CHAPTER 70

MODEL STUDIES OF A PERFORATED BREAKWATER

by

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ABSTRACT

The breakwater proposed for a yacht harbour on the Sussex coast of England comprises a solid base up to the level of low water and a cellular structure, having a perforated front wall and solid backwall, above low water level.

A model of the breakwater (scale 1:48) was tested in a flume at the Hydraulics Research Station, Wallingford, and measurements were made of wave reflections and wave forces.

For comparison force measurements were also made on a solid faced breakwater.

The reflection tests were carried out with waves of normal incidence and at 45° to the breakwater for waves (prototype) in the range 4 to 15 seconds and up to 15 ft. in height. The results are presented in graphical form and a simplified analysis is put forward to explain them.

The force measurements were made for 7 and 10 second waves (prototype) up to 22 ft. in height. The results are presented as a non-dimensional plot with envelope curves of maximum force.

The results are also given of stability tests on a rock mound against the solid base of the breakwater.

INTRODUCTION

In some situations where armour stone is not readily available rubble mound breakwaters may turn out to be expensive; vertical breakwaters although more economical in materials reflect a large proportion of the incident wave energy. An alternative solution is the perforated breakwater, originally suggested by Jarlan (ref.1), an example of which has been built at Baie Comeau, Quebec. Nevertheless, design information is still rather scanty and further model tests have been made to investigate the performance of a particular type of perforated breakwater for a yacht marina.

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Basically the perforated breakwater consists of a screen with openings, which may be a series of slots or holes, placed in front of a solid vertical face. Waves incident on the screen are partly reflected and partly transmitted, energy being lost mainly due to eddying at the perforations. The transmitted wave is reflected from the back face, again suffering energy loss and reflection in its passage through the screen. The superposition of these waves results in standing waves being set up in the chamber between the screen and back face and also outside, the amplitudes of the waves being dependent on the losses in the screen and the distance (L) between the screen and back face. If the reflection coefficient (R) is defined as the ratio of the reflected wave height (H_R) to the incident wave height (H_I), the maximum height of the standing waves outside is $(1 + R)H_I$. Reduction of R will therefore reduce wave activity and navigation risks for craft in the immediate harbour approaches.

The maximum energy loss (R minimum) will occur when the velocity induced by the standing wave system is a maximum at the screen. It may be conjectured that this will occur when $L = \lambda_2/4$ approximately (λ_2 = wave-length in the chamber) or an odd multiple of this distance. On the other hand when the system is such that it induces zero velocity at the screen, the energy loss is zero, the screen is inoperative and reflection occurs from the back face essentially as though the screen were absent. This occurs for waves such that $L = \lambda_2/2$ or an even multiple of $\lambda_2/4$. Thus with a fixed length of chamber the performance of the breakwater in suppressing reflections will be sensitive to wave-length (or period) of the incident waves.

Clearly the reflection will also depend on the resistance of the screen; if the screen is very resistive the transmitted wave will be weak and the incident wave will be nearly wholly reflected from the screen. Conversely if the screen is very open nearly complete reflection will occur from the back face. There is evidently an optimum porosity of the screen for minimum reflection. Also, since the resistance of the screen is proportional to the square of the velocity through the openings whilst the orbit velocity is proportional to the wave height it is easy to see that the optimum porosity depends on the height of the incident wave (H_I). Boivin in tests on a horizontal slotted screen found the optimum porosity was about one-third and for this ratio the reflection decreased almost linearly with wave steepness for $0.01 < H_I/\lambda_1 < 0.05$ (λ_1 being the length of the incident wave) (ref.2).

WAVE REFLECTION

(1) Experimental Work

A section (scale 1:48) of the proposed design of breakwater (Fig.1 and Plate I) of porosity 31% above low water level was tested in a flume 10 ft. wide. The results have been analysed on the basis of Froude's Law, but the important turbulent energy loss at the perforations in the screen clearly depend upon Reynold's Number (R_e), which, for the flow through the screen in the model, was about 5000 and consequently should have been sufficient to develop fully turbulent conditions.

In the first test all the cells of the breakwater were of the same size, the distance from the front face of the screen to the backwall being 34½ ft. (proto.). Wave heights varied from 1 to 5 ft. and periods from 4 to 14 seconds (proto.). The reflection coefficients were derived from the amplitude of the waves at the node (b) and antinode (a) of the standing wave pattern seaward of the breakwater by means of the formula $R = (a-b)/(a+b)$. The height of the incident wave was taken as $(a+b)/2$. These expressions are strictly only valid for sinusoidal waves. Difficulty was experienced in producing stable conditions in the flume due to the re-reflection of waves reflected from the breakwater and with steep waves repeatable results were not obtained.

The reflection coefficients derived from these tests showed a marked sensitivity to wave period, especially for the lower waves, with a minimum at 7½ seconds and a maximum at 4 seconds wave periods (Fig.1.).

One of the objects of the tests was to develop a design which would not give reflections across the harbour entrance in moderate weather conditions when waves of 4 to 6 second periods are dominant. The breakwater was therefore modified by reducing the depth of alternate cells to 20 ft. measured from the face of the perforated screen to the backwall. This was done by inserting a secondary backwall in every second cell. This modification reduced the reflection of the lower and shorter waves at the expense of some loss in performance with higher and longer waves. (Fig.2.).

Since the wave crests in nature will not normally be parallel to the breakwater and the performance of the breakwater with waves approaching from an angle was in doubt reflection coefficients were measured with the breakwater at 45° to the wave crests. The model was installed across the corner at the end of the flume with an opening in the opposite wall so that most of the reflected waves escaped into a large basin adjacent to the flume. This arrangement involved some loss of incident wave energy through the gap and also resulted in a small transverse wave in the flume. For these and other reasons the wave heights varied along the face of the breakwater..

Consequently the results of the experiment are subject to a greater degree of error than those with normal incident waves but nevertheless are considered to give a reasonable indication of the performance of the breakwater with oblique waves.

The wave heights were measured along a traverse at 90° to the face of the breakwater. The results (Fig.3.) show that reflection is generally less than for normal incident waves with a minimum coefficient for waves of about 6 seconds.

(2) Theoretical Treatment

For comparison with the experimental results discussed above the reflection coefficients shown in Figs 2 & 3. have been calculated by means of an analysis which is given in the Appendix and assumes that the incident waves are low and long enough for the approximations of the linear theory of long waves to be applicable. The only energy loss considered is that due to resistance of the screen which is proportional to the (water particle velocity)^2. This has been approximated by a fictitious resistance term which is proportional to the velocity, the constant of proportionality being chosen to give the same energy loss per wave period. The acceleration through the screen also introduces a "virtual mass" effect or a head difference across the screen which is in phase with the particle acceleration. This effectively increases the length of the chamber and hence the wave period with which the chamber will resonate. The linear theory while giving generally similar coefficients near resonance clearly predicts greater reflection for the higher and longer waves. At an incidence of 45° the discrepancies are more marked even for low waves.

HORIZONTAL FORCE MEASUREMENTS

Preliminary structural analysis of the breakwater indicated that the governing factor in the design would be sliding on the foundations or shear in the material immediately below the foundation rather than overturning or crushing of the foundation strata. Only horizontal forces were therefore measured, no attempt being made to record either vertical forces or the height of the thrust line above foundation level.

Two central bays of the model were fixed together and suspended from a stiff parallel motion spring system with strain gauges attached and of high enough natural frequency to enable the force variation to be followed.

Measurements were made with waves of 7 and 10 second period (proto.) both on the breakwater with the perforated front wall and with the perforations covered over with a plain solid face extending up to parapet level. For the larger waves, which broke in front of the breakwater, the resulting variable reflections caused the wave heights in the flume to vary, and a range of observations of wave height and force was therefore obtained from any one setting of the wave generator. In each run a continuous record of forces (F_c and F_t - Fig.3.) and wave height at the wall (H_w) for 50 or more waves allowed the highest forces relative to the wave height to be measured.

For low waves the forces on the breakwater were regular and only slightly higher than that induced by the hydrostatic pressure variation.

For larger waves considerable variation of peak force occurred between one wave and the next, and the highest waves frequently did not produce the largest forces. The force coefficient curves in Fig. 4 are the envelopes of numerous points derived from the records.

The maximum force coefficients in the record increased up to a wave height of about 12 to 15 ft. when the waves started to break and the face of the breakwater began to be overtopped. For further increase in wave height although the force coefficients diminish the maximum force remained sensibly constant up to the maximum waves (22 ft. proto.) that were recorded. Similar experiments with a plain face showed that for 7 second waves the peak positive force coefficients (in the direction of incident wave propagation) were about double those on the perforated breakwater. For 10 second waves the coefficients were similar for the perforated breakwater and the plain face, the maximum forces in this case being of the order of $1\frac{1}{2}$ tons per sq. ft. These results confirm the measurements of Marks which showed that generally the largest horizontal force reductions were to be expected for the lower period waves (ref.3).

STABILITY OF TOE MOUND

Although the perforated face of the proposed breakwater will not extend below low water level and will have a solid base below, scouring of the hard chalk on which it is to be founded is not expected. It is proposed, however, to place a low rock mound against the base near the harbour entrance to reduce wave reflection at low tide. Tests showed that with the most destructive waves that could be generated in the flume, which broke on the toe mound, armour stone of $4\frac{3}{4}$ tons average weight (proto.) was stable at a slope of 1 vertical to $1\frac{1}{2}$ horizontal. $2\frac{1}{2}$ ton stone at this slope was drawn down and the slope flattened to about 1 in $2\frac{1}{2}$.

CONCLUSIONS

The design criteria established by the investigation are:-

1. The length of the wave chamber should not be more than about one third the wave length of the shortest dominant wave to be catered for. With a porosity of 30%, provided the longest wave of significant height is not more than twelve times the chamber depth a maximum coefficient of reflection of 0.5 may be assumed.

2. Lower force coefficients were obtained with the perforated face than with a plain face for 7 second waves, but were little changed with 10 second waves. However some reduction in the forces is obtained at both wave periods due to the fact that the height of the waves at the wall is reduced as shown by the reflection tests.

It is evident from these two conclusions that the requirements for reduction in wave reflections and reduction in wave forces tend to conflict. While the 7 second period wave, which is about 7 times as long as the depth of the breakwater cells gives acceptable force coefficients, the 10 second period wave (length about $11\frac{1}{2}$ times the cell depth) tends to fill the cells and the breakwater then behaves like a solid structure. In practice it would seem that waves of length between 3 and 8 times the cell depth can be absorbed by a sturcture of the type tested; if longer waves of significant height ($H_W/h > 0.2$) are expected then a wider breakwater is necessary, in order to incorporate a greater cell depth, if the structure is not to be subjected to forces nearly as great as those which would be imposed on a solid breakwater.

REFERENCES

1. Jarlan, G.E. Application of acoustic theory to the reflective properties of coastal engineering structures, Quart Bull 1965, Nat. Res. Coun. Canada (1) 1965, 23-63.

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Appendix

Analysis

(i) Normal Incidence

We suppose that waves are incident normally on the screen at $x = 1$, the back face being situated at $x = 0$ (Fig. 5). In front of the screen the depth is constant (h_1) and the particle velocity u, wave elevation η; behind the screen the depth is h_2 and the particle velocity u^1, wave elevation η^1

The linearised equations of motion for the flow are

$$\frac{\partial \eta}{\partial t} + h_1 \frac{\partial u}{\partial x} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + g \frac{\partial \eta^1}{\partial x} = 0, \text{ for } x > 1; \quad (2)$$

and $$\frac{\partial \eta^1}{\partial t} + h_2 \frac{\partial u^1}{\partial x} = 0 \quad (3)$$

$$\frac{\partial u^1}{\partial t} + g \frac{\partial \eta^1}{\partial x} = 0, \text{ for } 0 < x < 1 \quad (4)$$

It is convenient to assume that η, u etc. are proportional to $\exp(i\sigma t)$ in which we will eventually reject the imaginary part, σ being the angular velocity of the waves $2\pi/T$, T being the wave period.

Equations 1-4 are satisfied by

$$\eta = A \exp ik_1x + B \exp -ik_1x \quad (5)$$

$$u = -\frac{\sigma}{k_1h_1}\left[A \exp ik_1x - B \exp -ik_1x\right], \; x > 1 \quad (6)$$

and

$$\eta^1 = A^1 \exp ik_2x + B^1 \exp -ik_2x \quad (7)$$

$$u^1 = -\frac{\sigma}{k_2h_2}\left[A^1 \exp ik_2x - B^1 \exp -ik_2x\right], 0<x<1 \quad (8)$$

with $$\sigma^2/k_1^2 = gh_1 = C_1^2 \quad (9)$$

and $$\sigma^2/k_2^2 = gh_2 = C_2^2 \quad (10)$$

$$\text{and} \quad k_1 = 2\pi/L_1, \; k_2 = 2\pi/L_2 \tag{11}$$

L_1, L_2 being the wave length in front of and behind the screen. A, B are constants representing the amplitudes of the incident and reflected waves in front of the screen and A^1, B^1 represent the transmitted wave and its reflection from the back face.

To determine the constants we have the boundary conditions that at the back face x = 0, $u^1 = 0$ and hence

$$A^1 = B^1 \tag{12}$$

and at the screen x = 1, we have from continuity and from the momentum balance

$$h_1 u = h_2 u^1 \tag{13}$$

$$\text{and} \quad g\,(\eta-\eta^1) + k_* u^1 |u^1| + a^1 \frac{\partial u^1}{\partial t} = 0 \tag{14}$$

where $a^1 \rho h_2$ is the effective virtual mass introduced by the screen, ρ being the water density, and k_* is the drag coefficient of the screen.

In order to proceed we have linearised the friction term in (14) by the usual Lorentz approximation to give

$$g\,(\eta-\eta^1) + (f + a^1 i\sigma)u^1 = 0 \tag{15}$$

$$\text{where} \quad f = 8k_* \tilde{u}^1/3\pi \tag{16}$$

in which $\tilde{u}^1$ is the amplitude of the particle velocity at the screen (x = 1).

We may now substitute for η,η^1, u,u^1 from equations (5)-(8) in (15)and (16) to determine the constants and after some manipulation we find the reflection coefficient $R = |B|/|A|$ as

$$R^2 = N_1/D_1 \tag{17}$$

where

$$N_1 = \left[\cos k_2 l - a^1 k_2 \sin k_2 l\right]^2 + \left(\frac{f}{c_2} - \frac{k_1}{k_2}\right)^2 \sin^2 k_2 l$$

and

$$D_1 = \left[\cos k_2 l - a^1 k_2 \sin k_2 l\right]^2 + \left(\frac{f}{c_2} + \frac{k_1}{k_2}\right)^2 \sin^2 k_2 l$$

with

$$\frac{f}{c_2} = \frac{8}{3\pi} k_* \frac{A}{h_2} \quad 2\sin k_2 l/D_1 \tag{18}$$

The latter being an implicit equation to determine f/c_2 in terms of the incident wave height.

We note that R = 1 when $k_2 l = 0, \pi$ .. etc. or the length l is a multiple of half the wave length. Also if we assume for the moment that f is constant, minimum values of R occur at

$$\cot k_2 l = a^1 k_2 \tag{19}$$

and

$$R^2_{min} = \left[(f/c_2 - k_1/k_2)/(f/c_2 + k_1/k_2)\right]^2 \tag{20}$$

with $R_{min} = 0$ when $f/c_2 = k_1/k_2$.

To estimate the reflection coefficient we need to estimate the drag coefficient of the screen k_* and the virtual mass coefficient a^1. For the former it has been assumed that a vena contracta is formed at the perforations of area 0.6 times the area of the openings and that the velocity head through the vena contracta is lost.

Thus if s is the area of the openings and S is the area on the downstream side of the screen up to high water, the head loss across the screen is given by

$$g(\eta^1 - \eta) = \frac{(u^1)^2}{2}\left[\left(\frac{S}{0.6s}\right)^2 - 1\right] \tag{21}$$

so that

$$k_* = \frac{1}{2}\left[\left(\frac{S}{0.6s}\right)^2 - 1\right] \tag{22}$$

In the present case s/S = 0.37 and hence $k_* = 9.5$.

There is little guide from theory for the effective value of a^1. Trial calculations were made of the wave periods to give minimum reflection coefficients with different values of a^1 and a value selected (a^1 = 6 ft) which gave agreement with experiment for a uniform chamber length l = 34.5 ft. This value was used in the calculations of R for the smaller length, 27¼ ft.

(ii) Oblique incidence

For waves incident on the screen at an angle Θ between the normal to the wave front and the normal to the screen, the equations of motion outside the screen ($x > 1$) are satisfied by

$$\eta = A \exp i(k_1\cos\theta x + k_1\sin\theta . y) + B \exp i(-k_1\cos\theta x + k_1\sin\theta y) \qquad (23)$$

$$u = -\frac{\sigma\cos\theta}{k_1h_1} \cdot \Big[A \exp i(k_1\cos\theta x + k_1\sin\theta y) - B \exp i(-k_1\cos\theta x + k_1\sin\theta y)\Big] \qquad (24)$$

$$v = -\frac{\sigma\sin\theta}{k_1h_1} \cdot \Big[A \exp i(k_1\cos\theta x + k_1\sin\theta y) + B \exp i(-k_1\cos\theta x + k_1\sin\theta y)\Big] \qquad (25)$$

In which η is the surface elevation and u, v are the velocity components normal and tangential to the screen Ox.

and $\sigma/k_1 = c_1$ as before.

In these equations B is the amplitude of the reflected wave and it has been assumed that the angle of incidence and reflection are equal.

Behind the screen ($0 < x < 1$) the elevation (η^1) and the normal velocity (u^1) are again given by (7), (8) and (12) and to satisfy continuity and friction loss across the screen we again suppose equations (13) and (15) to apply. Substituting for u, η from (23) and (24) in these equations gives after some manipulation

$$R^2 = N_2/D_2 \qquad (26)$$

where

$$N_2 = \left[\cos k_2 l - a^1 k_2 \sin k_2 l\right]^2 + \left(\frac{f}{c_2} - \frac{k_1}{k_2\cos\theta}\right)^2 \sin^2 k_2 l$$

$$D_2 = \left[\cos k_2 l - a^1 k_2 \sin k_2 l\right]^2 + \left(\frac{f}{c_2} + \frac{k_1}{k_2\cos\theta}\right)^2 \sin^2 k_2 l$$

which is similar to equation (17) but with $k_1/k_2 \cos\theta$ substituted for k_1/k_2. If f is taken constant to a first approximation, we note that R is a minimum when $\cot k_2 l = a^1 k_2$ as for the case of normal incidence, so that the angle of incidence has no effect on the selectivity of the breakwater to wave period. This is in agreement with the experimental results.

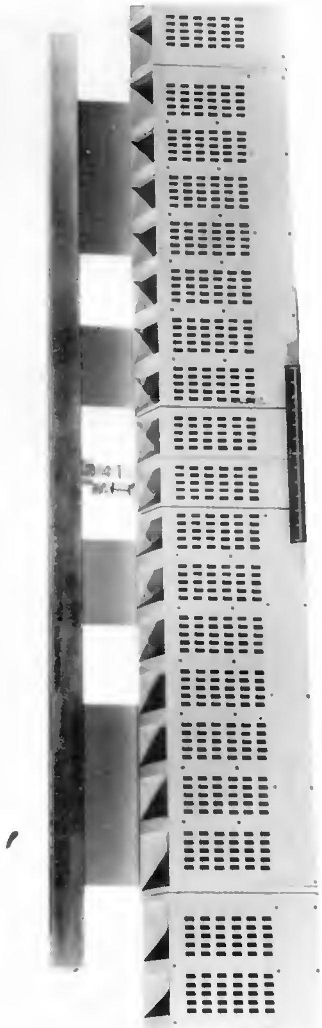


PLATE 1. MODEL BREAKWATER SHOWING PARALLEL CANTILEVER SUSPENSION OF CENTRE SECTION FOR FORCE MEASUREMENT

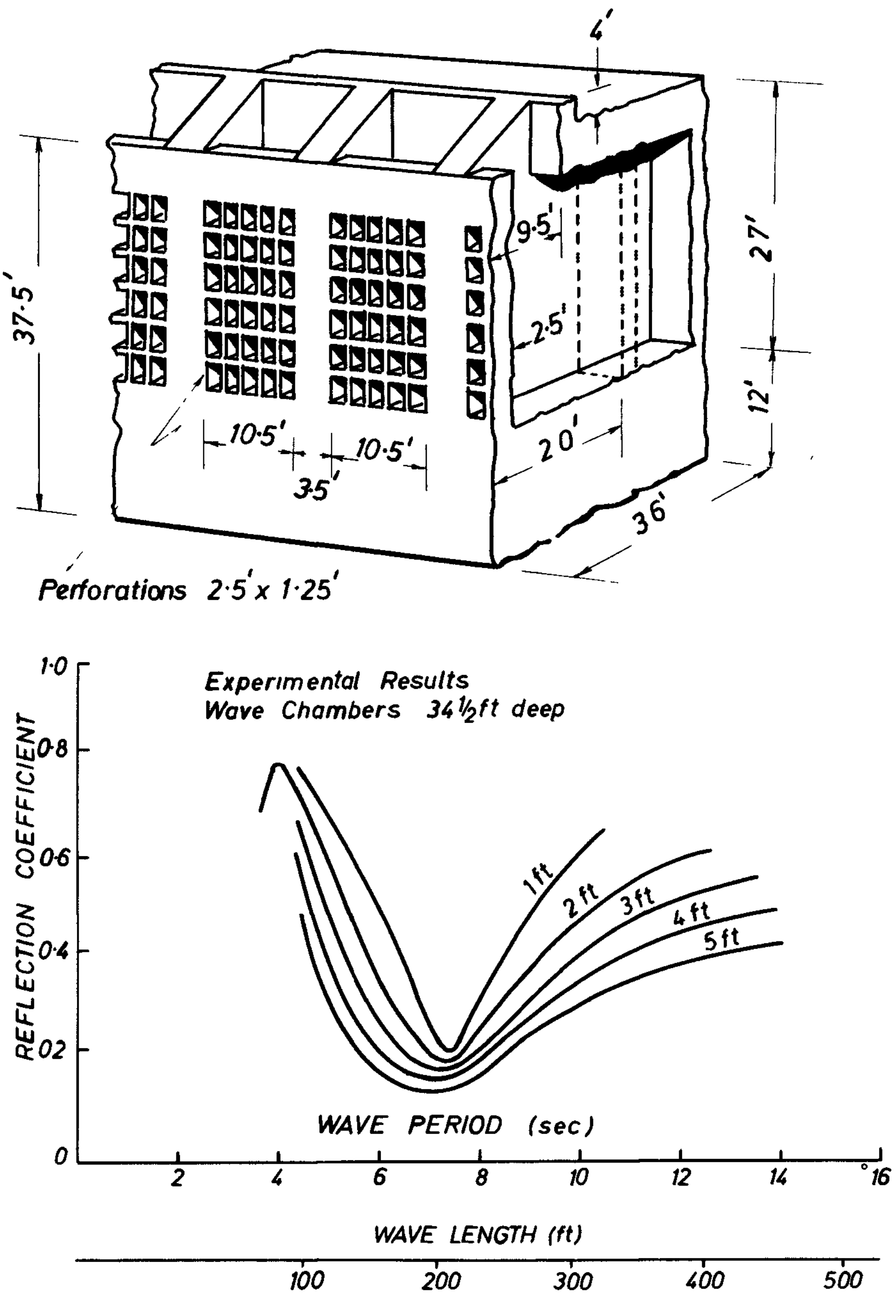


FIG 1 REFLECTION COEFFICIENT - NORMAL INCIDENCE

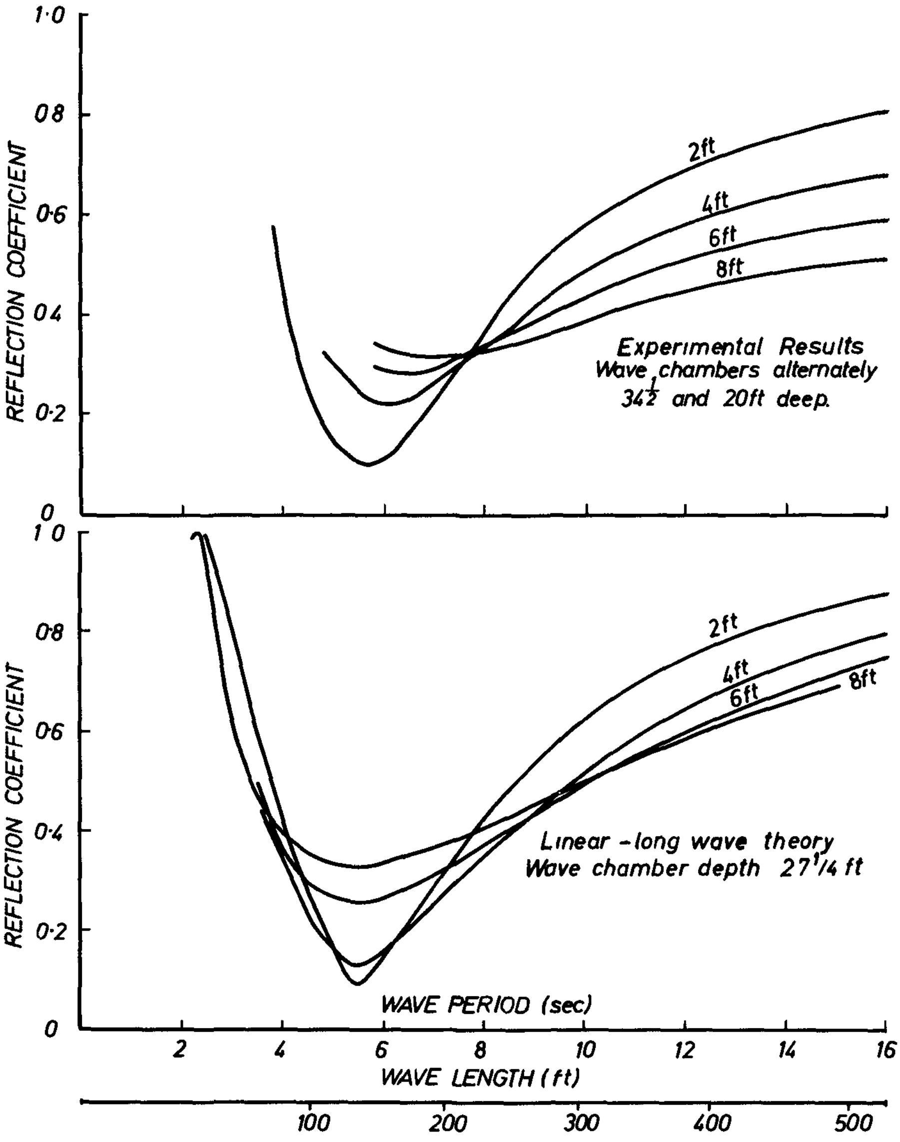


FIG 2. COMPARISON OF EXPERIMENTAL AND THEORETRICAL REFLECTION COEFFICIENTS-NORMAL INCIDENCE.

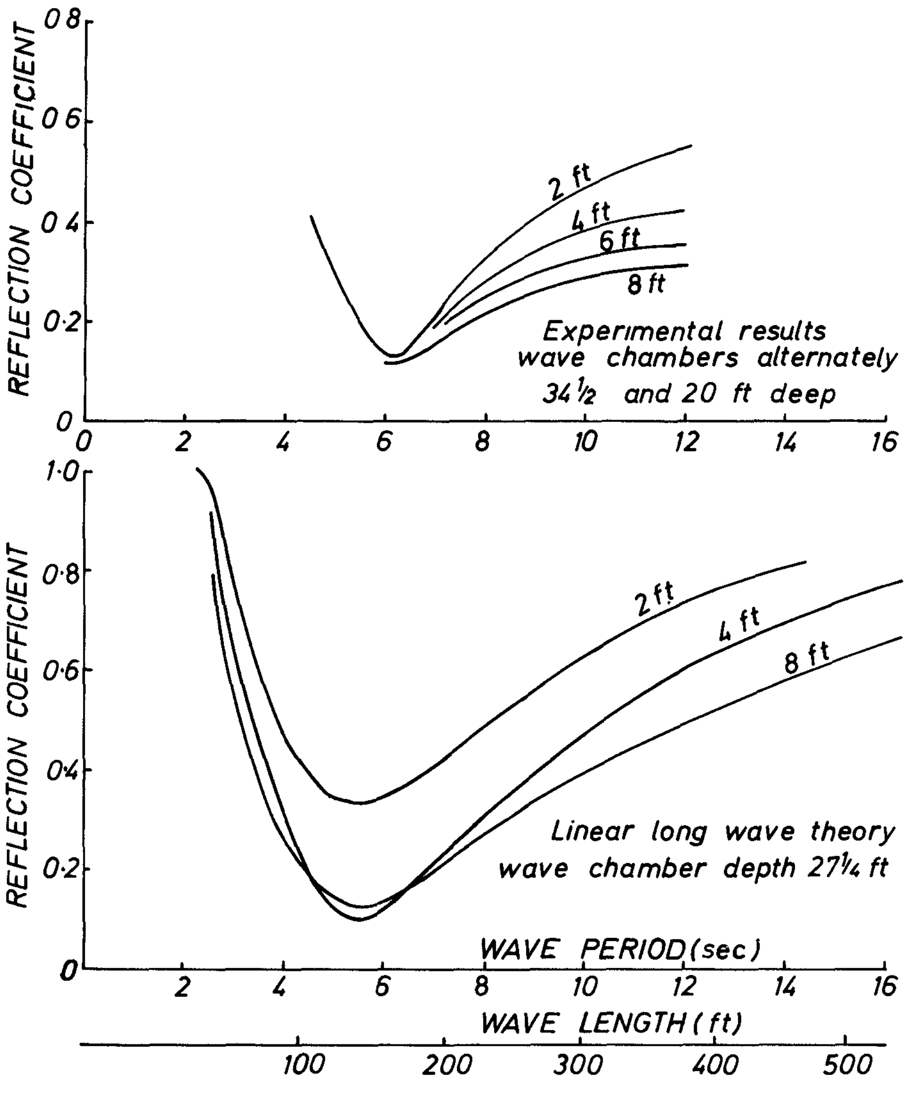
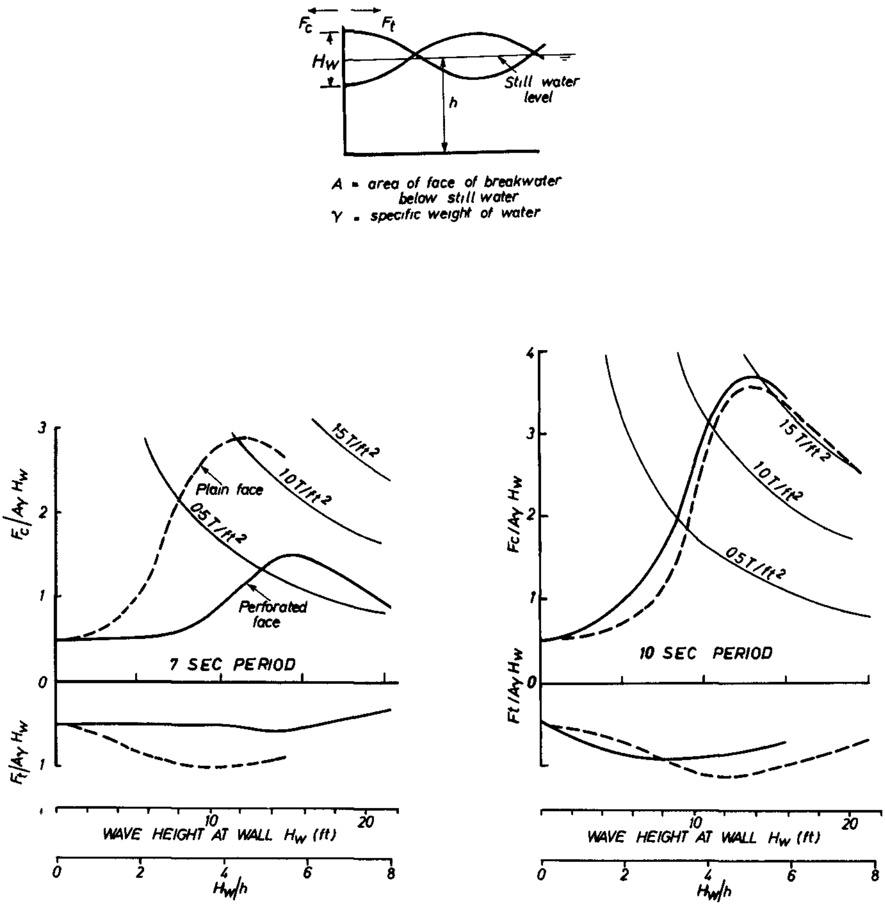


FIG 3 COMPARISON OF EXPERIMENTAL AND THEORETICAL REFLECTION COEFFICIENTS –45° INCIDENCE



ENVELOPE OF PEAK HORIZONTAL FORCE

FIG 4

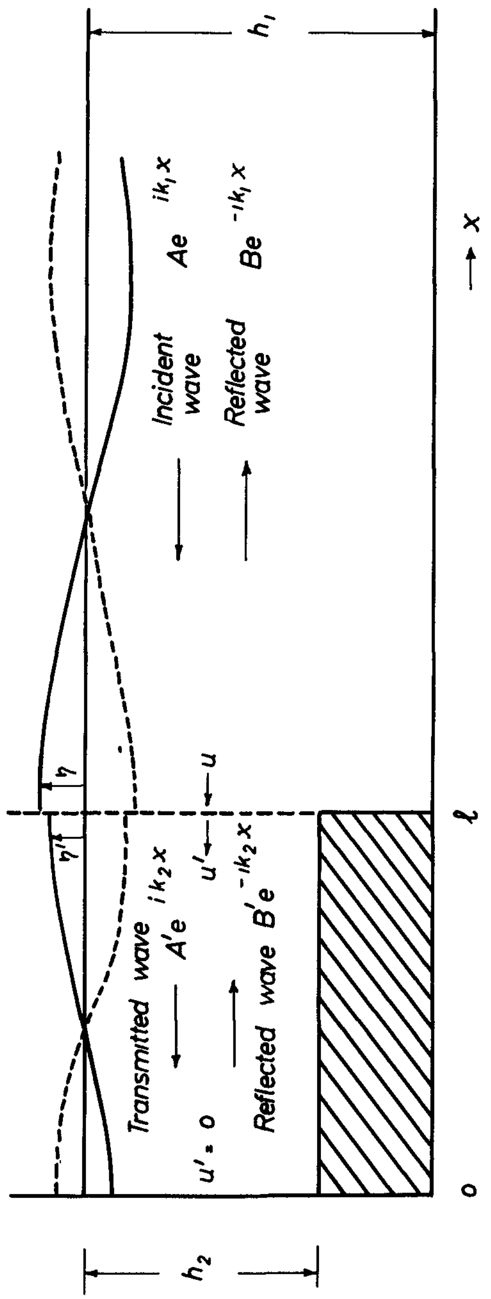


FIG 5 REFLECTION OF WAVE FROM PERFORATED FACE