WAVE ACTION ON SUBMERGED BREAKWATERS

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1.0 Introduction

A submerged breakwater is a barrier which is constructed so that its top is at, or slightly below, the still water surface. This type of structure absorbs some of the incident wave energy by causing waves to break over the crest prematurely. Some of the remaining energy is reflected and some transmitted shorewards.

Submerged breakwaters are usually less costly to construct and maintain than the conventional type of breakwater. In many locations, submerged breakwaters offer a feasible solution to coastal engineering problems. Where complete protection from waves is often neither necessary nor desirable, submerged breakwaters are used to control wave action at inshore locations, to reduce the rate of littoral drift, to protect eroding beaches, to protect harbour entrances, etc. But in localities where the tidal range is appreciable, an underwater structure might be relatively ineffective during high tides. Further, during low tides, the top of the structure will be above the still water level and the structure would therefore act as a conventional type breakwater, and would be subjected to larger wave forces than it would otherwise have to withstand. Therefore, submerged breakwaters are best suited for localities where the tidal range is relatively low.

This type of breakwaters are constructed of steel sheet piling, natural rock or concrete armour units. In certain instances, natural reefs and sand bars act as underwater structures.

The concept of submerged breakwaters will be viable economically against beach erosion and problems created by rising sea level due to global warming at locations with a low tidal range. Therefore this is an appropriate application for island states like Sri Lanka and Maldives, where the tidal ranges are low and where natural coral reefs, which can be modified as underwater structures, exist in some localities along the coast-line.

Even though at present submerged breakwaters are increasing in popularity, the theoretical behaviour of such structures is not completely understood. A preliminary review of literature identified that there is no substantiated body of theoretical or experimental work to facilitate a reliable or safe design. Most applications have been designed on an experimental basis. The most reliable quantitative data available on the influence of submerged breakwaters on wave action are those which have been obtained in laboratory model studies. In these studies, a wide variety of types of structures have been investigated.

2.0 Objectives of the paper

The principal objective of this paper is to review the important investigations conducted on wave action on submerged breakwaters and to identify areas which need further investigations. This paper reviews theoretical and experimental work which have been conducted in the last three decades and attention is focused on important findings which have an impact on the design of submerged structures. A summary of the review is presented in Table 1, which identifies the researchers, the methods of investigation and the types of structures investigated.

3.0 Review of previous investigations

A theoretical treatment on the change in wave height after waves passed over a reef is given by Lamb (1945). Other theoretical work included wave action over submerged rectangular barriers by Jeffreys (1944), which gives a mathematical expression for the transmission coefficient for solid rectangular under water barriers:

Dean (1945) studied the case of a thin rigid sumberged barrier extending from the bottom of the sea to a distance 'h' beneath the still water level, in infinitely deep water. Dean found that the transmission coefficient H_t/H_i to be a function of h/gT^2 (which is also a function of h/L_0). Wiegel (1964) suggested a theoretical expression for the transmission coefficient which is a modification of that developed by Jeffreys for finite water depth, and given by the equation

$$\frac{H_t}{H_i} = \sqrt{1 - \frac{\dfrac{4\pi\left(\frac{y+d}{L}\right)}{\sinh\left(\frac{4\pi d}{L}\right)} + \dfrac{\sinh 4\pi\left(\frac{y+d}{L}\right)}{\sinh\left(4\pi\frac{d}{L}\right)}}{1 + \dfrac{\frac{4\pi d}{L}}{\sinh\left(\frac{4\pi d}{L}\right)}}}$$

In early investigations on the performance of the submerged breakwaters, the Beach Erosion Board (1940) reported on the damping effects of submerged vertical walls and barriers with rectangular, triangular and trapezoidal cross sections. Morison (1949) investigated wave action over rectangular barriers. In all these cases, the experiments were two dimensional models, where the wave crests were parallel to the barrier axis.

In addition to the above investigations, model studies have also been done on wave action over various idealized reefs (Beach Erosion Board - 1944). Generally three major types of reefs have been investigated.

(i) An abrupt discontinuity followed, shorewards by a horizontal shelf.

(ii) An abrupt discontinuity followed shorewards by a uniformly shoaling bottom.

(iii) An abrupt discontinuity followed by a horizontal shelf, a depression and a continuation of the horizontal shelf.

The above structural forms are illustrated in Figure 1. These experiments were concerned primarily with the change in the wave length after waves passed over the reef's seaward edge. No information was given on the reduction in wave height in similar circumstances.

Johnson, Fuchs and Morison (1951) carried out a series of model tests to determine the general effectiveness of rectangular submerged breakwaters in reducing wave action, using a one foot wide wave channel. The variables of these tests were the depth of still water, the height and width of the barrier, wave length and wave height. Various dimensionless parameters were used to represent the relationship between the transmission coefficient and the other variables. Figures 2, 3 and 4 represent the data obtained by Johnson, Fuchs and Morison.

According to the experimental data it was concluded that a barrier of a given relative height h/d where h = barrier height and d = still water depth, is more effective in damping relatively steep waves than relatively less steep waves; this is to be expected since, a wave near the critical steepness for breaking can easily be made to break by an external disturbance. It was also concluded that the effect of steepness is relatively diminished when the top of the barrier is at or slightly above the still water level. This conclusion was also established theoretically by Jeffreys (1944) for waves of small amplitude in shallow water. The theoretical relationship established by Jeffreys is plotted in Figure 5 with the transmission coefficient H_t/H_i shown as a function of the relative barrier height h/d and various selected barrier widths, W/L.

These results led to an interesting conclusion that the most effective damping action for a particular barrier height and still water depth occurs when the width of the barrier is L/4, 3L/4, 5L/4 ...... times $(1 - h/d)^{1/2}$. Another finding was that the damping effect is greater when the barrier width becomes large and the relative depth becomes small. This conclusion appears reasonable and might be predicted qualitatively if it is recognised that a larger percentage of wave energy is concentrated in the upper layers of the depth for higher d/L values than for lower. Hence, such energy can be spilled over the top of the barrier more easily than when the energy is more uniformly distributed throughout the depth. Finally, Johnson, Fuchs and Morison showed a fairly good agreement between theory and experimental results for small amplitude waves (waves of low steepness) but for steeper waves the assumptions underlying theoretical investigations are no longer valid.

Costa and Perestrelo (1959) identified one of the performance criteria of submerged breakwaters as that of utilisation of refraction in a manner to concentrate wave energy in an area where it is not harmful and to cause an associated area of low density where necessary. Mobarek (1962) showed that the conclusions of Costa and Perestrelo are essentially valid.

Dick and Brebner (1968) re-examined the behaviour of submerged breakwaters by experiments aimed at finding the transmission and reflection coefficients for solid rectangular and thin submerged breakwaters. The experiments were extended to both permeable as well as impermeable submerged breakwaters. The concept of equivalent wave height was used to define the transmitted waves. The total transmitted wave energy is represented by a wave having the same frequency as that of the incident wave and was defined by

$$H_{eq} = \frac{2\sqrt{2}}{T} \int_0^T \eta^2(t)\, dt \qquad 2)$$

where
T = incident wave period in seconds
η = water surface displacement from mean water level in feet
t = the time coordinate

The transmission coefficient was then defined as

$$C_T = \frac{H_{eq}}{H_i} \qquad 3)$$

where H_i = incident wave height

This procedure gives a clear implication that the frequency of the transmitted waves is not equal to that of the incident wave. The experimental results for transmission and reflection coefficients for thin submerged breakwaters in infinitely deep water were in good agreement with Dean's theory as shown in Figure 6. For general cases of thin submerged breakwaters, it was found that for large wave numbers, $kh > 3.14$ (where k = wave number and h = still water depth), Dean's theory performed well but for small wave numbers, $kh < 0.35$, Ogilvie's theory was better. The intermediate zone remains unknown and a suggested trend for that zone is shown in Figure 7. The deviations between the experimental results and theoretical values were assumed to be due to energy losses at the breakwater.

The analytical results obtained for reflection and transmission coefficients of submerged breakwaters are shown in Figures 8 and 9. These results show a considerable scatter. In this case since the transmitted wave field was quite complicated, the transmitted wave energy was evaluated using the equation 2. This is a considerable simplification of the actual situation. Finally it was concluded that for solid rectangular breakwaters, maximum reflection occurs when the incident wave has the same period as a standing wave on top of the breakwater and with a wave length equal to the crest width of the barrier. At least 50% of incident wave energy was found to be lost due to the wave breaking over the crest of the submerged breakwater. It was also found that 30% - 60% of the energy transmitted is transferred to frequencies higher than the incident wave frequency.

Nakamura, Shiraishi and Sasaki (1972) studied the wave damping effects of sumberged dikes. From experimental studies it was observed that submerged dikes damp considerably waves of high amplitude while waves of comparatively smaller amplitude pass freely over them. It was also found that the incident wave was apt to break with an enlargement of the width of the dike. The transmission coefficient H_t/H_i was calculated by comparing the incident and transmitted wave heights and the final conclusions were :

(i) dissipation of wave energy through the submerged breakwater is mainly caused by reflection and breaking.

(ii) when the waves passed over a submerged dike without breaking, the wave damping is mainly affected by reflection and friction.

(iii) the transmission coefficient is more affected by the height of the submerged dike and the depth of water on the dike crown than by its width.

Dattatri, Raman and Shanker (1978) conducted comprehensive laboratory investigations to evaluate performance characteristics of submerged breakwaters of various types and shapes, both permeable and impermeable. The equivalent wave height concept of Dick and Brebner was used to evaluate the transmission coefficient. A dimensional analysis was carried out to study wave transmission characteristics.

Consequent to this study it was discovered that th steepness of incident waves has an important influence on the wave-breaking phenomenon and that waves near the critical steepness rather than flatter waves could be induced to break by submerged structures. This was in agreement with the findings of Johnson, Fuchs and Morison and also with that of Dick and Brebner. It was found that the depth of submergence of the breakwater plays a significant role in wave transmission and a relative submergence greater than 0.4 was not likely to be of any practical significance in wave damping. An attempt was also made to determine the influence of the width of the breakwater on transmission characteristics and wave breaking. It was concluded that in the case of submerged breakwaters with very small crest widths, even the waves which have limiting steepness for breaking do not break because they enter relatively deep water quickly after passing the crest before the breaking action is initiated. Therefore it was concluded that an increase in crest width over the minimum necessary to trigger breaking is unlikely to have any influence of transmission characteristics, which agrees with the findings of Nakamura, Shiraishi and Sasaki.

Unlike many others Dattatri, Raman and Shanker extended experiments to ascertain the influence of shape and slope of submerged breakwaters on transmission characteristics. From these investigations it was found that the shape and slope has no significant influence on transmission characteristics. However, for rectangular submerged breakwaters problems arise due to standing wave formation in front of the structure as a result of reflection, and also due to scour problems. The effect of permeability of the structure on wave transmission was also investigated and it was found that the behaviour of a permeable structure was quite similar to that of an impermeable one, an observation which is in contrast with the findings of Dick and Brebner.

In addition to the above investigations, a spectral analysis was carried out for some of the transmitted waves; this showed that the transmitted waves were a system of harmonics with a fundamental frequency equal to that of the incident wave. It was also found that the energy content of the higher harmonics was considerably less than that corresponding to the fundamental frequency. Thus it was concluded that transmitted waves have the same fundamental frequency as the incident wave, but a part of the energy is transmitted to higher frequencies. This conclusion agreed well with that of Dick and Brebner.

Khader and Rai (1980) who performed a series of experiments on impermeable submerged structures observed the existence of a critical value of relative height (height of structure/water depth) for each of the structures. Its value varied from 0.43 to 0.66. For values less than the critical value the structure was not effective in damping waves. As the relative height increased the damping effect increased significantly. It was also observed that a relatively wide barrier exhibited better damping characteristics than a narrower one and of the shapes investigated, the rectangular cross-section breakwater, was the most effective.

The performance of low crest rubble mound breakwaters which at its extreme could be considered as a form of submerged structures has been investigated by Allsop and Ojo (1982) and Allsop (1983). Rock armoured low crest rubble mound breakwater sections were investigated in random waves. Observations and measurements were made of the number of overtopping waves, the transmitted waves and of the damage to the armour in both front rear slopes of the breakwater. Allsop identified the importance of several pre-board parameters in relation to overtopping and subsequent damage.

Mason and Keulegan (1944) in one of the early research studies investigated the profiles of waves passing over rectangular reefs. Unlike many others, attention was directed to transformed wave characteristics rather than reflection or transmission coefficients. The studies developed a criterion for the regular passage of waves over a reef (that is without forming multiple crests) and this criterion was given as

$$(H_i L_i)^{\frac{1}{2}} \leq 2C_b \qquad 4)$$

where
H_i = incident wave height
L_i = incident wave length
C_b = water depth over the reef

Horikawa and Wiegel (1959) verified the criterion of Mason and Keulegan. Investigations were carried out for various wave characteristics and still water depths for possible multiple crest formations with channels having no bottom discontinuities.

McNair (1970) focussed attention on the characteristics of monochromatic wave breaking over a submerged bar and noted that the broken waves regrouped into a complex wave form. Applying power spectral analysis, it was found that the reformed wave has a fundamental period equal to the period of the incident wave. It was also noted that these complex waves resulted from steep waves that passed over the bar without breaking.

In further investigations on submerged breakwaters, Jolas and Byrne (1969) conducted laboratory investigations on multiple wave crests. Madsen and Mei (1969) focused attention to the transformation of a solitary wave over an uneven bottom using both numerical and experimental techniques, for wave height to still water depth ratios 0.1 to 0.2. Some of the transformed waves closely resembled cnoidal or even possibly sinusoidal waves rather than solicitary waves. Galvin (1970) found that periodic sinusoidal waves of finite amplitude generated in constant depth to shallow water break into two or more waves, travelling at speeds independent of their heights; these were termed "solitons". Experiments were carried out over a very wide range of still water depth to wave length and wave height to still water depth ratios. The results obtained in these experiments are shown in Figure 10.

Pierce, Chandler, Robert and Sorenson (1972) investigated the transformation of non-breaking waves over a submerged long-shore bar. Waves reaching the shore with considerable height and steepness remove material from the beaches and deposit them some distance away form the shore line, creating long-shore bars. Water depths over these bar formations are often reduced to the point that waves passing over the bar begin to shoal and their steepness increases. Shoreward of the bar in the deeper water of the trough, waves decrease in steepness and transmit shoreward the energy that was not reflected or expended in their passage over the bar. The waves appearing on the shoreward side of the bar had noticeably shorter period components superposed on the fundamental wave form. Therefore these long-shore bars have characteristics similar to those of submerged breakwaters or natural submerged reefs.

Pierce, Chandler Robert and Sorenson designed laboratory experiments to investigate the characteristics of gravity water waves passing over a submerged long-shore bar. The incident and transformed waves thus obtained are shown in Figure 11. After a spectral analysis of both the incident and transformed waves the results of the experiments defined an envelope of transformation as shown in Figure 12 which is somewhat similar to soliton wave appearance defined by Galvin. The phenomenon of wave transformation was considered to be due to the generation of non-linear wave forms in the passage of the incident waves over the bar. It was also found that in deeper water, on the shoreward side of the bar, the non-linear wave changes to a sinusoidal form. The actual alteration of the wave profile over the bar was found to agree closely with the results of Madsen and Mei on the transformation of solitary waves.

Kobayashi (1989) developed a numerical model to predict monochromatic wave reflection and transmission over a submerged impermeable breakwater. The computed transmission and reflection coefficients are shown to be in agreement with available small scale test data. The numerical model also predicts the special variation of the energy dissipation, the mean water level, etc.

The US Army Corps of Engineers (1990) undertook a laboratory study on macro-features of wave breaking over bars and artificial reefs. A large number of experiments was conducted on this subject and it was concluded that waves break differently on reefs and barriers compared to a plain slope; wave breaking properties such as breaker index and plunge distance also change. Equations were developed incorporating seaward bar or reef angle and deep water wave steepness for describing the breaking process.

4.0 Concluding remarks

This paper has reviewed important investigations both theoretical and experimental on the performance of submerged coastal structures. The submerged structures include, typical breakwaters, reefs and bars. The important findings from these investigations have been presented.

Most of the work done by different researchers on the subject of wave transmission over submerged breakwaters has been limited to non-breaking waves and greater emphasis has been placed on parameters such as transmission and reflection coefficients. The available theoretical expressions for those parameters are also valid for non-breaking waves over the submerged breakwater. Researchers have not succeeded in establishing a sound theoretical formulation to explain the transmission of breaking waves over submerged breakwaters.

Various theoretical and experimental investigations prove that a substantial amount of wave energy is lost after waves pass over submerged breakwaters or reefs. These energy losses have been found to be as a result of wave transformation processes such as reflection, refraction and bed friction. Even though most of the available data refer to non breaking waves, the fundamental characteristics of wave action over submerged structures should be applicable for breaking waves. An additional amount of energy losses will take place due to wave breaking and this has to be taken into consideration. Investigations on wave re-formation in the shoreward side of such a structure also indicate that transmitted waves regroup in to individual crests of cnoidal, solitary and sinusoidal waves having a lesser energy content.

This review clearly indicated that there is no clear theoretical formulation for the energy reduction process resulting from wave action over submerged structures. Hydraulic model studies are thus recommended in the design of such structure for which hydraulic model study results are not available. There is a strong demand for further theoretical work supported by detailed experimental invetigations. Such a study would no doubt enhance the reliability of the design and the applicability of this type of structure.

Table 1 - SUMMARY OF PREVIOUS INVESTIGATIONS

Researcher	Type of investigation	Types of structures
Beach Erosion Board	Experimental	Submerged reefs,
Jeffreys (1944)	Theoretical	Solid rectangular submerged barriers
Mason and Keulegan (1944)	Theoretical	Rectangular submerged reefs
Lamb (1945)	Theoretical	Submerged reefs
Dean (1945)	Theoretical	Thin rigid submerged barriers
Morison (1949)	Experimental	Submerged rectangular barriers
Johnson, Fuches and Morison (1951)	Experimental	Rectangular submerged breakwaters
Horikawa and Wiegel (1959)	Experimental	Rectangular submerged reefs
Wiegel (1964)	Theoretical	Thin rigid submerged barriers
Dick and Brebner (1968)	Experimental	Thin and rectangular submerged breakwaters of both permeable and impermeable
Jolas and Byrne (1969)	Experimental	Submerged reefs

Researcher	Type of investigation	Types of structures
Madsen and Mei (1969)	Numerical Experimental	Uneven bottom formations
McNair (1970)	Experimental Analytical	Submerged bars
Galvin (1970)	Experimental	Waves breaking in shallow water
Nakamura, Shiraishi and Sakaki (1972)	Experimenatl	Submerged dikes
Piers, Chandler, Robert and Sorenson (1972)	Experimental Analytical	Submerged longshore bars
Dattatri, Raman and Shanker (1978)	Experimental Analytical	Thin, Rectangular, Triangular and Trapezoidal breakwaters of both permeable and impermeable.
Khader and Rai (1980)	Experimental	Impermeable submerged structures
Allsop (1983)	Experimental	Low-crest rubble mound breakwaters
Kobayashi (1989)	Numerical	Submerged impermeable breakwaters
US Army corps of engineers (1991)	Experimental	Submerged bars and artificial reefs

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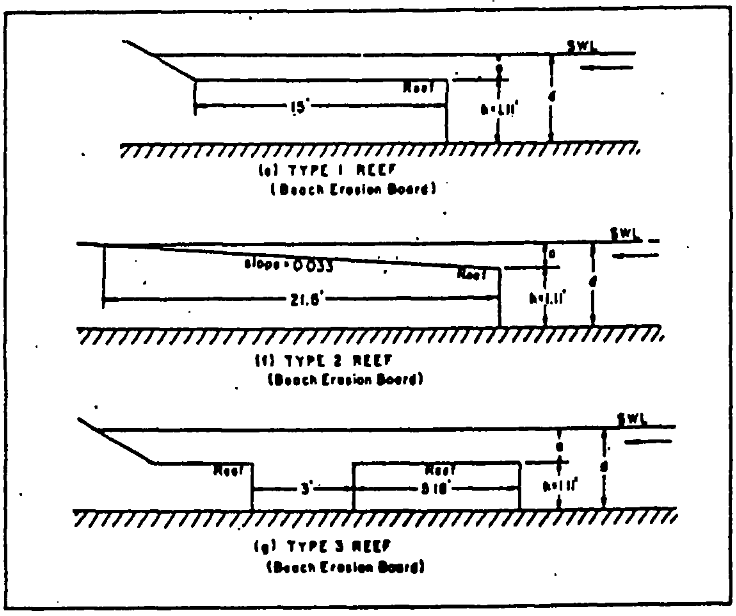

Figure 1) - Various types of idealized reefs investigated by Beach Erosion Board (1944).

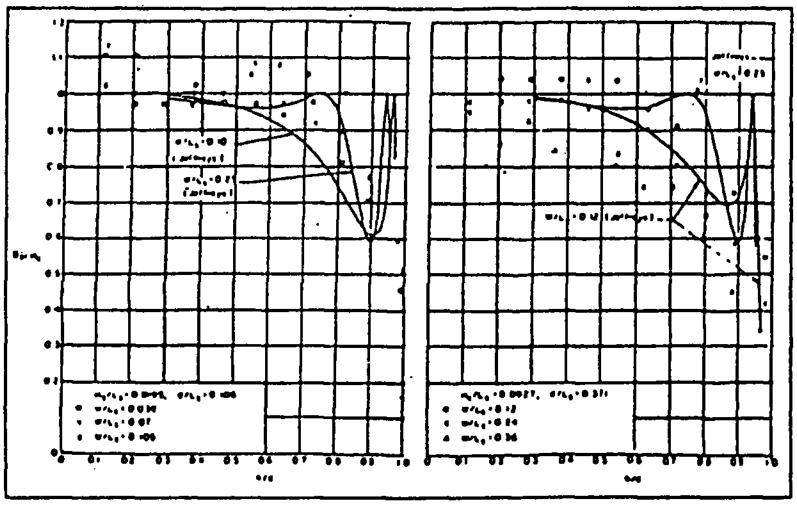

Figure 2) - Effect of relative width of the barrier on wave action over a rectangular barrier. Johnson, Fuchs and Morison (1951)

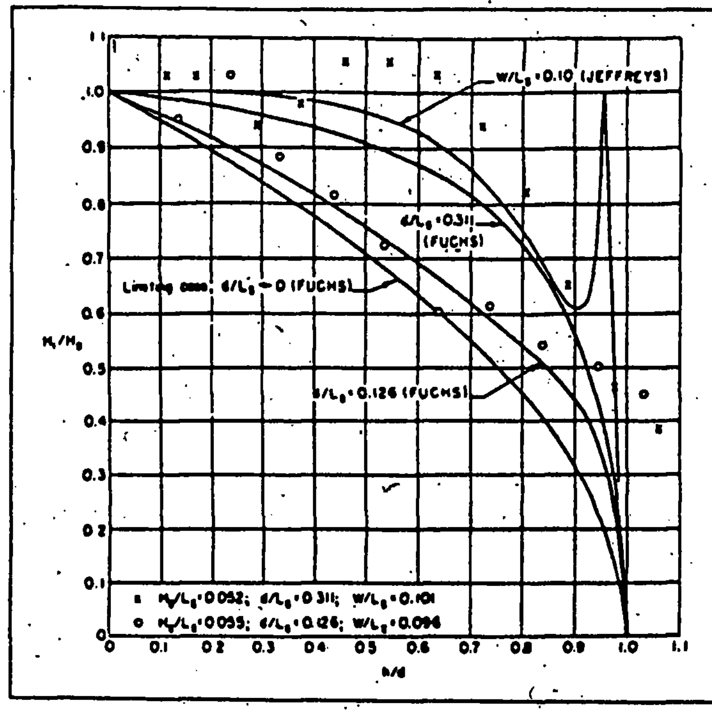

Figure 3) - Effect of relative depth on wave action over a rectangular underwater barrier.
Johnson, Fuchs and Morison (1951)

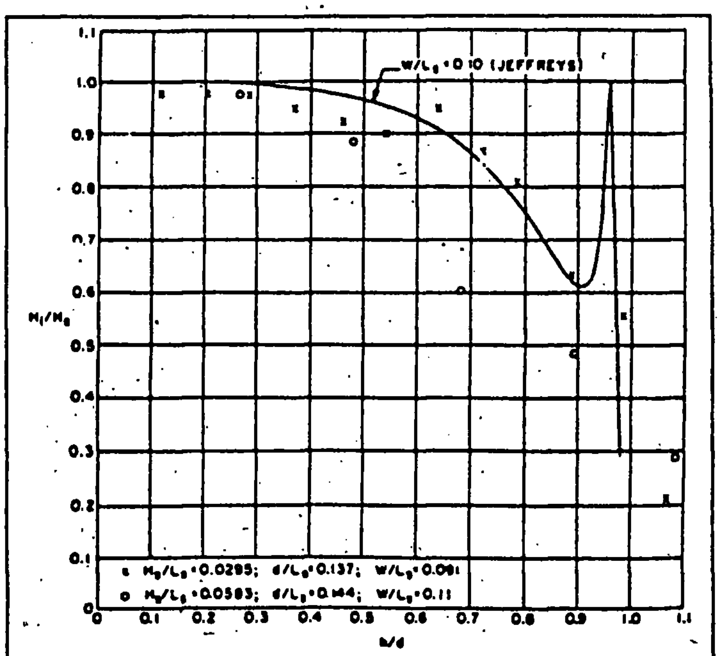

Figure 4) - Effect of wave steepness on wave action over rectangular underwater barriers.
Johnson, Fuchs and Morison (1951)

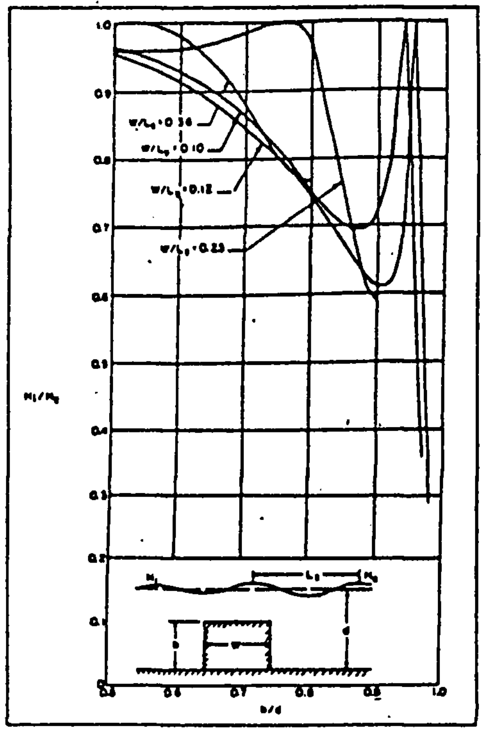

Figure 5) - Theoretical transmission coefficients.
Jeffreys (1944)

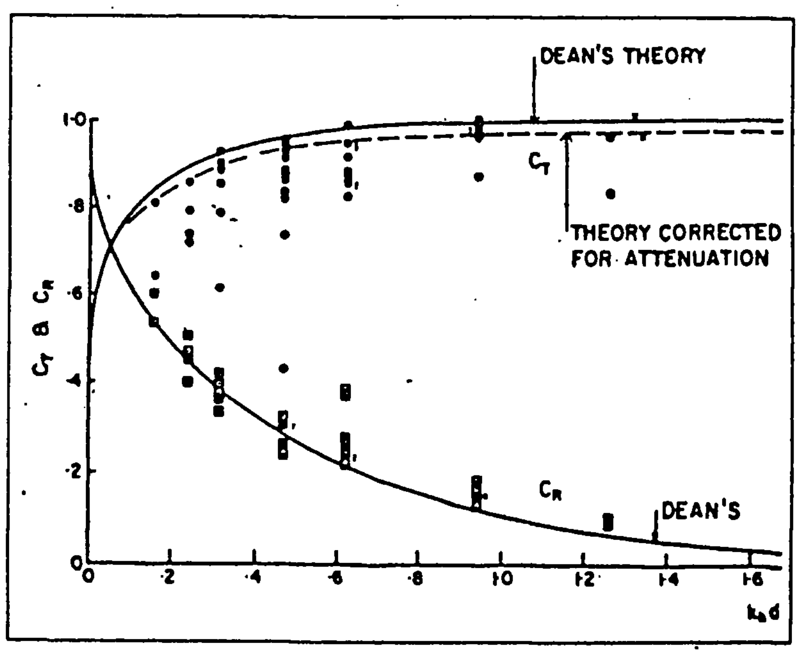

Figure 6) Comparison of experimental results with Dean's theoretical results.
Dean (1945)

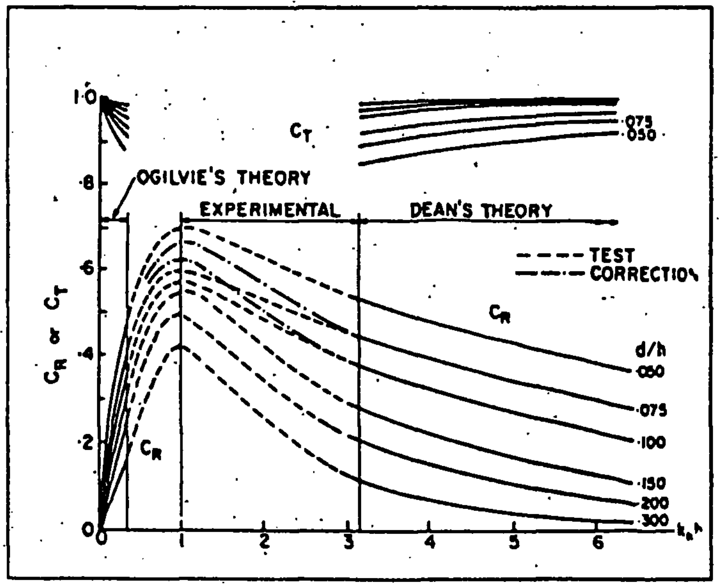

Figure 7) - Reflection and transmission coefficients across wave number spectrum.
Dick and Brebner (1968)

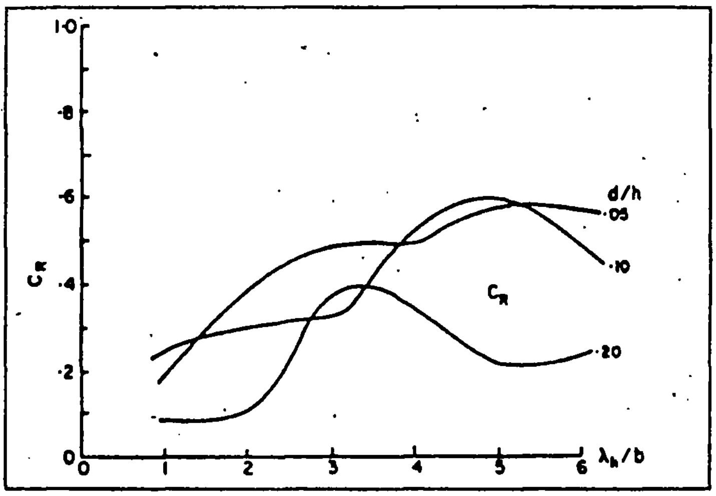

Figure 8) - Variation of reflection coefficient with d/L. Dick and Brebner (1968)

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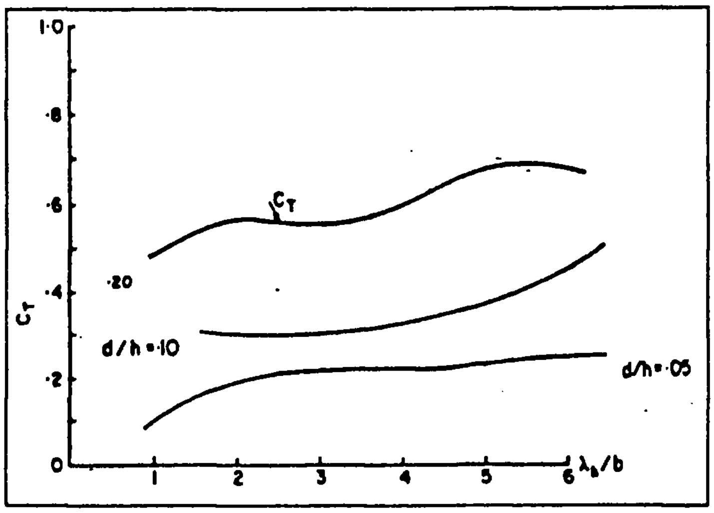

Figure 9) Average trends for transmission coefficient. Dick and Brebner (1968)

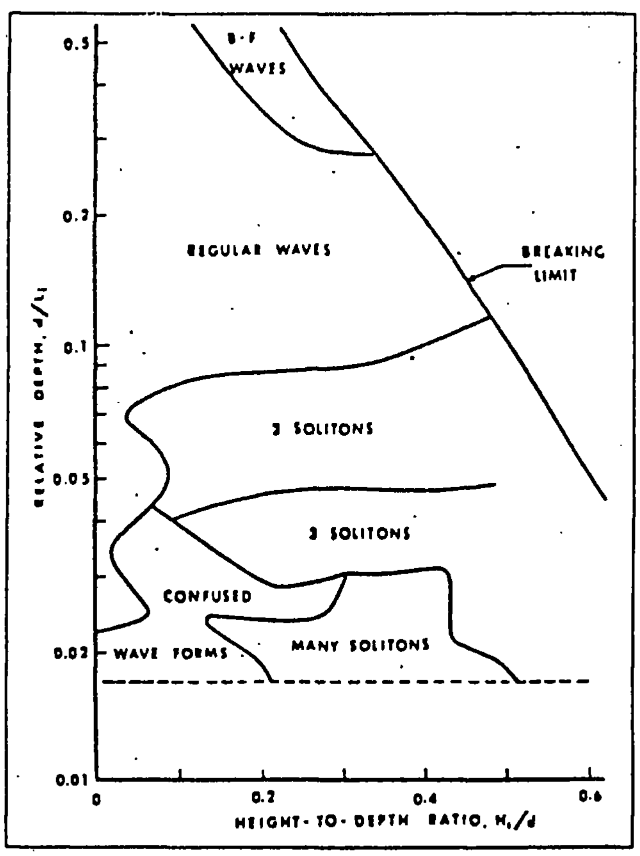

Figure 10) - Different wave forms at constant water depth. Galvin (1970)

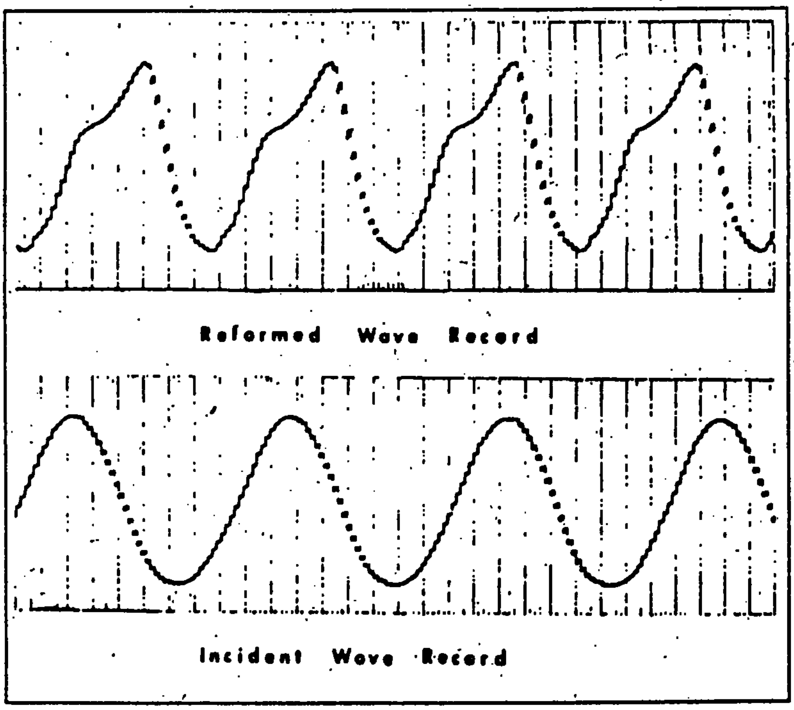

Figure 11) - Typical wave records
Pierce, Chandler, Robert and Sorenson (1972)

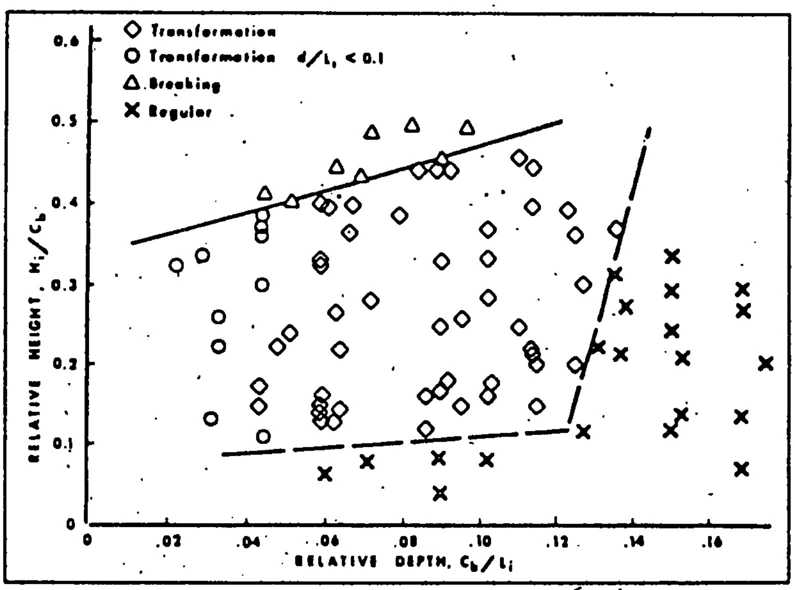

Figure 12) - The envelope of wave transformation.
Pierce, Chandler, Robert and Sorenson (1970)