CHAPTER 72

SOLID AND PERMEABLE SUBMERGED BREAKWATERS

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ABSTRACT The behaviour of thin and rectangular solid submerged breakwaters is re-examined. Dean's theory is found to be correct for a thin barrier in infinitely deep water. An empirical and theoretical relationship for the reflection coefficient of a thin breakwater across the wave number spectrum is proposed. Rectangular solid breakwaters have a maximum reflection 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. A submerged permeable breakwater for depths of submergence greater than 5% of the total depth transmits less wave energy than the solid over a certain frequency range. The minimum is transmitted when the criterion above for solid breakwaters is also met. Both permeable and solid rectangular breakwaters cause a substantial loss in wave energy and at least 50% of the incident energy is lost to turbulence. A substantial proportion, 30 to 60% of the energy transmitted is transferred to higher frequencies than the incident wave.

INTRODUCTION

In many locations, submerged breakwaters offer a potentially economic solution to coastal engineering problems. Complete protection from waves is often neither necessary nor desirable and it is in these situations a submerged breakwater becomes feasible. Submerged breakwaters have been used to protect harbour entrances, to control wave action at inshore fishing grounds and to reduce the rate of littoral drift Most applications have been designed on the basis of ad hoc experiments since there is no substantiated body of theoretical or experimental work to permit reliable or safe design

NOTATION

The notation on Fig 1 is largely self-explanatory. H_1 and H_3 are the incident and reflected wave heights respectively The transmitted wave in theory is denoted by H_2 and refers to the height of a sinusoidal wave. In the tests however, except for the thin breakwater, the transmitted wave was not simple but the resultant of a basic carrier wave with the same frequency as the incident wave and waves of higher frequencies. It is believed that the latter were usually harmonics of the incident wave The total transmitted wave energy was therefore represented by a wave having the same frequency as the incident wave and a wave height defined by

$$H_{eq} = \frac{2\sqrt{2}}{T} \int_0^T \eta^2(t)\, dt \tag{1}$$

where

T is the incident wave period (secs)
η is the displacement of the water surface from the mean water level (ft)
t the time coordinate.

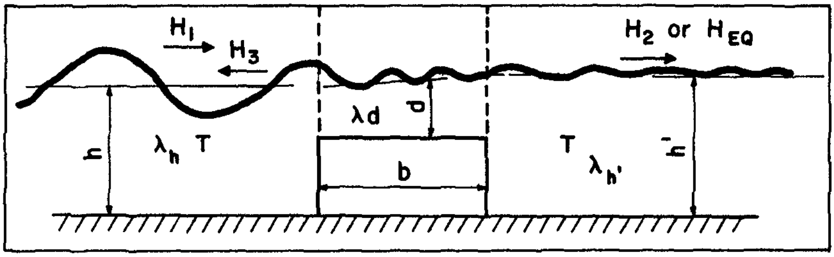

Fig. 1. Notation for Breakwater

The imaginary sinusoidal wave of height H_{eq} is called the equivalent wave and contains the same energy as the actual transmitted irregular wave. A useful idea adopted by most authors is the transmission and reflection coefficients defined by

$C_T = H_2/H_1$ or H_{eq}/H_1 $\qquad C_R = H_3/H_1$

Wave energy losses occur at the breakwater and if these losses are made equivalent to a wave of height H_L of the same period as the incident wave and the depth of water is h then it is readily shown by the conservation of wave energy flux that

$$C_T^2 + C_R^2 + C_L^2 = 1 \tag{2}$$

where $C_L = H_L/H_1$.

SOLID BREAKWATERS

Thin Breakwater. Dean (1945) developed a theoretical expression from linear wave theory for C_T and C_R for a thin lamina extending from infinite depth to some distance d ft below the still water surface. Later Ogilvie (1960) obtained a solution for very long waves in depth h. Solutions for waves occurring in the intermediate zone between shallow water waves and deep water waves are non-existent and recourse must be taken to empirical studies. These two theories cited indicate that the important parameters for the thin breakwater are the relative depth of submergence d/h and the ratio $2\pi d/\lambda_h$.

Rectangular Breakwater An expression for C_T was obtained by Jefferys (1944) for the case of shallow water waves A deep water solution was found by Newman (1965) provided the width of the barrier was great compared with the wave length. Takano (1960) obtained a series solution for a rectangular barrier embracing all wave lengths and widths but unfortunately the solution did not converge rapidly and since 19 simultaneous equations must be solved to obtain the 1st three terms the solution was very cumbersome. However the theories show that d/h and λ_h/b or $\lambda d/b$ are important parameters.

An engineering approach to the problem considered the flux of wave energy and assumed that energy being propagated above the crest level passes over the breakwater and reappears as a wave on the lee side This approach was proposed by Johnson et alii (1951) and in that paper is attributed to Fuchs. Their equation is

$$C_T = \left[1 - \frac{2k(h-d) + \text{SINH } 2k(h-d)}{2kh + \text{SINH } 2kh} \right]^{1/2}$$

where $k = 2\pi/\lambda_h$
h = depth of water in front of breakwater
d = depth of water over breakwater crest
λ_h = wave length in depth h.

Apparatus. The tests were run in a wave tank which was 3 ft wide and contained 2 ft of water. Waves were absorbed by a permeable beach which had a coefficient of reflection of the order of 5% The test breakwater was located 110 ft from the wave machine and 35 ft from the beach. Waves were measured in front of the breakwater by a movable probe which was not moved more than 17 ft from the breakwater. Transmitted waves were measured by a probe fixed at a distance of 25 ft from the breakwater face. The wave probes were the capacitive type and employed #22 gauge teflon covered wire.

Test Procedure In nature, a wave striking a submerged barrier will result in some of its energy being reflected offshore where it is ultimately dissipated by wind and internal stresses. In the laboratory flume the reflected wave strikes the wave paddle and is almost totally reflected. In turn the reflected wave is again partially reflected at the submerged barrier and so on. The net result is a wave system which differs considerably from the simple model in nature, that is assuming monoperiodic waves could occur in nature. In the tests done for this study the wave machine paddle was set in motion very quickly producing a reasonably short wave front. After the primary reflection of the full sized wave had passed the movable probe in the negative direction, the latter was moved to pick up the wave envelope. The waves a short distance in front of the barrier are the sum of the incident and reflected wave trains. Where the waves were exactly in phase then the measured wave height was $H_{MAX} = H_1+H_3$ and where exactly out of phase by π^c then the wave height was $H_{MIN} = H_1-H_3$. Once H_{MAX} and H_{MIN} were measured then H_1 and H_3 were easily calculated. The transmitted wave H_2 or H_{eq} was derived from the fixed wave probe record.

RESULTS

Thin Breakwater-Deep Water Case: The coefficients of reflection and transmission were obtained for wave lengths of 2 and 4 feet which complied with the deep water condition In these experiments the transmitted wave height was measured directly as H_2 and not by equation 1, since there was little distortion of the sinusoidal wave This was only true if the trough of the waves in front of the breakwater did not fall below the crest level When this occurred irregularities and harmonics were superimposed on the transmitted wave. Tests were run for depths of submergence d = 0.10, 0.15, 0 20, 0.30, 0.40 and 0.60 feet. Varying wave steepnesses were employed All the test results have been plotted on Fig. 2 on which has also been drawn curves calculated from Dean's theory. When Dean published his results he evaluated C_T and C_R only to $2\pi d/\lambda_0 \leq 0.25$ because approximate methods were valid up to that point. We have however extended the numerical solution with an electronic computer. Our measurements of C_T and C_R contain the effect of viscous wave attenuation but we have made a correction only to C_T as shown in Fig. 2. Manifestly, the theory and experiments are in good agreement and one can conclude that Dean's theory for a thin breakwater in infinitely deep water is sensibly correct

Thin Breakwater-General Case As for the deep water case values of C_T and C_R were obtained for incident wave lengths of 6, 8, 10 and 12 feet. All the results for λ_h = 2 to 12 were plotted using as parameters λ_h/h and d/h. In Fig. 3 is shown a typical plot[1] of the test measurements upon which has been superimposed Dean's, Ogilvie's and Fuchs' theories. The experimental points have fairly well defined trends and average curves for C_T and C_R were sketched in carefully as indicated by the dotted lines in Fig. 3. All these trend lines have been assembled in Fig. 4 which indicates a theoretical and experimental relationship for C_R, d/h and $2\pi d/\lambda_h$ across the wave number spectrum. For $k_h h > 3\ 14$ Dean's theory is assumed to hold and it has been replotted here in another form. For very small wave numbers, i.e. $k_h h < 0.35$ Ogilvie's theory has been drawn in by interpolation from his published solution. In the intermediate zone for $1.0 < k_h h < 3.4$ the experimental trend lines are shown dashed. We have also indicated by a dashed-dot line a possible correction to the present empirical trend lines. The remaining gap for $0.35 < k_h h < 1.0$ remains unknown but we have hazarded that it may be of the form indicated.

At the top of Fig. 4 are plotted the theoretical values of C_T but it was found that the experimental results, because of losses

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[1] There is insufficient space here to show all the experimental data This can be found in detail in "Solid and Permeable Submerged Breakwaters", T.M. Dick, Civil Engineering Research Report, 1968, Queen's University, Kingston, Ontario.

at the breakwater did not accord with the theory. Consequently, the empirical curves for C_T have been plotted in Fig. 5. We have indicated a dashed line as a correction for d/h = 0.10 to make it comply with the other experiments. The transmitted wave heights as measured deviate from forecasts made by the theory. It seems that because of energy losses at the breakwater the most reliable method for estimating transmitted wave heights will be from empirical graphs.

Rectangular Breakwater-General Case A rectangular breakwater was constructed which had a crest width of 2 feet and three depths of submergence, namely, 0.1, 0.2, and 0.4 feet. Wave lengths of 2 to 12 feet with varying wave heights were employed. The transmitted wave height was generally not a simple wave but was distorted by varying degrees. Hence the transmitted wave energy was evaluated from equation 1. The reflected wave height was obtained in the usual way. A typical test result[1] is shown in Fig. 6 with the trend line sketched through the points. In order to compare the variations caused by the depth of crest submergence, the trend lines have been gathered together in Fig. 7 and 8. It is readily seen that C_R undulates with λ_h/b but the same tendency is not so evident in C_T. We believe that when the reflection is small, the higher wave which tries to pass over the breakwater is eradicated by turbulence and breaking on the crest. In turn when the reflection is high the lower wave which is transmitted tends to pass over the breakwater with less breaking and relatively more energy is transferred. The net result is that C_T is smoothed out. The loss coefficient C_L was calculated from equation 2. The major role played by the wave breaking and turbulence in destroying the incident wave energy is quite evident and was one of the rather unexpected results in the investigation. In the solid case the losses account for greater than 50% of the incident wave energy.

Examination of the maxima exhibited by C_R in Fig. 7 enabled Table 1 to be drawn up.

TABLE 1. Parameters at Maximum Reflection

	d/h	
	0.20	0.10
C_R(MAX)	.40	.60
λ_h/b	3.4	4.9
λ_d/b	2.1	1.9

From Table 1, it seems that the maximum reflection occurs when the length of the wave on the breakwater crest equals twice the crest width. Or, restating, the maximum reflection occurs when the period of a standing wave of length b on top of the breakwater has the same period as the incident wave. A substantial proportion of the transmitted energy is found at frequencies higher than the input frequency. The fundamental wave height H_F was abstracted by obtaining the amplitudes of the Fourier coefficients corresponding to the frequency $2\pi/T$ from the same portion of record used to establish H_{eq}. Defining $C_F = H_F/H_I$ the experimental trend lines[1] are shown in Fig. 8. As would be expected the value of C_F is always less than C_T but remarkably the ratio C_F/C_T does not vary greatly with d/h for constant λ_h/h. The ratio C_F/C_T has also been plotted on Fig. 8 and lies in the range $0.6 < C_F/C_T < 0.8$. This means that between 36 to 64% of the transmitted energy is being transferred to waves with a greater frequency than the incident wave In nature one might expect these higher frequencies to be less of a problem than the incident swell or significant storm wave. Consequently, the useful attenuation in the wave height may be somewhat greater than that indicated by the equivalent wave height method of calculation.

PERMEABLE BREAKWATER

The possibility of improving the effectiveness of a submerged breakwater by increasing turbulence and wave interference seemed interesting. It was decided to construct a permeable rectangular structure, composed of nested tubes which had their axes parallel to the incident wave direction. A rigid horizontal flat plate was placed on top of the tubes. This arrangement had several objectives. Firstly, the waves passing over the breakwater would continue to lose energy by breaking. Secondly, turbulence and friction would tend to reduce the effect of the pulse passing through the breakwater and lastly, the wave passing over the breakwater could be out of phase with waves caused by the pulse through the tubes. If the latter could be achieved and the phase difference was π then the waves would tend to cancel In addition since the component wave periods would be the same, the beat phenomenon would not occur. The effect of the permeable breakwater on the reflected wave energy was not known but it seemed likely that reflection would be less. Reflected energy was considered to be controlled by the amount of solid surface constituting the forward face of the breakwater. This factor was defined by the porosity (p) given by,

$$p = \frac{\text{Area of apertures within selected zone}}{\text{Total area of selected zone}}$$

We are also assuming that the porosity is uniformly distributed over the forward face of the breakwater.

TEST RESULTS

The model breakwater which had a porosity of 0.72 was composed of nested 1" D aluminum tubes which had the intertubular instertices plugged with plasticene. Other porosities of .18, 0.40 were obtained by placing a 1/8 plate perforated on the same centres as the nested tubes with 1/2" and 3/4" D holes respectively. In order to take matters to the limit, a number of tests were run by removing the tubes entirely, leaving only the top plate in place so that the porosity = 1.0. Tests were run as for the solid rectangular breakwater. A typical result[1] is shown in Fig. 9. A trend line has been carefully sketched through the experimental points obtained for C_T, C_R and C_L so that equation 2 was satisfied. In Figs. 10, 11, 12 all the trend lines have been gathered together for varying porosities and the results for the solid breakwater p = 0 added for comparison. It can be concluded from Figs. 10, 11 and 12 that the permeable breakwater behaves differently from the solid and that all the permeable breakwaters have sensibly the same behaviour. In Fig. 10 the permeable breakwater transmits slightly greater waves and as the wave length increases the solid type is consistently better Concomitantly the waves reflected from the permeable type are less than the reflection from the solid structure. Losses at the permeable breakwater are slightly larger.

However in Figs. 11 and 12, the behaviour changes and one finds that over a certain wave length range that the permeable breakwater provides a substantial improvement in attenuation over the solid structure This is especially marked in Fig. 12 It is also quite evident that the value of C_R fluctuates in value with the variable λ_h/b and that C_T passes through a minimum when C_R is a maximum. In order to study the influence of the crest width a series of tests were run using only the submerged plate as representative of the permeable type. Crest widths of 1.25 and 3 00 feet were selected.

It was found that the minimum C_T gradually increased with crest width and that the breakwater behaviour was very similar. However the minimum C_T or maximum C_R occurred at various values of λ_h/b. These maxima or minima were picked off from the plotted results[1] and the parameter $\beta = 2\pi b/\lambda_d$ calculated. The results are tabulated below in Table 2.

TABLE 2. Lag Angle β for Horizontal Plate in π Radians

b	d/h .05	.10	.20
	C_T MINIMA		
1.25	1.2	.9	.8
2.00	1.6	1.1	.9
3.00	-	-	1.1
	C_T MAXIMA		
3 00	-	2.1	1.75

The parameter β is a lag angle which represents the time taken for a wave to transit the crest of the breakwater. In the table minimum transmission occurs when $\beta \simeq \pi^c$ and maximum transmission when $\beta \simeq 2\pi^c$. It can be shown from physical reasoning that these results are compatible and confirm one another. Hence for minimum energy transmission

$$\frac{2\pi b}{\lambda_d} \simeq \pi \qquad \text{or} \qquad \lambda_d \simeq 2b$$

In the same way as for the solid case, the height of the fundamental wave was abstracted from the Fourier series which was equivalent to the analogue wave trace. The results[1] were sensibly the same as for the solid breakwater.

CONCLUSIONS

1. Dean's theory for the transmission and reflection of waves at a thin barrier in infinitely deep water has been confirmed provided the trough of the incident wave system does not fall below the crest level.

2. A relationship across the wave energy spectrum for the reflection coefficient at a thin solid submerged breakwater has been proposed in Fig. 4.

3. In both breakwaters a major portion of the wave attenuation results from energy losses caused by turbulence and breaking at the breakwater.

4. Of the energy transmitted between 36 to 64% has been transferred to frequencies higher than the incident wave. Both breakwaters have about the same characteristics in this regard.

5. The transmission coefficient for the permeable breakwater passes through a minimum and over a certain range transmits a smaller wave than the solid breakwater with the same dimensions. At very shallow depths of submergence both breakwaters are similar in behaviour.

6. The maximum reflection coefficient for the permeable and solid breakwaters occurs when the incident wave has the same period as a standing wave on top of the breakwater. The solid breakwater has no well defined minimum transmission coefficient because turbulence and breaking eradicate fluctuations. However, the permeable breakwater has a well defined minimum coefficient of transmission.

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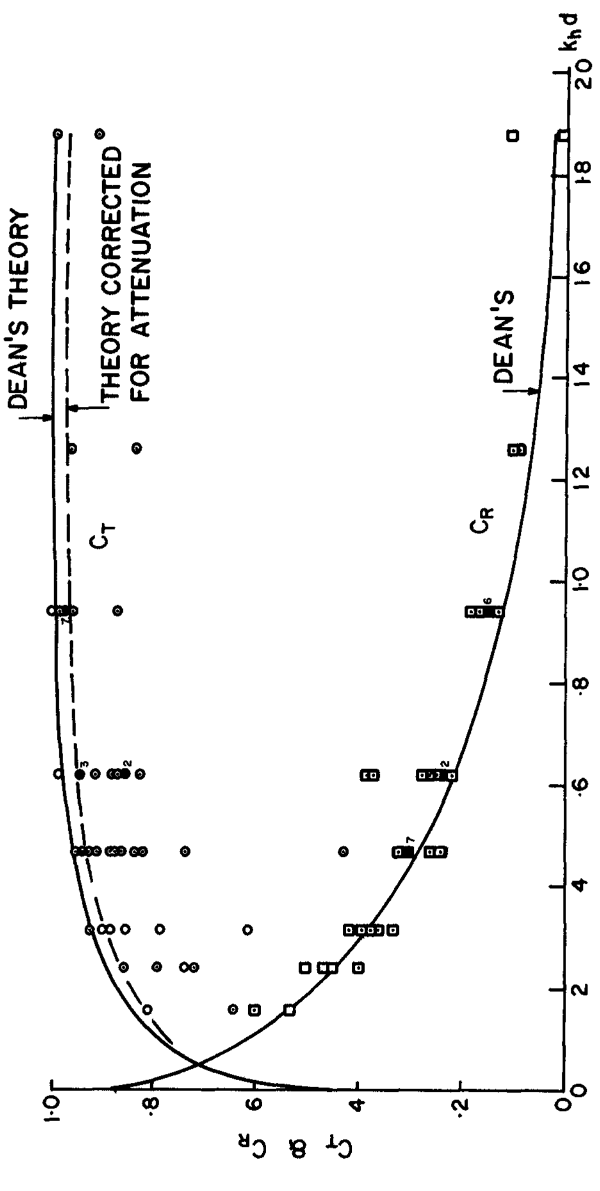

FIG. 2 COMPARISON OF THEORY AND EXPERIMENT FOR THIN BREAKWATER IN INFINITELY DEEP WATER

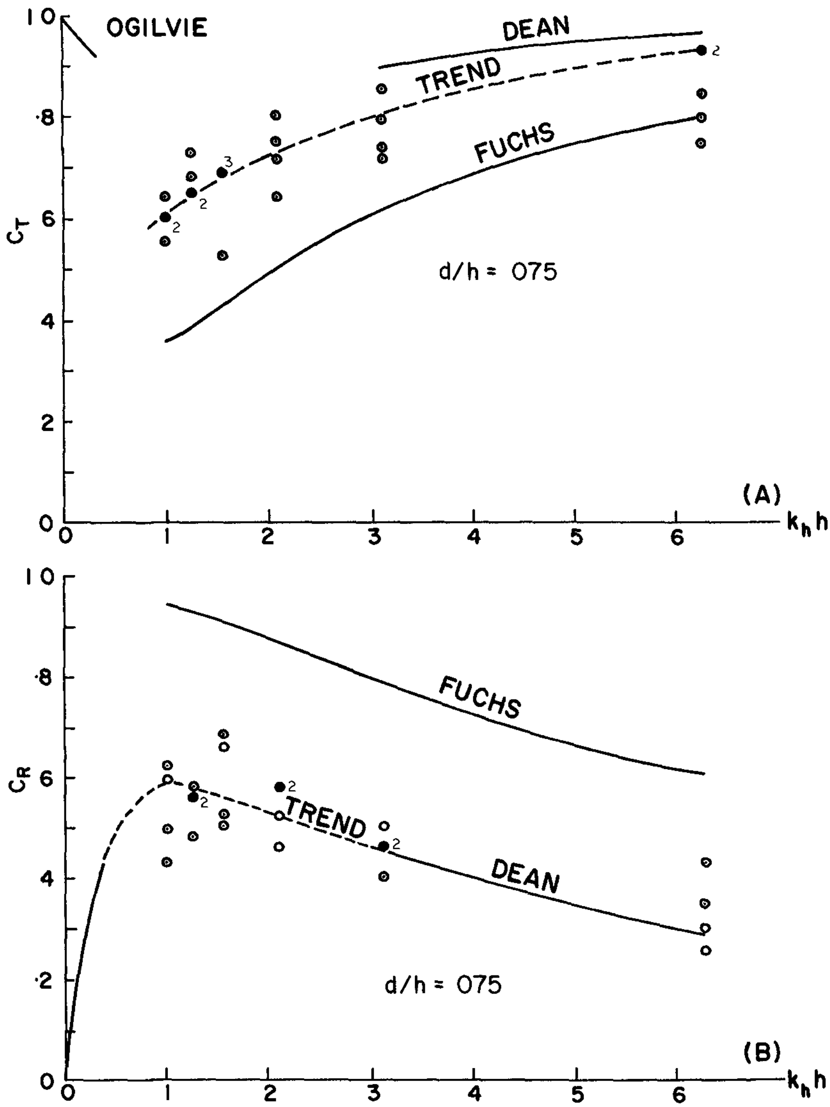

FIG.3 TYPICAL THIN BREAKWATER TEST WITH AVAILABLE THEORY

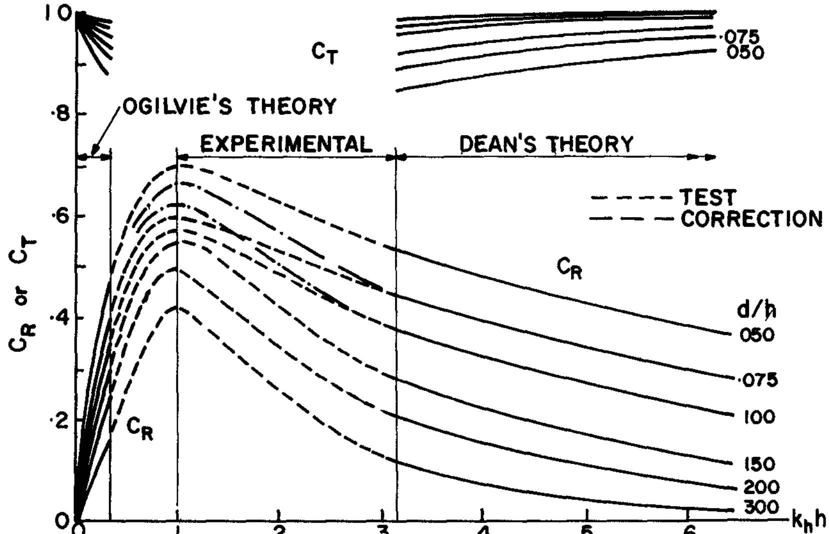

FIG. 4 REFLECTION COEFFICIENT ACROSS WAVE NUMBER SPECTRUM

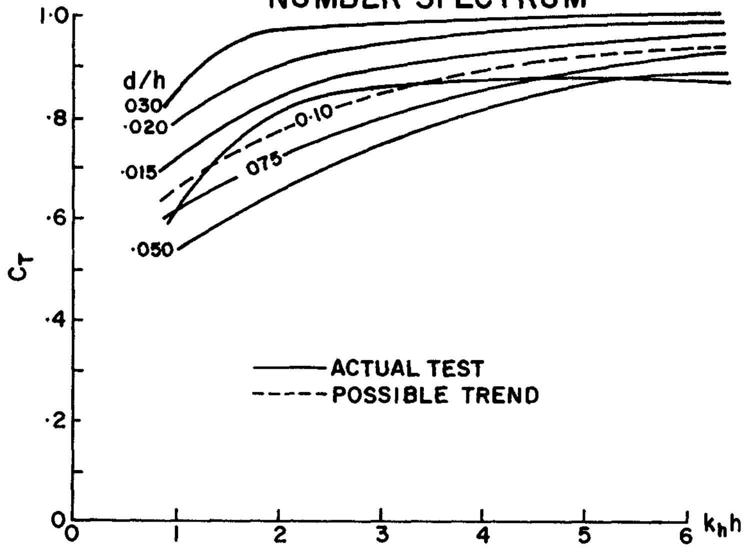

FIG. 5 EMPIRICAL TRANSMISSION COEFFICIENT ACROSS WAVE NUMBER SPECTRUM

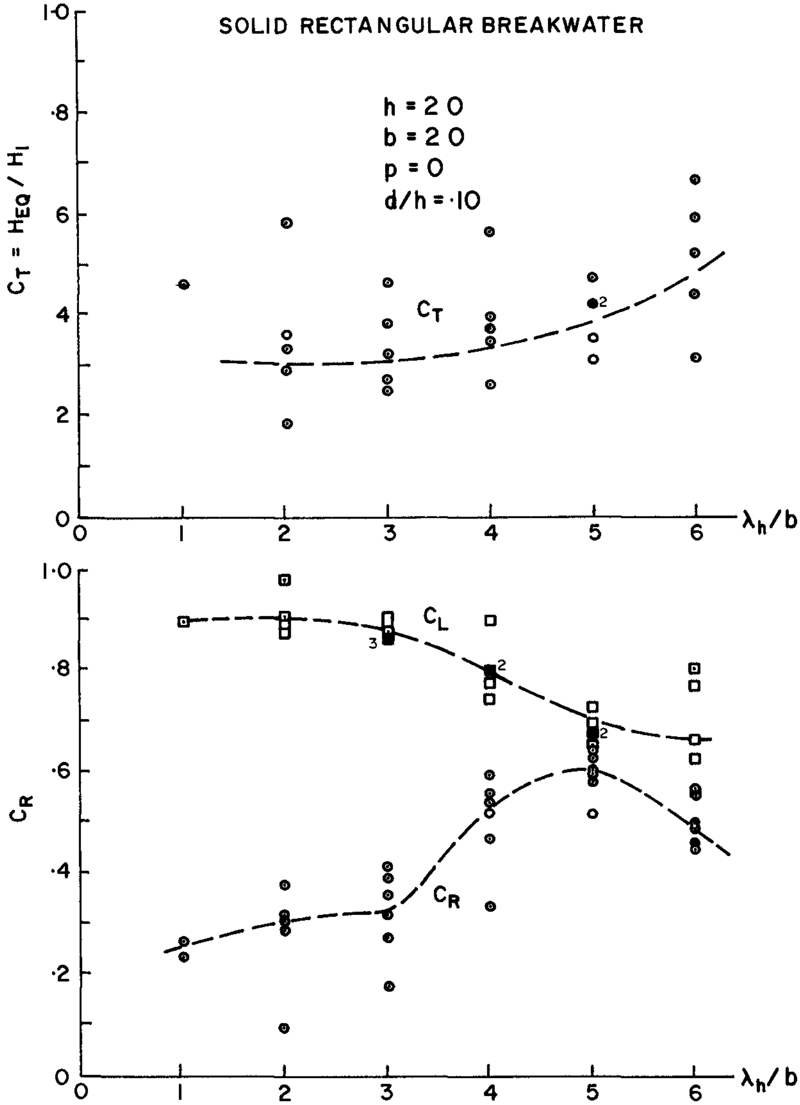

FIG. 6 TYPICAL TEST RESULT

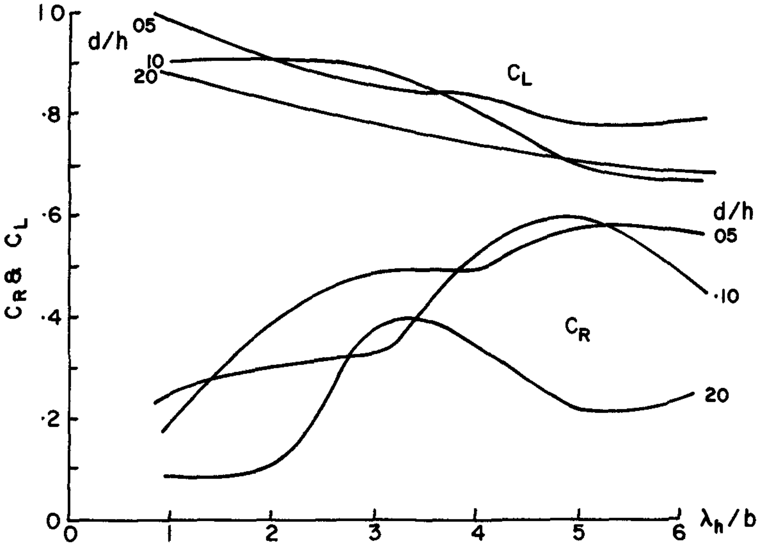

FIG. 7 VARIATION OF C_R WITH d/h

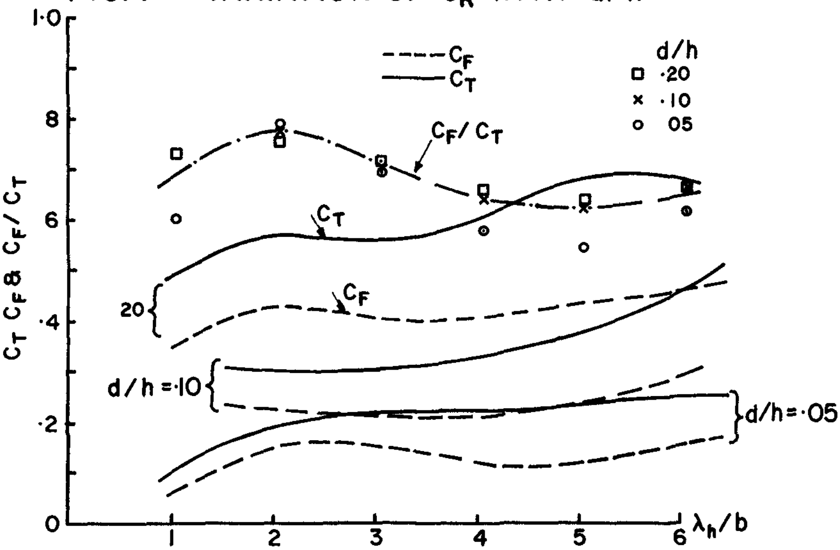

FIG. 8 AVERAGE TRENDS FOR C_F & C_T

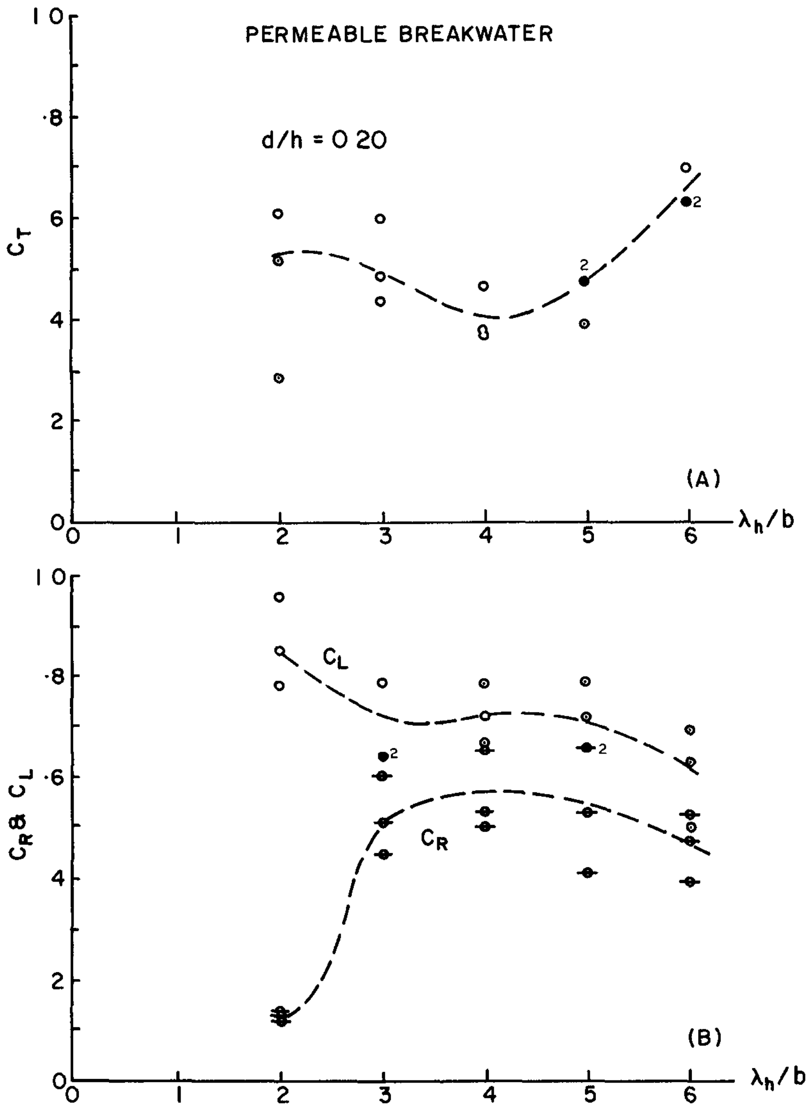

FIG. 9 TYPICAL TEST RESULTS POROSITY = 0·40

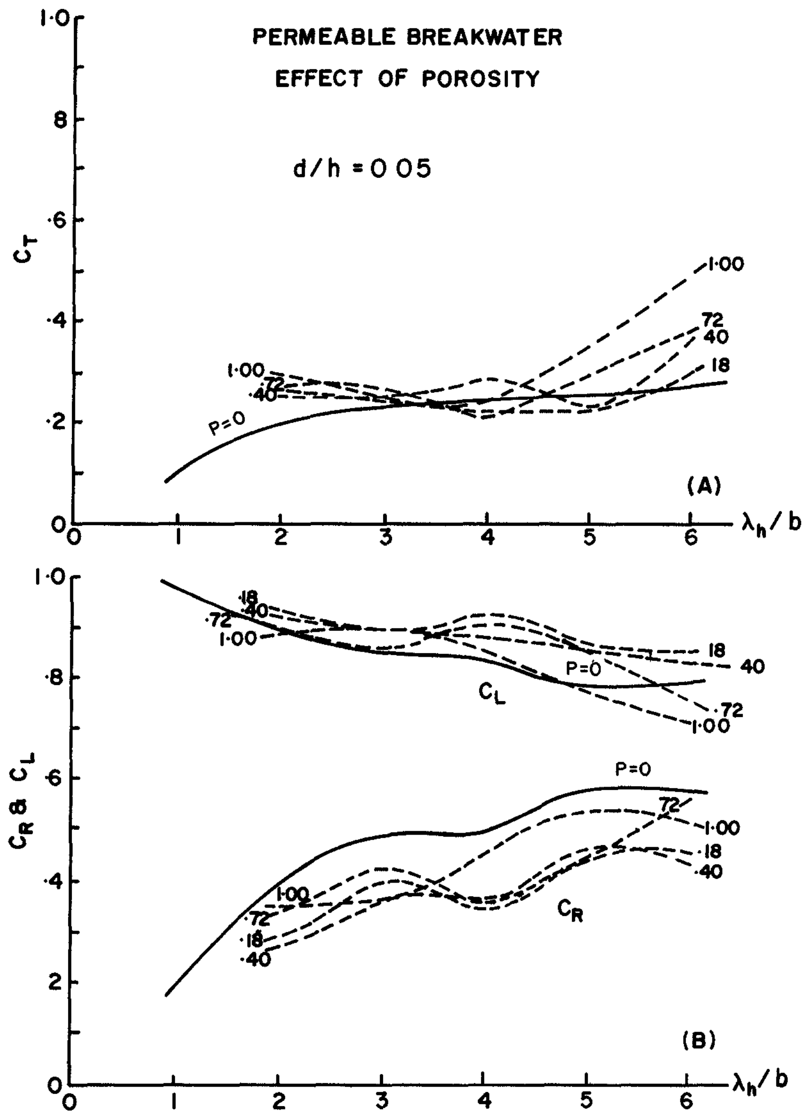

FIG.10 AVERAGE TEST RESULTS $d/h = 0{\cdot}05$

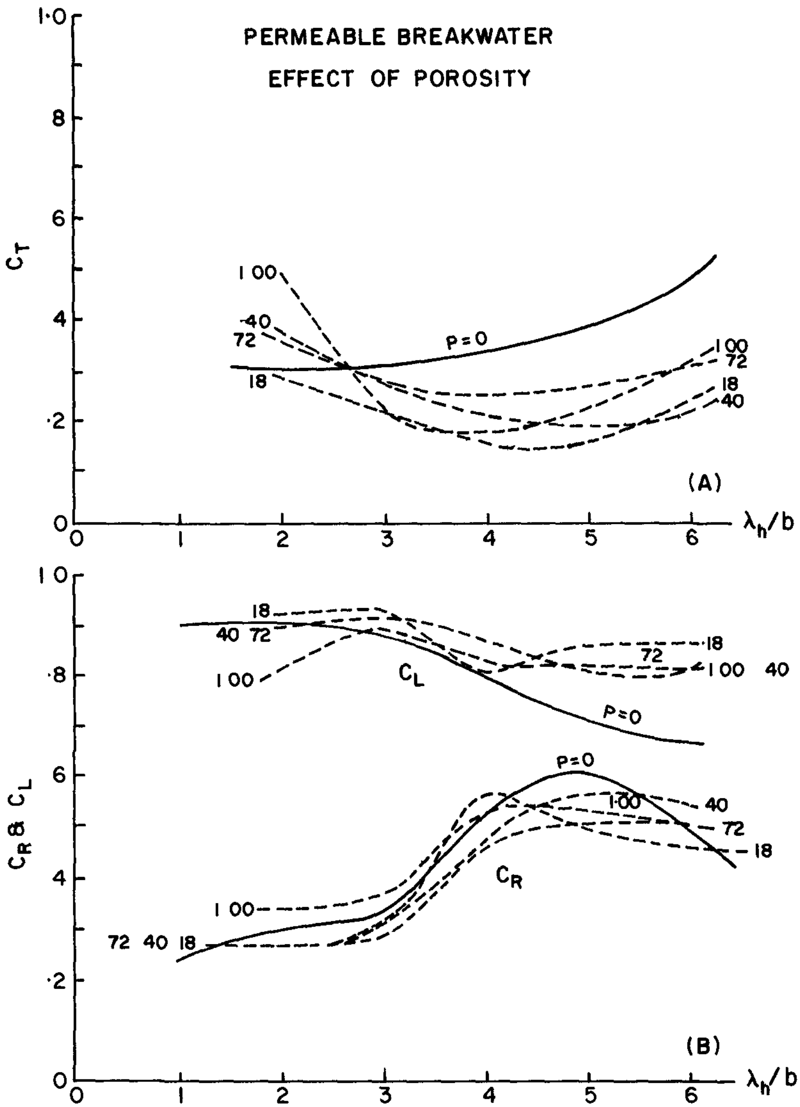

FIG.11 AVERAGE TEST RESULTS $d/h = 0{\cdot}10$

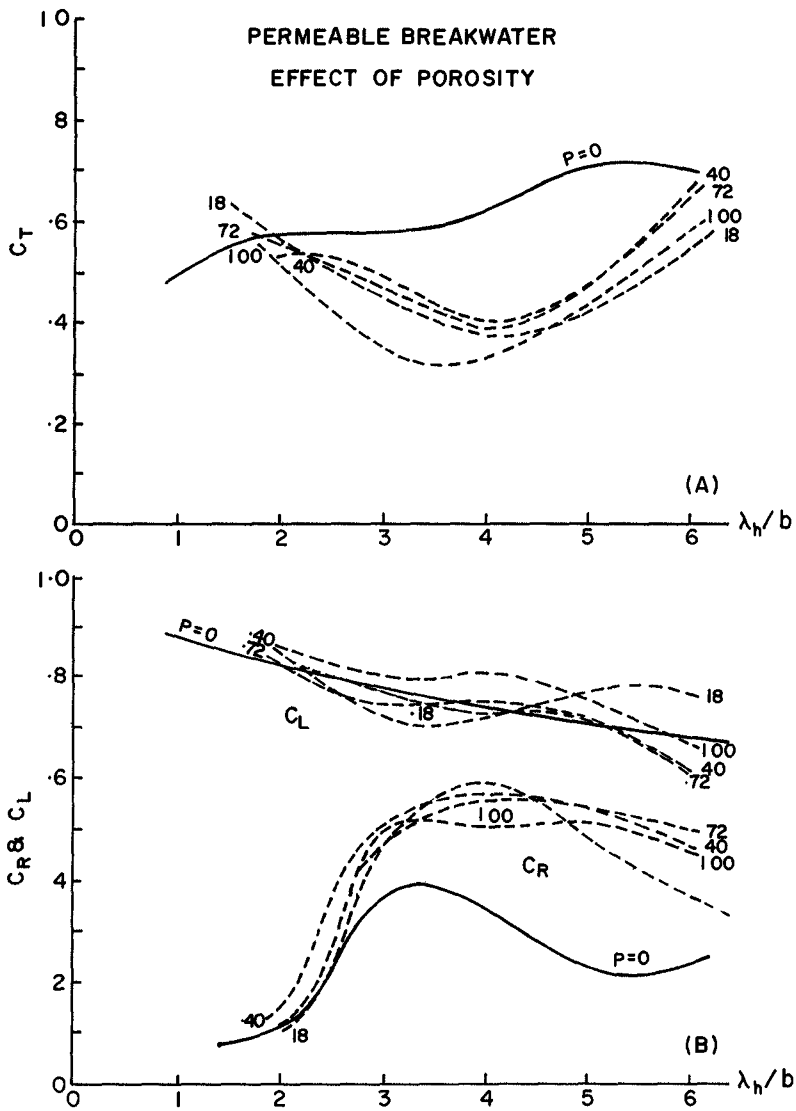

FIG. 12 AVERAGE TEST RESULTS d/h = 0·20