.3 - 71.6	55.1 - 83.0	91.6 - 93.7
	12	0.71 – 2.81	42.4 - 57.5	8.5	26.5 - 54.6	89.1 - 92.7

Water depth (m)	Random Waves					
	Wave Period T_p (sec)	Wave height H_s (m)	Ed_1/E_i %	Ed_2/E_i %	Ed_3/E_i %	Ed/E_i %
7	4	1.39	75.3	89.3	93.5	93.7
	6	1.64	56.8	80.6	91.9	93.2
	8	1.86	39.0	71.7	91.6	91.6
	10	1.94	26.3	62.1	89.1	89.1
8	4	1.23	76.9	90.1	96.5	97.1
	6	1.65	64.0	80.1	94.4	97.4
	8	1.83	54.0	69.5	93.2	96.7
	10	1.92	51.0	55.8	83.6	94.7
9	4	1.25	53.2	71.0	91.7	96.4
	6	1.65	33.3	62.2	89.7	97.4
	8	1.85	37.9	49.1	84.9	96.7
	10	1.94	42.7	34.6	79.0	95.6
10	4	1.40	38.9	53.4	86.2	95.2
	6	1.77	17.5	54.4	79.6	96.0
	8	1.90	22.8	44.9	80.7	94.7
	10	1.95	29.5	27.4	58.1	93.2

TABLE 2b : Percentage of wave energy dissipation at the sections where wave transmission was measured.
Trapezoidal Layered Breakwater with a Berm. (Statically stable)
Scale 1:20

Water Depth (m)	Type of Wave	Wave Period (sec)	Wave Height (m)
15	Regular	6	1.52, 1.72, 1.92, 2.15
		8	1.18, 1.49, 1.91, 2.39
		12	1.38, 1.72, 2.89, 3.32
	Random H_s ,T_p	8.9	2.90
		10.1	4.96
		11.3	6.59
		12.0	7.29
		15.1	2.66
		16.2	4.73

TABLE 3a : Prototype conditions investigated experimentally on Re-shaping Berm Breakwater. (Dynamically stable)
Scale 1:36



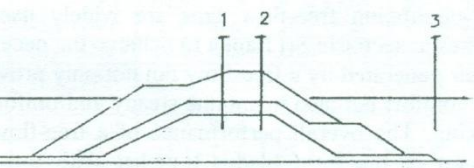
Water Depth (m)	Regular Waves				
	Wave Period (sec)	**Wave Height (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
15	6	1.52 - 2.15	87.1 – 89.6	89.5 – 91.5	92.1 – 93.2
	8	1.18 - 2.39	62.4 – 77.1	77.2 – 85.6	87.7 – 89.8
	12	1.38 - 3.32	25.3 – 50.1	59.3 – 69.3	79.7 – 84.0

Water Depth (m)	Random Waves				
	Wave Period T_p (sec)	**Wave Height H_s (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
15	8.9	2.90	74.9	82.6	88.4
	10.1	4.96	73.2	81.6	86.3
	11.3	6.59	60.7 – 66.4	76.9 – 82.2	83.2 – 86.3
	12.0	7.29	52.2	75.2	83.2
	15.1	2.66	34.9	58.1	75.0
	16.2	4.73	36.2	61.7	75.0

TABLE 3b : Percentage of wave energy dissipation at the sections where wave transmission was measured.
Re-shaping Berm Breakwater. (Dynamically stable)
Scale 1:36

Water Depth (m)	Type of Wave	Wave Period (sec)	Wave Height (m)
15	Regular	6	1.58, 1.87, 2.22, 2.46
		8	1.16, 1.43, 1.87, 2.31
		12	1.65, 2.04, 2.76, 3.29
	Random H_s ,T_p	4	1.10
		6	1.48
		8	1.63
		10	1.75
		11.3	6.69

TABLE 4a : Prototype conditions investigated experimentally on Re-shaping Berm Breakwater. (Dynamically stable)
Scale 1:36
[Correction factor applied to the weight of model armour to account for the use of fresh water in experiments]



Water Depth (m)	Regular Waves				
	Wave Period (sec)	**Wave Height (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
15	6	1.58 – 2.46	87.5 – 91.2	88.1 – 91.4	90.4 – 92.7
	8	1.16 – 2.31	74.8 – 83.8	78.6 – 86.0	87.7 – 89.7
	12	1.65 – 3.29	54.6 – 61.3	64.7 – 68.2	76.0 – 79.7

Water Depth (m)	Random Waves				
	Wave Period (sec)	**Wave Height (m)**	**Ed_1/E_i %**	**Ed_2/E_i %**	**Ed/E_i %**
15	4	1.10	88.4	89.1	89.7
	6	1.48	86.6	87.5	91.0
	8	1.63	79.6	82.2	89.2
	10	1.75	72.0	76.7	87.0
	11.3	6.69	70.5 – 73.1	77.9 – 80.4	84.0 – 86.3

TABLE 4b : Percentage of wave energy dissipation at the sections where wave transmission was measured.
Re-shaping Berm Breakwater. (Dynamically stable)
Scale 1:36
[Correction factor applied to the weight of model armour to account for the use of fresh water in experiments]