CHAPTER 58

Reflections from coastal structures

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Abstract

Wave reflections at and within a coastal harbour may make a significant contribution to wave disturbance in the harbour. Reflected waves may lead to danger to vessels navigating close to structures, and may reduce the availability of berths within the harbour. Wave reflections may also increase local scour or general reduction in sea bed levels.

In the design of breakwaters, sea walls, and coastal revetments, it is therefore important to estimate and compare the reflection performance of alternative structure types. In the use of numerical models of wave motion within harbours, it is essential to define realistically the reflection properties of each boundary. This paper presents results from a study of the reflection performance of a wide range of structures used in coastal and harbour engineering.

1 Introduction

The importance of wave reflection from coastal and harbour structures has historically been given relatively little weight in the design of harbours or of coastal protection schemes, despite the problems that may arise from the cumulative increase in wave energy. Typically, increased wave action due to reflections may lead to:

a) danger in navigating vessels through steep seas arising from the interaction of incident and reflected wave trains, this often occurs at harbour entrances;
b) increased berth down-time within the harbour arising from unacceptable vessel motions during loading or unloading;
c) damage to vessels, moorings, or fenders, arising from increased mooring forces;
d) increased wave velocities, and hence shear stresses, at the structure toe, leading to potentially greater local scour or sea bed erosion.

This paper summarises results from a study of the reflection performance characteristics of a wide range of structure types used in

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coastal and harbour engineering. The report on that study (Ref 1) discusses the design and use of wave absorbing structures, and derives values of empirical coefficients for the prediction of reflection performance in random waves. Some of the results of that study have been employed in the derivation of appropriate boundary conditions for the numerical modelling of wave disturbance in harbours (Ref 2).

2 Wave absorbing structures

Coastal structures devised to absorb or dissipate wave energy may be considered under three main categories:

a) non-porous, slopes;
b) armoured, porous, slopes;
c) porous vertical face or faces.

Each of these structure types will dissipate some proportion of the incident wave energy and will generally reflect the greatest part of the remainder. At the extremes the reflection performance of such structures may be compared either with that of a vertical wall, for which the proportion reflected approaches unity, or with a gently sloping yet porous beach for which the energy reflected approaches zero.

A number of different mechanisms may be employed to absorb or dissipate wave energy. These will depend upon the properties of both the structure, and of the incident waves. A number of empirical methods have been developed to aid the identification of wave behaviour at such a structure. Of these a single parameter of particular relevance to wave action on sloping structures is the Iribarren number, Ir, sometimes known as the surf similarity parameter, introduced by Battjes. For regular waves:

$$Ir = \tan \alpha/(H/L_o)^{\frac{1}{2}} \tag{1}$$

On non-porous rough slopes wave run-up and reflections are generally similar to those on the equivalent smooth face, but with some further energy dissipation due to the greater frictional and turbulent losses.

The behaviour of waves at an armoured rubble slope is different in that a significant depth of porosity in the armour and under-layers, and perhaps the core, is available for energy dissipation. Much of the incident wave energy may be converted to flows over and within the armour and under-layers, thence being dissipated in turbulence within the voids. Some of this energy may be converted to pumping water into the mound, particularly under long period waves when the phreatic surface inside a rubble mound may be considerably elevated. Energy from such flows will be substantially lost in frictional flow within the porous rock layers.

The advantages of vertical face structures over those with sloping faces lie in the efficient use of space, economy of material, and the ability to moor vessels alongside. These factors are of considerable importance to the harbour engineer. Problems due to the reflections from solid vertical faces suggest a number of alternative forms of construction. Porous vertical walls must dissipate wave energy in a gradual manner to avoid undue reflections. Significant energy absorption will require a reasonable depth of structure in relation to the incident wave length. Examples of types of structures to do this include:

a) cribwork or gabion walls;
b) piled wave screens;
c) perforated caissons; and
d) stacked voided blockwork.

Each of these structure types offer some considerable advantage over sloping face structures in the greater utilisation of the harbour area. In general, however only the last three types (b)-(d) are likely to be used in harbours.

The simplest wave absorbing vertical walls used in harbours are single or multiple wave screens. These may be formed of closely spaced elements such as steel or timber piles, concrete or timber planks, or other pre-cast concrete elements. In a single screen porosities, n_a, of around 5-20% will commonly be used. The screen elements are generally supported on a steel or timber pile structure. This may allow the provision of two or more screens on the same structure. Examples of the design and/or construction of single or double wave screens are described by Gardner et al (Ref 3), and Hutchinson & Raudkivi (Ref 4).

A single screen alone will absorb or dissipate relatively little of the incident wave energy. Most will be either reflected or transmitted. Certain arrangements of two or more screens may be devised to yield acceptable levels of reflection, whilst restricting wave transmission.

The simplest multiple screen in general use incorporates a perforated front screen separated from a solid rear screen by a spacing B. For B equal to around 0.25 of the local wavelength Ls, waves transmitted through the front screen will reflect off the rear screen to return to the front screen exactly out of phase with the next wave. The resulting interference leads to a significant dissipation of wave energy between the two screens, and hence yields particularly low reflections. For wavelengths other than the optimum of 4B, the reflection performance will be less good. By judicious choice of screen porosity n_a, and screen spacing B, acceptable reflection performance may be obtained over a reasonable range of wavelengths, or wave periods.

Similar principles may be used in the design of pre-cast concrete caissons with a perforated front face. Such caissons will incorporate at least two chambers: one open to wave-induced flows; the other filled with sand or concrete to ensure adequate resistance to sliding or overturning. The front face may be perforated by horizontal or vertical slots, or by circular holes. The perforations may extend only part depth and/or vary in spacing with depth. The size and shape of the void chamber may vary, as may its complexity.

Some of the hydraulic characteristics of the wave-absorbing caisson can be obtained on a smaller scale by the use of voided concrete blocks. These may be stacked vertically to form breakwaters, sea walls, or in some instances quay walls. A variety of these blocks have been developed, and most have been widely patented. Examples of stacked voided blocks are:

Igloo	Perforcell
Neptune	Pilock
Cross-hollow	Triun
Warock	Diaer
Monobar	Tine
Arc	H. W.

3 Calculation of reflection performance

The prediction of the level of reflected wave energy has been investigated using both theoretical and of experimental studies. Methods to allow predictions reflection performance have been identified using three main approaches:

a) empirical equations;
b) mathematical modelling;
c) graphical presentation of model test results.

Empirical equations and coefficients have been developed from the results of hydraulic model tests. Most of the available literature is based on studies with regular waves and often assumes the validity of linear wave theory. Apart from some model tests pertaining to particular structures, few detailed studies have been performed using random waves. The following general empirical equations have been presented:

$$C_r = f\ (a\ Ir^b) \tag{2}$$

$$C_r = a\ Ir\ /\ (Ir + b) \tag{3}$$

$$C_r = a\ Ir^2\ /\ (Ir^2 + b) \tag{4}$$

$$C_r = a\ (1 - \exp\ (-bIr)) \qquad (5)$$

where a and b are empirical coefficients.

For random waves, the significant wave height, H_s, and the wave length corresponding to the period of peak energy density, L_p, are used to define a modified Iribarren number Ir':

$$Ir' = \tan\alpha/(2\pi H_s/gT_p^{\,2})^{\frac{1}{2}} \qquad (5)$$

Smooth slopes

Much of the most useful information for the prediction of wave reflection from non-porous sloping structures is presented by Seelig & Ahrens, a summary of which was later given by Seelig (Refs 5 and 6). For simple smooth slopes Seelig advocates the use of equation 4 with values of a = 1.0 and b = 5.5, giving:

$$C_r = \frac{1.0\ Ir^2}{Ir^2 + 5.5} \tag{6}$$

Seelig also compares the use of equation 4 with coefficients a = 1.0 and b = 6.2 for a smooth slope, with measured data, and the other empirical equations, Figure 1.

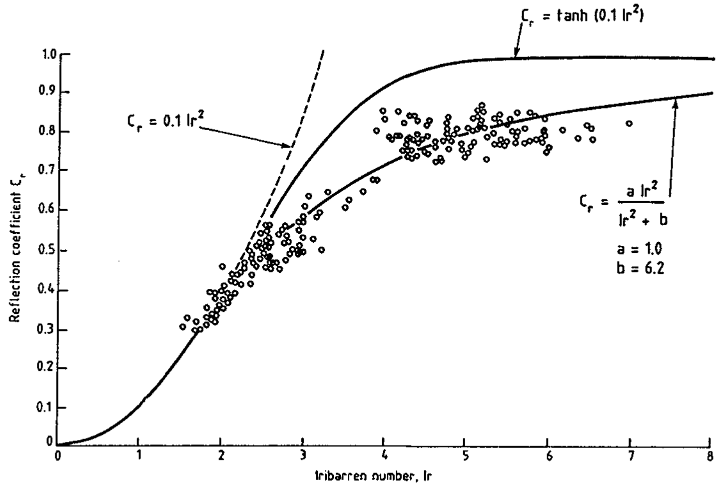


Fig 1 Reflection performance of smooth slopes, after Seelig

Results from earlier studies at Hydraulics Research have been re-analysed. Measurements were made of random wave reflections from smooth slopes of 1:1.33, 1:1.5 and 1:2.0. For conditions within the range 3 < Ir' < 6, prediction equation 4 with Ir = Ir', and empirical coefficients a = 1.08 and b = 5.7, provides a good fit to the experimental data:

$$C_r = \frac{1.08\ Ir'^2}{Ir'^2 + 5.7} \qquad (7)$$

These results are illustrated in Figure 2. It is noted that the predicted values for C_r using these coefficients and the modified Iribarren number, Ir', are slightly greater than those recommended by Seelig.

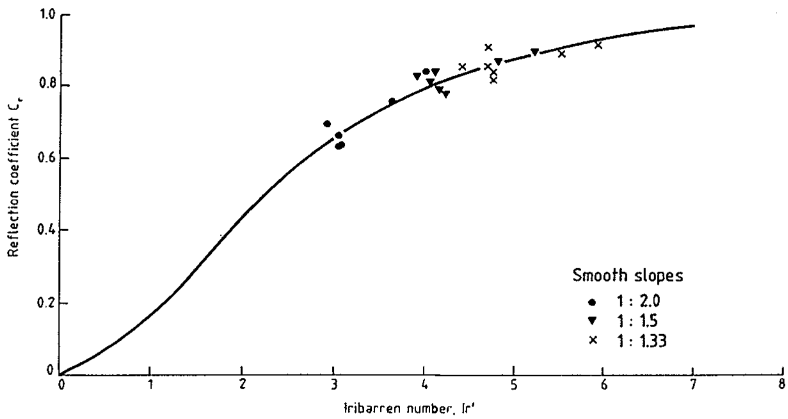


Fig 2 Reflection performance of smooth slopes under random waves

Rough slopes

The reduction in the reflection coefficient due to the placement of rockfill on the surface of an otherwise impervious structure has been investigated by Seelig and Ahrens. For a revetment with layers of armour rock, they recommend values of empirical coefficients to correct predicted reflection coefficients for smooth sloping surfaces using equation 4.

Porous sloping structures

Generally rubble breakwaters, sea walls and revetments will dissipate significantly more wave energy than the equivalent non-porous slope. The principal structure parameters governing this are the armour, underlayer, and core porosities, permeabilities, and available void volume.

For rock armoured structures, Seelig argues that the calculation method based upon the use of equation 4 may be further extended by defining $a = a_1 a_2 a_3$, where the empirical coefficients a_1 a_2 and a_3 take account of relative water depth, thickness of armour and underlayer, and relative armour size. The method is based on successive modifications to the expression for smooth slopes. Alternatively, Seelig suggests that quick and conservative estimates may be made by using equation 4 with $a = 0.6$, $b = 6.6$.

Concrete armour

A sea wall or breakwater armoured with concrete armour units will exhibit a reflection performance that is essentially similar to that of the equivalent rock armoured slope. Some types of concrete armour unit are more open and permeable to wave action than rock armouring, and reduced reflections may therefore be expected. Conversely bulky armour units such as cubes have sometimes been placed very closely with low armour layer porosity, and hence higher reflections will result than might be predicted.

Measurements of the reflection performance of laboratory slopes armoured with concrete armour units have been re-analysed for this study. The results are presented in Figures 3-6 as values of reflection coefficient C_r against Iribarren number Ir, or Ir' for random waves. Empirical equations of the form of equation 4 have been fitted to the data and the results are summarised below:-

Armour	Wave	Range of slope angles	Range of Ir or Ir'	Coefficients in equation 4 a	b
Dolos	Regular	1.5-3.0	$1.5 \leq Ir \leq 5.5$	0.56	10.0
Cobs	Regular	1.33-2.5	$1.5 \leq Ir \leq 4.5$	0.50	6.54
Tetrapods or Stabits	Random	1.33-2.0	$2.5 \leq Ir' \leq 6.0$	0.48	9.62
Sheds or Diodes	Random	1.33-2.0	$3.0 \leq Ir' \leq 6.0$	0.49	7.94

An alternative use of either rock or concrete armouring is in a mound placed against a vertical wall. Such protection will significantly reduce the reflections, as well as protecting the wall from wave impact. Rock or concrete armour may also reduce

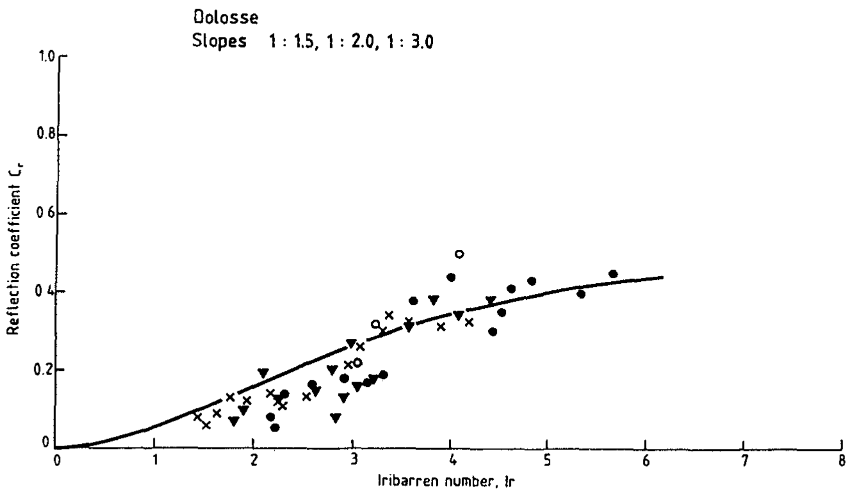


Fig 3 Reflection performance of Dolos armoured slopes, regular waves

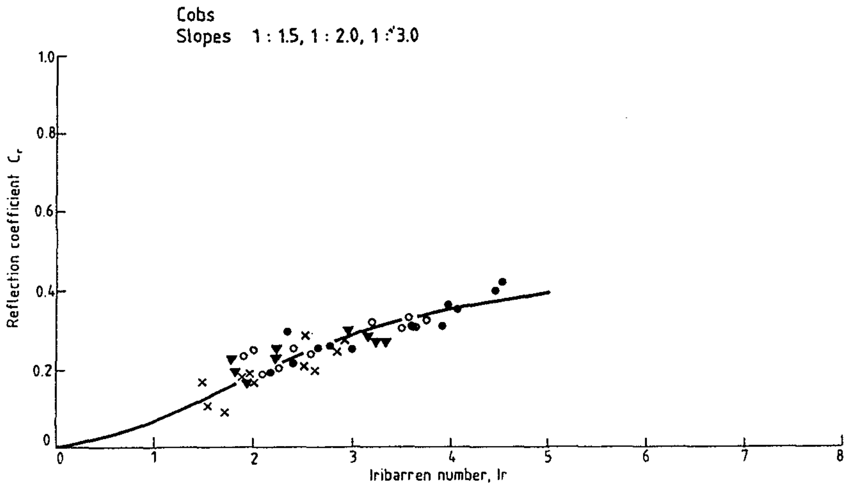


Fig 4 Reflection performance of Cob armoured slopes, regular waves

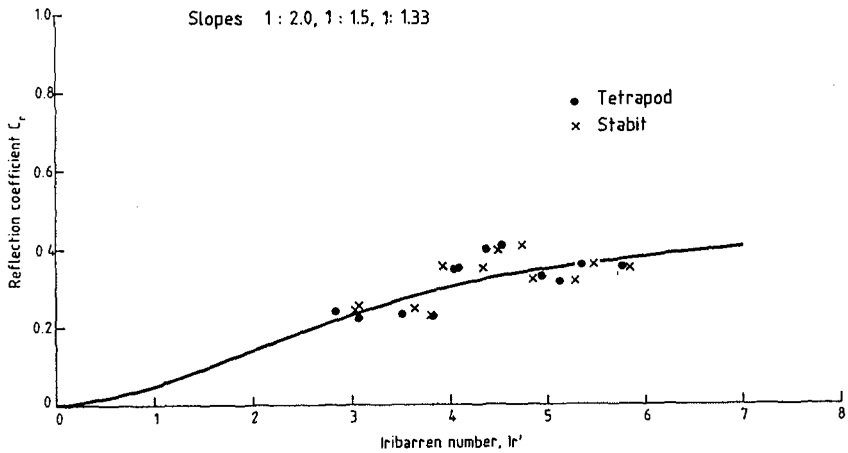


Fig 5 Reflection performance of Tetrapod or Stabit armoured slopes, random waves

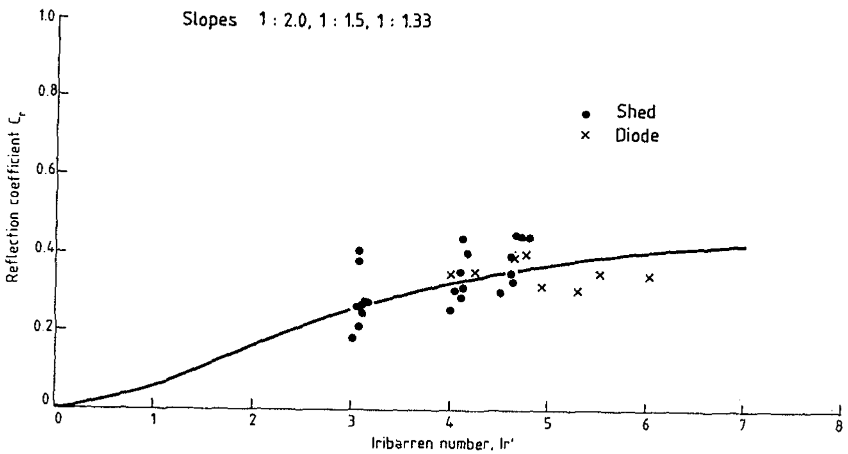


Fig 6 Reflection performance of Shed or Diode armoured slopes, random waves

overtopping. An example of protection to an existing sea wall was discussed at a seminar (Ref 7). Measurements of reflections for three sections are presented in Figure 7. The existing wall, section 1, has high reflections. At low water levels, wave breaking in front of the wall has reduced the reflections to around 0.65. At the higher water levels C_r approaches 0.9. The reflection performance of the alternative rock protection, sections 2 and 3, varies with water level, and particularly with the relative position of the berm formed by the crest of the rock protection. For those water levels close to the crest level of the rock the reflection coefficient reaches minimum values with C_r around 0.20–0.30. When the waves reflect from the armour slope the performance deteriorates slightly with C_r generally nearer 0.4.

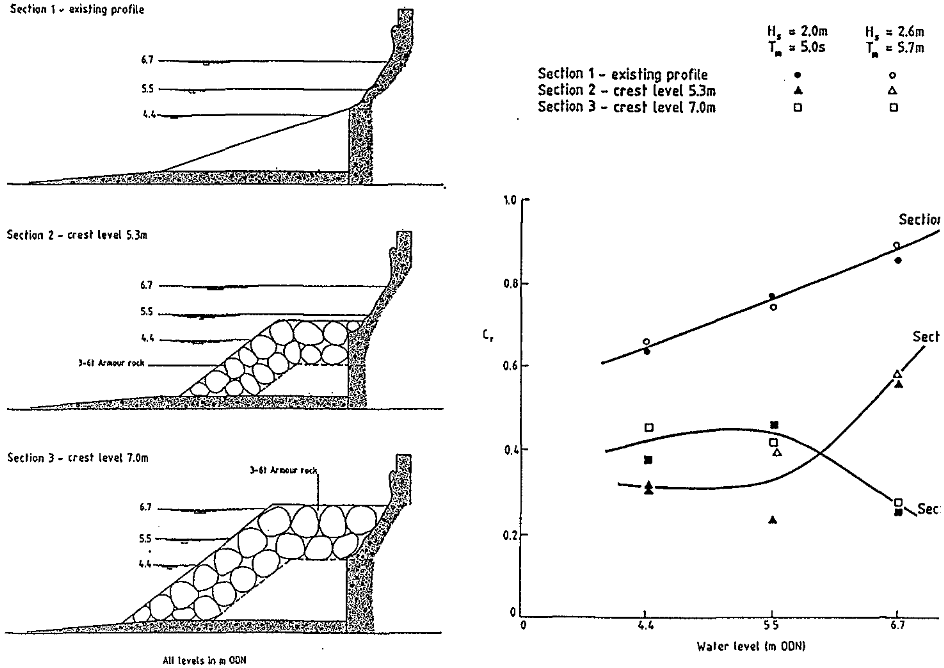


Fig 7 Performance of rock protection to existing wall

Vertically faced structures

Pervious wave screens or pile arrays have been much studied by researchers concerned with wave energy transmission, dissipation, and reflection. Results from model tests for single wave screens have been presented previously by Kakuno (Ref 8) and Allsop & Kalmus (Ref 9). Example summaries of their results are shown in Figure 8.

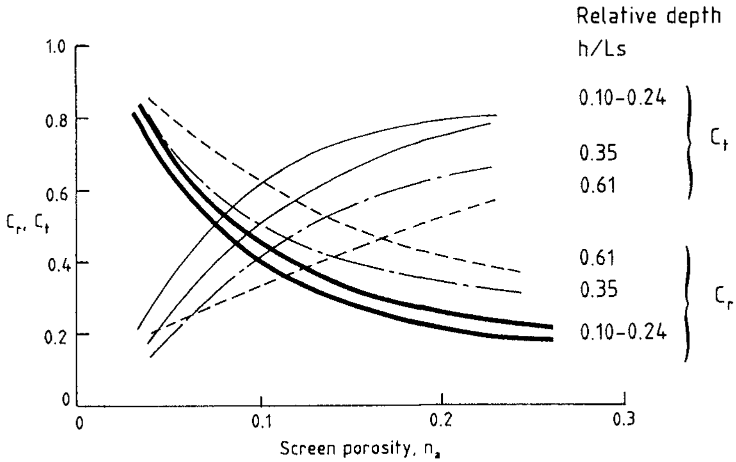
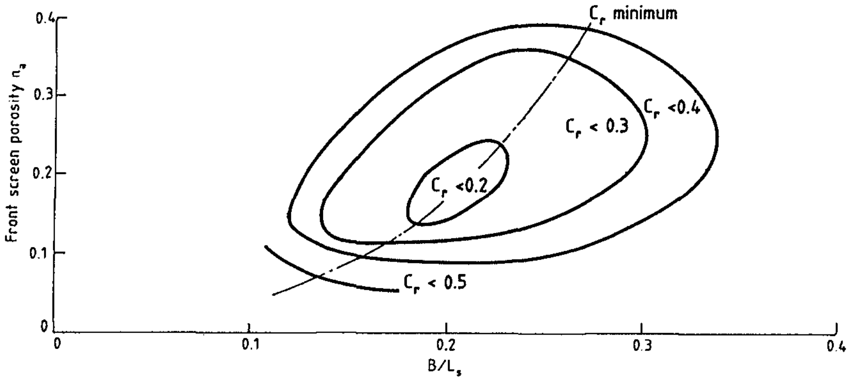


Fig 8 Reflection and transmission for single wave screens

In many instances in coastal and harbour engineering, wave-absorbing structures such as quays or sea walls are built with a solid rear face. The performance of the double wave screen used by Gardiner et al (Ref 3) at Plymouth has been described by Allsop & Kalmus (Ref 9). A simple summary of the effects of front screen porosity, n_a, screen spacing, B, and local wave length, h_s, on the reflection performance is shown in Figure 9. These results, derived from measurements in random waves, seem to indicate that the optimum performance is given by a front screen of porosity, n_a between 0.15 and 0.25. At the lower end of this band the range of wavelengths that give low reflections, say $C_r < 0.4$, is significantly wider than for a screen of porosity around 0.3.

It should be noted that a full description of the processes of wave reflections from a structure would require details of the reflection coefficient function with frequency, of the effects of wave breaking, particularly in shifting energy over frequencies, of the phase shift at reflection, and of the effects of oblique wave/structure interactions. The methods presented in this study therefore represent a considerable simplification of the processes involved. The reader is therefore advised to use the results with some care and circumspection.



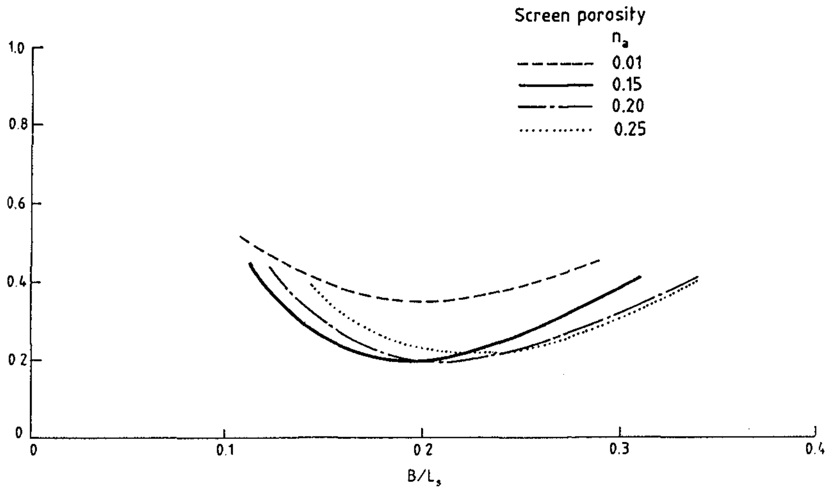


Fig 9 Wave reflection performance of wave screen with impermeable rear wall

4 Conclusions and recommendations

The reflection performance of a range of structure types have been examined and quantified. A general empirical expression of form advanced by Seelig has been used to describe the reflection characteristics of permeable or impermeable slopes. Results from random wave model tests have given values for the empirical expression for permeable slopes armoured with Dolos, Tetrapod, Stabit, Cob, Shed, and Diode, units, and for smooth impermeable slopes. During this study it was not however possible to quantify the reflection performance of rock-armoured slopes under random waves. It was therefore recommended that a systematic series of random wave model tests be conducted to quantify the effect of structure slope, armour size, armour thickness, and berm configuration on wave reflections. (These tests have been conducted, summer 1988, and will be described in a future report, Reference 10).

Vertically faced structures offer the harbour designer potential space saving and enhanced use over structures with sloping faces. This study has reviewed the reflection performance of a range of caisson and voided block systems. This paper has summarised the reflection performance of single and double wave screens under random waves.

5 Acknowledgements

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7 NOTATION

A, B	Empirical coefficients
a, b	"
B	Structure width, in direction normal to face
C_1, C_2, C_i	Empirical or shape coefficients
C_r	Coefficient of reflection, defined $H_r/H_i = (E_r/E_i)^{\frac{1}{2}}$
D	Particle size or typical dimension
D_n	Nominal particle diameter
E_i	Incident wave energy
E_r	Reflected wave energy
g	Gravitational acceleration
H	Wave height, from trough to crest
H_o	Offshore wave height, unaffected by shallow water processes
H_s	Significant wave heigbt, average of highest one-third of wave heights
h	Water depth
Ir	Iribarren or surf similarity number
Ir'	Modified Iribarren number
L	Wave length, in the direction of propagation
L_o	Deep water or offshore wave length, $gT^2/2\pi$
n	Porosity, usually taken as n_v
n_a	Area porosity, proportion of unobstructed area in a screen
S_i	Incident spectral energy density
S_r	Reflected spectral energy density
s	Wave steepness, H/L_o
s_p	Steepness of peak period, $2\pi H_s/g\ T_p^2$
T	Wave period
T_m	Mean wave period
T_p	Spectral peak period, inverse of peak freauency
W	Armour unit weight
W_{50}	Median armour unit weight
α	Structure front slope angle
β	Angle of wave attack