CHAPTER 109

Reflection Performance of Rock Armoured Slopes in Random Waves

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Abstract

Waves reflected from breakwaters and sea walls may cause navigation or mooring problems in or near harbours, and may increase beach erosion or local scour.

This paper gives results of hydraulic model tests on the reflection characteristics of idealised rock armoured slopes. Examples of the performance of a number of practical structures are also discussed.

1. Wave Reflections

The importance of wave reflections from coastal and harbour structures has historically been given relatively little weight in the design process. Recently it has been appreciated that local problems may often arise due to cumulative increases in wave energy, particularly within harbours. Typically, increased wave reflections may lead to:

(a) Danger to vessels, often close to the harbour entrance.
(b) Disruption to handling operations in the harbour due to excessive vessel motions.
(c) Damage to vessel or mooring systems.
(d) Local bed scour.
(e) General increases in erosion at adjoining sites.

Recent studies at Hydraulics Research on wave reflections were prompted by problems experienced in harbours in the Caribbean. Changing wave patterns within these harbours arose from increased reflections from new structures, and from the refraction effects of dredging, (Refs 1, 2). A detailed review of the data available on the wave reflection performance of coastal structures was conducted (Ref 3), and was summarised at the 1988 ICCE (Ref 4). The review noted that data on the reflection performance of rock armoured slopes was sparse, and was restricted

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to regular waves only. It was therefore agreed that a short series of random wave flume tests would be conducted to provide data of general application, and to be used in the numerical modelling of the harbours of interests. This paper presents results from those tests on simple and bermed rock armoured slopes (Ref 5). The paper also presents results from tests on some practical example structures.

2. Measurements and Definitions

In each of the tests considered in this paper, reflections have been measured in a random wave flume. Three wave probes were placed in a constant water depth in front of the test section. Incident and reflected spectra were calculated from the wave probe output by a program developed by Gilbert & Thompson (Ref 6), based on the method of Kajima (Ref 7). This method calculates the reflection coefficient function $C_r(f)$ over the frequency range $0.5f_p < f < 2.0f_p$, where f_p is the frequency at peak energy density for the generated wave spectrum. The reflection coefficient function gives information on the reflection performance with frequency, and is often used in cases where it may be assumed that reflection is a linear process.

At coastal structures wave breaking will have a significant influence on the reflection performance. For this work a total energy approach has therefore been adopted. The reflection coefficient, C_r, is defined in terms of the total reflected and incident energies, E_r and E_i respectively, each parameter measured over the same frequency range:

$$C_r = (E_r / E_i)^{½} \tag{1}$$

3. Reflections from Simple and Bermed Slopes

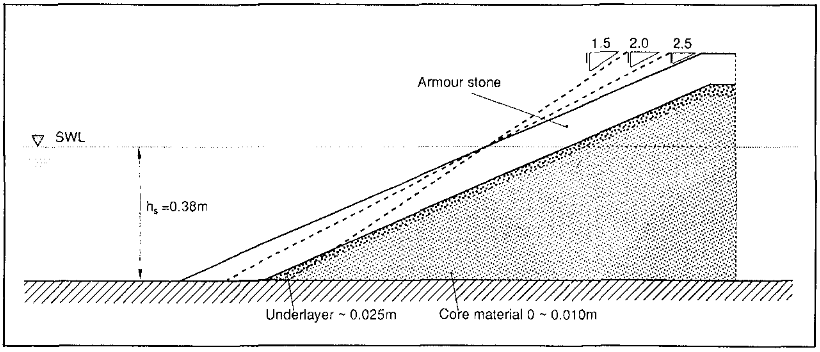

Figure 1 Simple slopes tested

A total of 19 cross-sections were used in these tests to explore the effects of:

(a) front face slope angle, α;
(b) smooth or armoured facing;
(c) armour layer thickness, t_a;
(d) armour unit size, M_{50}, D_{n50};
(e) berm length, B.

For the simple slopes, 3 slope angles were used, cot α = 1.5, 2.0 and 2.5. Smooth and armoured slopes were tested at each angle, Figure 1. A further series of tests explored the influence of 3 berm widths, Figure 2. Armoured slopes were tested with single or double layer armour placement.

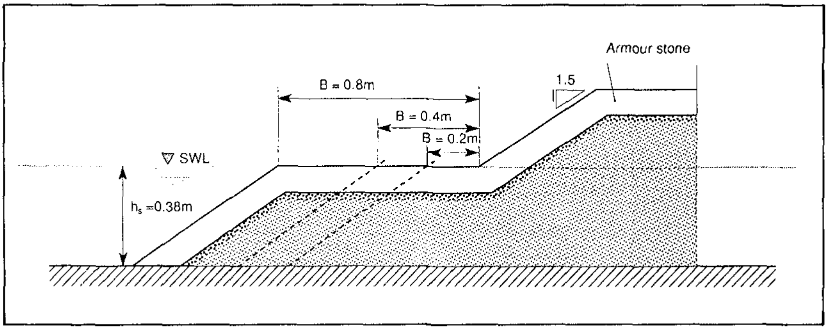

Figure 2 Bermed slopes tested

A set of 9 sea states were used with mean sea steepness, $s_m = H_s/L_m$, from 0.0043 to 0.52. Relative mean local wave lengths, L_{ms}/h_s, varied from 6.2 to 14.8. Values of the Iribarrennumber for the simple slopes, $Ir_m = \tan\alpha/s_m^{½}$, varied between 1.7 and 10.2.

4. Test Results

Simple slopes

The results of the tests were presented as graphs of C_r against Ir for the simple slopes. To these results have been fitted simple empirical equations of the form used by Seelig (Ref 8):

$$C_r = \frac{a\, Ir_m^2}{b + Ir_m^2} \quad (2)$$

This equation was preferred as it is well-known and simple to use, and has been found to give a good description of the reflection coefficient over most of the range of practical interest, see Reference 4. Values of the empirical coefficient a and b were derived for each of the simple slopes tested, both smooth and armoured.

In the preliminary analysis it was noted that the curves calculated by simple regression did not give a good fit over the full range of values tested, and tended to under-estimate C_r at higher values of Ir_m for the rock armoured slopes. A revised analysis was therefore attempted in which a weighting was applied at the larger values of Ir_m. This is not a fully satisfactory approach, it did however give consistently better descriptions of much of the data for smooth and armoured slopes. Examples of the test results are shown in Figures 3 to 6 and values of the empirical coefficients are summarised below:

Test section	a	b
Smooth	0.96	4.80
Rock armour, 2 layer	0.64	8.85
Rock armour, 1 layer	0.64	7.22
Large rock, 2 layer	0.64	9.64
Large rock, 1 layer	0.67	7.87

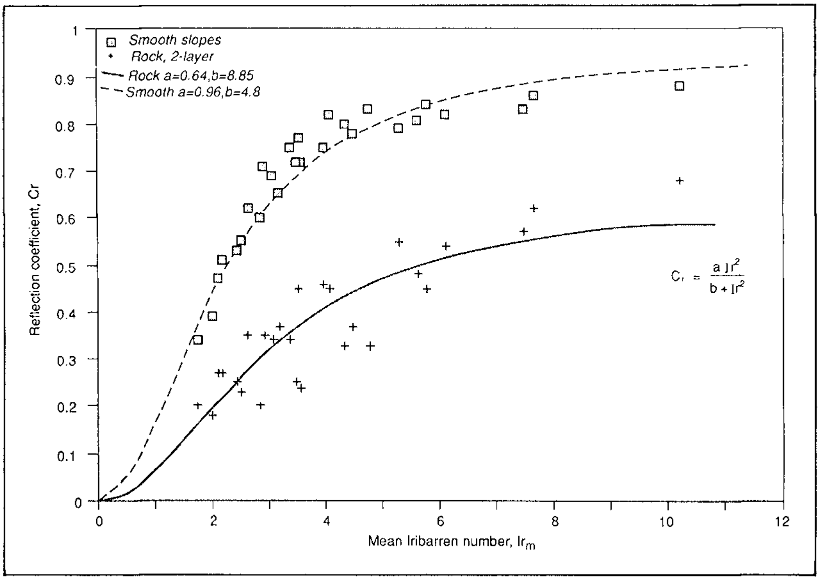

Figure 3 Reflections, smooth and armoured slopes

The results in Figures 3-5 are presented as values of C_r against Ir_m, where the calculation of Ir_m is based upon the deep water wave length of the mean wave period, T_m:

$$L_m = g\,T_m^2/2\pi$$

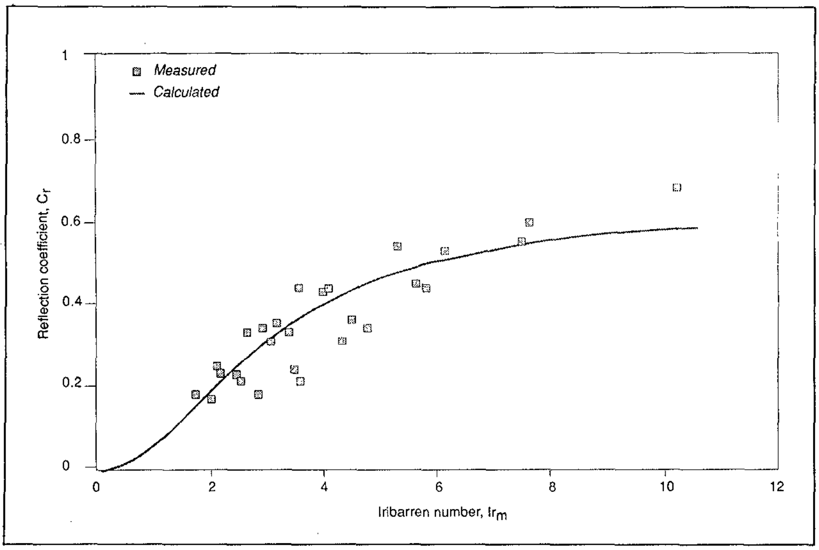

Figure 4 Reflections, large rock, 2 layer

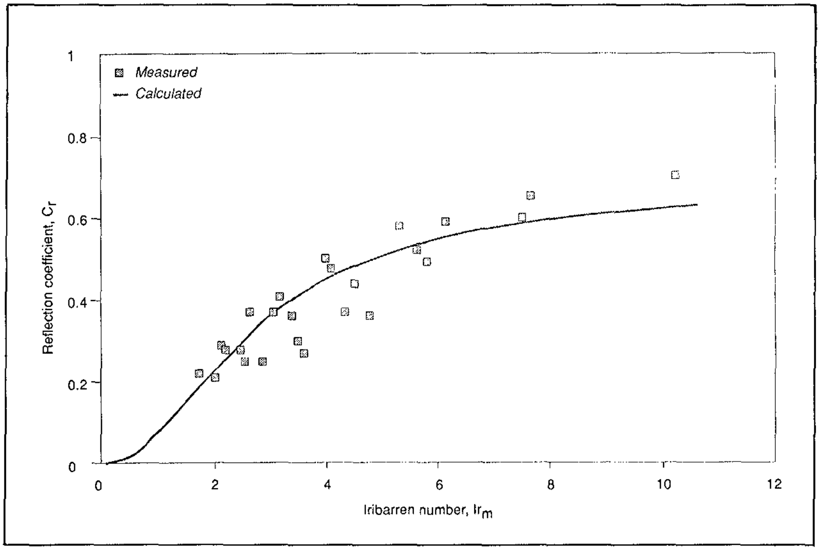

Figure 5 Reflections, large rock, 1 layer

The use of L_m in the calculation of Ir intended to represent the local wave breaking may seem somewhat obstruse. It might be the water depth local to the structure, L_{ms}, would give a more reliable description. The results shown in Figure 3 were therefore re-polotted as C_r against Ir_{ms}, where Ir_{ms} was calculated using the wavelength of the mean period in the water depth at the test section, L_{ms}. These results are shown in Figure 6. Surprisingly there appears to be no improvement through the use of L_{ms} which, being less easy to calculate, complicates the use of any prediction formula based upon it.

This conclusion is similar to one drawn by Yoo (cited by Southgate, Ref 11), who noted the paradox of using an offshore wave parameter to described an inshore process, but found that the use of L_{mo} gave a clearer classification of wave breaking.

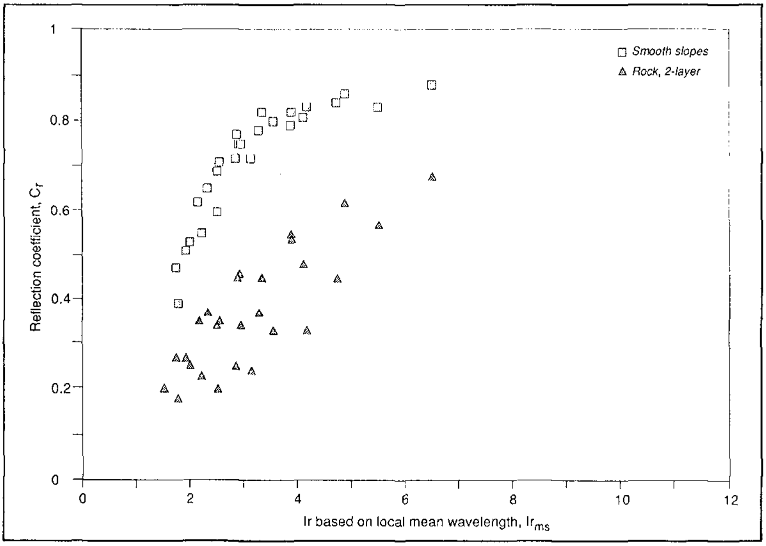

Figure 6 Simple slopes, effect of Ir_{ms}

Bermed slopes

It is difficult to justify the use of the Iribarren number in analysing the performance of bermed slopes. The dimensionless parameter that has been found most useful for such structures is the ratio of berm length to wave length, B/L. The use of this parameter is however complicated by the choice of which wavelength best represents random wave conditions. In this study the wavelength was calculated for the mean wave period both in deep water and in the test water depth, giving L_{mo} and L_{mo} respectively. No clear difference in the fit of the data emerged, and L_{mo} is used in the results shown in Figure 7.

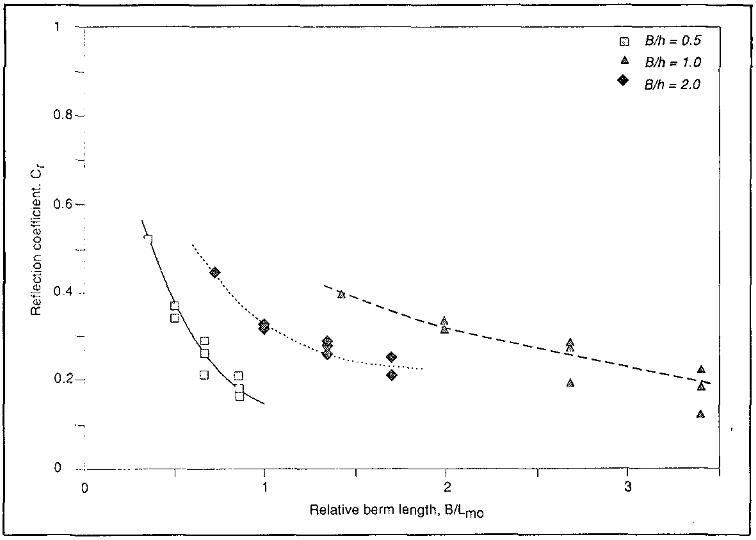

Figure 7 Effect of berm width

Careful consideration of the results shown in Figure 7 suggests that the effect of increasing B on the reflection performance is negligible over the berm widths tested. The separation of the curves for different berm lengths is due primarily to the effect of B in the parameter B/L_{ms}. The data does however suggest that for values of $B/L > 0.05$, the reflections will be reduced to about 50-65% of those from the equivalent simple slope.

5. Comparisons with Other Data

Practical examples of coastal or harbour structures often differ from those for which the test data is used to derive empirical design methods. It is instructive therefore to compare the results of the simple prediction methods available with those measured for realistic structures. Three such examples will be considered here.

Seawall at Blue Anchor Bay

Vertical or slightly battered walls are known to reflect at around 90-100%. These reflections frequently increase local scour, often undermining the wall. Increasingly refurbishment of such seawalls has involved the construction of a rock armoured slope against the wall, reducing wave impacts on the wall, and reducing the level of reflections. Such protection may also improve the wave overtopping performance of the seawall, although some configurations may make matters worse!

In an example described previously (Ref 4), the engineer considered two rock armoured slopes as alternatives to an asphalt grouted toe. The site is subject to a large tidal range, and the wall only experiences significant wave action above about neap high water level, Figure 8.

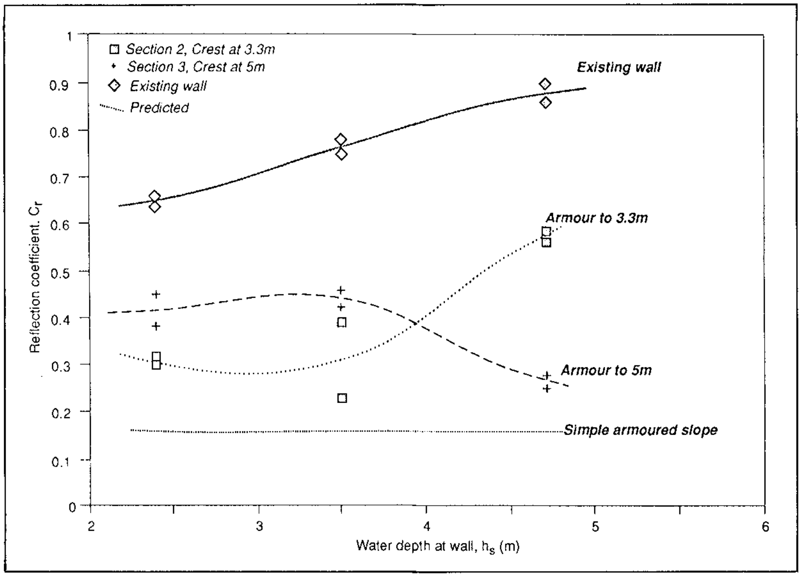

Figure 8 Blue Anchor Bay, sea wall reflections

For the existing structure, C_r reduced from around 0.85 at h_s = 4.7m, to about 0.65 at h_s = 2.4m, principally due to the increasing influence of the (relatively) smooth asphalt slope. Even at the lower test level the rear wall greatly influenced the reflections. A continuous smooth slope at the 1:2.86 angle of the asphalt would reflect at C_r = 0.30 using the data in Section 4.1 above. Two protection schemes were considered, each using rock placed at 1:2.5, to crest levels at 3.3m or 5.0m above the toe. Both schemes reduced the reflections significantly, and in the prototype considerable beach material has built up against the rock. Of interest here however is the comparison of the reflections measured, and those predicted for a continuous armoured slope. For the wave conditions tested, the idealised slope would give C_r = 0.16, but those measured generally exceeded 0.3.

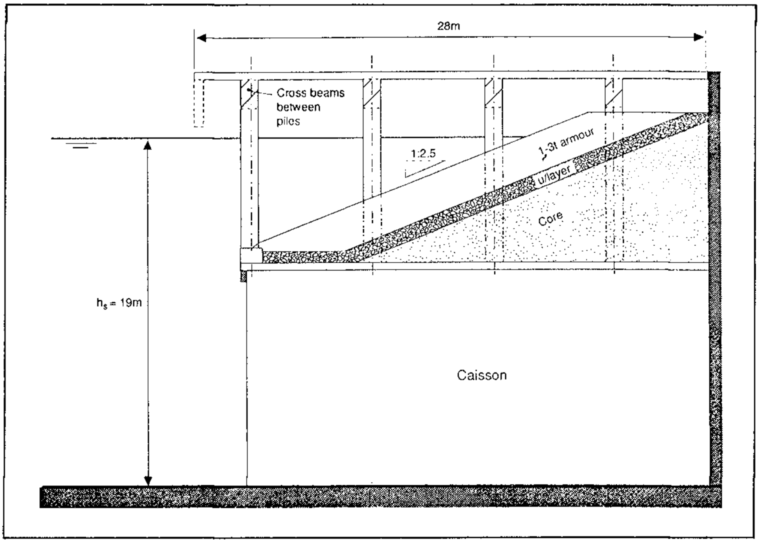

Figure 9 Coal berth quay, option A1/A2

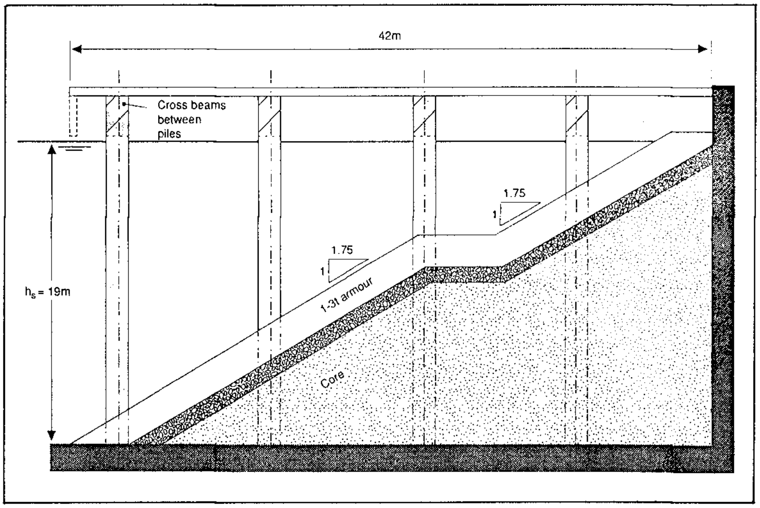

Figure 10 Coal berth quay, option B

Coal berth armoured slopes

Reflections from two alternative harbour structures were compared in a recent study. Both structures were formed by an armoured slope beneath a piled deck. In the first instance, models A1-A3, the rock armoured slope at 1:2.5 was to be constructed on a part-depth caisson, see Figure 9. Models A1 and A2 were very similar, differing only in fine details of the underlayer construction. In both sections waves were able to ride over the crest of the armour. The seaward edge of the armoured slope was about 7m from the impermeable rear wall. Section A3 differed in the crest detail only. For this section the void behind the 4th row of piles was filled, in prototype by a service duct laid on fine fill and concrete footing.

The alternative structure, model B, used a full depth slope at 1:1.75 with a small berm at half water depth, Figure 10. The crest of the armour was very close to the water surface, as was the impermeable rear wall.

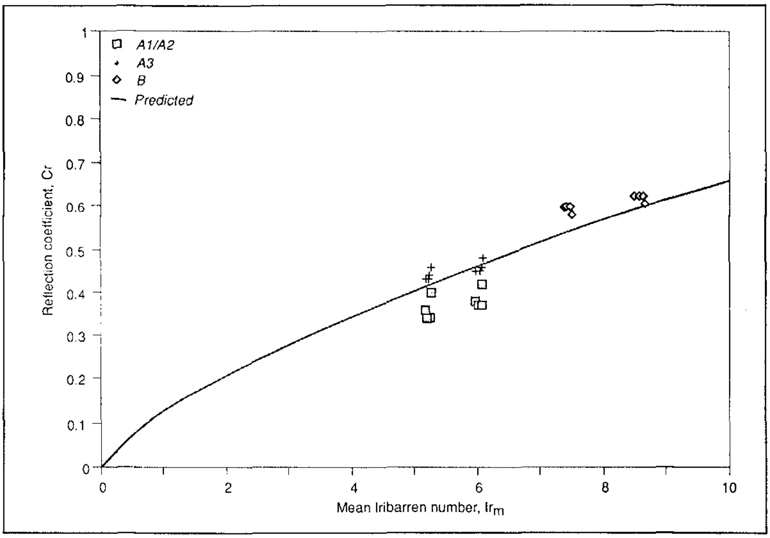

Figure 11 Coal berth quay, reflection performance

The results of the tests may be compared with values of C_r predicted by Seelig's equation with a = 0.64 and b = 8.85. The results are shown in Figure 11. Somewhat to the designer's surprise, model A reflected least, with values below the prediction. The reflections from model A3 were more severe, due to the proximity of the rear wall. The reflections from model B were significantly greater than for A, but when plotted against Ir_m again lie only slightly above the prediction line.

Analysis of other data by Postma

Reflection data measured by van der Meer (Ref 10) on simple armoured slopes have been analysed by Postma (Ref 9), using the surf similarity parameter, or Iribarren number, defined using the steepness of peak period in deep water, $s_{op} = 2\pi H_s/g T_p^2$. For all of van der Meer's data, Posma derived a simple prediction equation:

$$C_r = 0.14\ Ir_p^{0.73} \qquad \text{where} \qquad Ir_p = \tan\alpha / s_{op}^{1/2} \qquad (3)$$

Postma also fitted an equation of the form of (3) to the data in Reference 5:

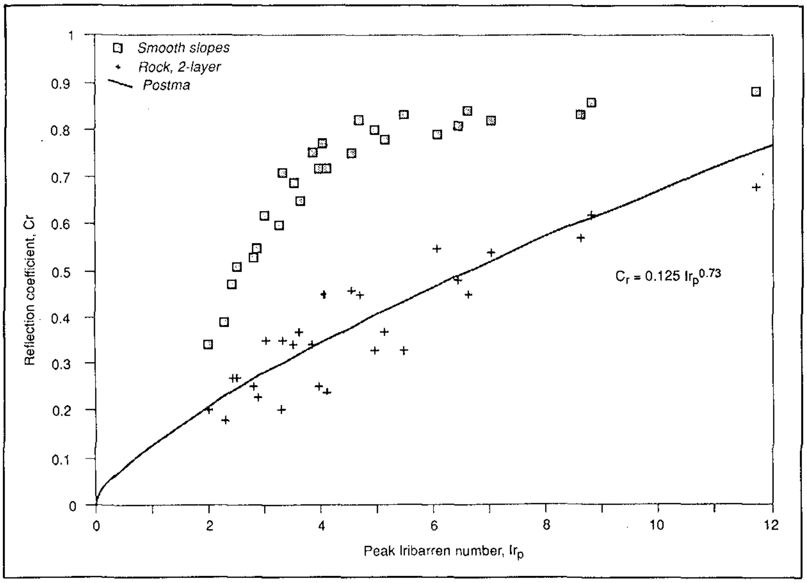

Figure 12 Simple slopes, comparison with Equation 4

$$C_r = 0.125\ Ir_p^{0.73} \qquad (4)$$

Equation 4 is compared with the smooth and armoured slope results in Figure 12. Postma's simple curve gives a good fit to the data for simple rock armoured slopes over the range $2 < Ir_p < 9$.

6. Conclusions and Recommendations

Tests with random waves on idealised simple slopes have given new values for the empirical prediction equation for C_r derived by Seelig. Comparisons of the performance of practical examples have shown that their reflection performance may be strongly influenced by small geometric variations around the water line. Where the structural geometry departs from the idealised structures tested, particularly close to the water level, hydraulic model tests will be required to quantify the reflections.

7. Acknowledgements

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8. References

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