INVESTIGATION OF WAVE REFLECTION 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 cause mooring problems. Wave reflections may also increase local scour or general reduction in sea bed levels. In the design of breakwaters, seawalls and coastal revetments it is very important to estimate and compare the reflection performance of alternative structural types with respect to wave energy dissipation characteristics. This paper presents the results from a study of the reflection performance of a wide range of structures used in harbour and coastal engineering.

1. Objective of the paper

This paper presents selected results of a detailed study the objectives of which were to assess the hydraulic performance of coastal structures with respect to energy transformation processes. The study investigated various aspects of wave/structure interaction of a wide range of coastal structures used in practice. This paper focuses attention on wave reflection an important design parameter which is a quantitative measure of the hydraulic performance with respect to wave energy dissipation. The reflection performance of different configurations are discussed based on research data obtained as part of this investigations and analysis of data from previous investigations conducted at leading research laboratories. Types of prediction methods are identified and empirical equations are presented as design guidelines.

2. Wave absorbing structures for coastal and flood defence

Coastal structures are used to dissipate and/or reflect wave energy to protect land or water behind them from the effects of waves. Although tide or surge-induced water movements may influence the water levels at the structure giving rise to local currents, it is the action of wind waves and swell which constitute the principal forces acting on the structure. These structures may be broadly classified into five main categories.

a) Non-porous slopes
b) Armoured porous slopes
c) Non-porous vertical walls
d) Porous vertical walls
e) Porous sloping protection to vertical walls

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

Wave action on a coastal structure results in a number of processes of interest to the designer. Wave energy arriving at a structure will experience three main transformations, namely,

a) dissipation
b) transmission, by overtopping and due to the permeability of the structure, where applicable
c) and reflection

The conservation of energy will be satisfied by an energy sum;

$$E_i = E_r + E_t + E_d \tag{1}$$

where
E_i = total incident energy
E_r = energy reflected
E_t = energy transmitted
E_d = energy dissipated at the structure

In effect the purpose of the structure is to alter the balance of these three processes to reduce the amount of wave action reaching the land or water behind and/or to reduce reflections. The conservation of energy shows that in order to decrease the significance of a particular process it is necessary to increase the significance of the others or to reduce the amount of energy reaching the structure.

The wave reflection coefficient (Cr), the transmission coefficient (Ct) and the dissipation coefficient (Cd) are correlated by the relationship.

$$Cr^2 + Ct^2 + Cd^2 = 1 \tag{2}$$

where
$$Cr = (E_r / E_i)^{½} \tag{3a}$$

$$Ct = (E_t / E_i)^{½} \tag{3b}$$

$$Cd = (E_d / E_i)^{½} \tag{3c}$$

Each of these energy components is considered to be expressed by the corresponding square of the wave height ($E \propto H^2$) and measured over the same frequency range.

The total energy dissipated E_d may be divided into the dissipated energy components on and in the armour layer (E_{da}), in the underlayer (E_{du}) and in the core (E_{dc}).

Therefore $$E_d = E_{da} + E_{du} + E_{dc} \tag{4}$$

so that the following relationship for the corresponding local dissipation coefficients will result.

$$C^2_{da} + C^2_{du} + C^2_{dc} = 1 \tag{5}$$

where $$C_{da} = (E_{da} / E_d)^{½} \tag{6a}$$

$$C_{du} = (E_{du} / E_d)^{½} \tag{6b}$$

$$C_{dc} = (E_{dc} / E_d)^{½} \tag{6c}$$

Most wave energy absorbing structures possess a significant degree of porosity. Armoured slopes are constructed with voids between and sometimes within the armour units. In this context the term 'porous' in general refers to the presence of voids of a sufficient size as to allow a significant quantity of water to pass and hence pressure gradients to remain low, over the time of a typical wave period. Conversely 'non-porous' implies that the slope or wall would not allow significant flows under wave action. Hence it is evident that 'non-porous' does not imply that the structure is necessarily impermeable to the quasi-hydrostatic flows induced by water level changes of tides and surges. Similarly the terms 'smooth' or 'rough' are measures of relative hydraulic friction of the slope or wall in relation to wave-induced flows.

Wave reflections from coastal structures are of considerable importance both in relation to coastal harbours and the open coast.

The interaction of incident and reflected waves will often lead to a confused sea state in front of the structure, giving rise to occasional steep and unstable waves of considerable hazard to small boats. Reflected waves can also propagate into areas of a harbour previously sheltered from wave action.

Reflection of wave energy at a coastal structure leads to increased peak orbital velocities, increasing the likelihood of movement of beach material. The reflection of obliquely incident waves will tend to excite littoral currents, which taken together with the increased bed velocities, will further enhance the tendency for sediment to be transported away from the area immediately seaward of the structure. Such conditions will lead to potentially greater local scour or sea bed erosion. This aspect is of particular significance to the performance of seawalls used for coastal and flood defense. Although a seawall will protect land behind it, it may not necessarily protect the coastline on its own. If, for example, such a wall is sited on a naturally eroding coastline it may not prevent the overall erosion process and in instances may aggravate the situation. The exact effect of a seawall on the erosion/accretion process is difficult to assess and in the case of seawalls whose main function is to prevent or alleviate flooding it is extremely important that the design takes full account of the relevant coastal processes. Therefore, all seawalls reflect a certain proportion of the incident wave energy, thereby modifying the near-shore wave field and the sediment transport potential. It is now established that significant wave reflection can increase local scour, reduce foreshore levels and undermine the wall itself.

An important element of the design process for coastal structures is to identify the possible failure modes and to design against them. Table 1 from CIRIA guidelines on Maintenance of Coastal Revetments illustrates the more common causes of seawall failure based on a survey in the United Kingdom. It identifies the marked dominance of toe failure normally caused by scour and beach lowering. Thomas and Hall(1992) in analysing fault trees in relation to seawalls identified that a common initial failure is associated with low beach level which can lead to toe failure and also permit higher waves to reach the seawall.

3. Types of prediction methods for wave reflection

The importance of wave reflection has led to several investigations on the prediction of the level of reflected wave energy using both theoretical and experimental studies. Measurements of wave reflection have been made in model studies of the structural categories identified earlier and methods which allow prediction of reflection performance of similar structures have been identified using three main approaches:

a) graphical presentation of model test results
b) empirical equations based on model test results
c) mathematical modelling

In developing empirical equations which have wider applications, attention should be focused on the following criteria,

1. The equations should be consistent with the current understanding of the physical processes.
2. The equations should approach logical limiting values.
3. The equations should be relatively simple and not include variables of questionable or marginal influence.
4. The equations should be consistent with data from a wide range of wave and structure conditions, but not at the expense of criteria (1) or (2).

Most predictive equations have been based on the Iribarren number, Ir, sometimes known as the 'surf similarity' parameter, as introduced by Battjes (1974).

The Iribarren number is defined as

$$Ir = \tan\alpha / (H/L)^{1/2} \qquad (7)$$

where

$\tan\alpha$ is the slope of structure

H is the wave height and

L is the wave length.

The slope of the structure, the wave height and the wave length (wave steepness) have a direct influence on wave reflection and wave transmission through the structure. In this context it is a valid variable to be incorporated in empirical equations.

The following general empirical equations have been used.

$$Cr = a.\,Ir^{b} \quad (8)$$

$$Cr = a(1-\exp(-b.Ir)) \quad (9)$$

$$Cr = a.Ir^{2}/\,(Ir^{2}+b) \quad (10)$$

where Cr is the reflection coefficient; Ir is the Iribarren number; *a* and *b* are empirical coefficients.

The reflection coefficient, Cr is defined in terms of the total reflected and incident energies, E_r and E_i respectively. The empirical calibration coefficients account for effects such as porosity, surface roughness, wave breaking offshore of the structure and multiple layers of armour.

Of the above equations, researchers have preferred the use of Equation 10 which primarily satisfies the first, second and third criteria. The continued use of the equation has proved that it is consistent with data from a wide range of wave and structure conditions and as such it can be used with confidence in the design procedure.

The value of the Iribarren number will depend on the relevant parameters used for the definition of wave height and wave length.

For random waves the significant wave height, H_s is usually used as the wave height parameter. In the case of wave length there are several options available depending on which value of wave period and wave length is used for the definition of wave steepness. The mean wave period, T_m , or the period corresponding to the period of peak energy density, T_p , can be used to compute the wave length which could either be the deep water value (L_{om} or L_{op}) or that corresponding to the water depth local to the structure (L_{sm} or L_{sp}). The latter may seem to represent the local wave breaking in a more realistic form, although it is less easy to calculate and complicates the use of any prediction formulae. Thus, in the case of random waves, four possible definitions can be used for Iribarren number depending on wave length and wave period. Using the same notations these will be denoted by: Ir_{om}, Ir_{op}, Ir_{sm} and Ir_{sp}.

For regular waves the Iribarren number is usually based upon the incident wave height and the wave length corresponding to deep or local water depth at the structure and are denoted here as Ir_o and Ir_s, respectively.

Both analytical and numerical techniques have been used to model wave action on porous coastal structures. In most cases the greater emphasis has been on predicting internal wave height decay and external wave transmission through the structure. The available models are subject to a number of simplifying assumptions and also require information on the porosity and on hydraulic parameters relating to the permeability characteristics of the structure. At present such information is primarily available for rock structures. A summary of the numerical modelling techniques was presented by Hall and Hettiarachchi (1991).

4. Discussion of results

4.1 Presentation of results

The hydraulic performance of a range of coastal structures were assessed via review and re-analysis of data from previous investigations covering both experimental and field studies. These include recent investigations conducted by the authors. Table 2 describes the structural configurations of which reflection performance were examined. Wave transmission characteristics were also investigated for rock armoured trapezoidal structures.

Tables 3 and 4 present the empirical equations and relevant description of wave reflection for the different types of structures investigated. These two tables refer to results from experimental and field investigations respectively. In the tables provided a differentiation is made between empirical equations which have been quoted directly from references and those equations which have been derived by re-analysis of data by the authors. The equations and information can be used in the design of such structures which have to accommodate the impacts of wave reflection.

4.2 Non porous slopes

Non porous slopes can be broadly classified into simple smooth slopes and simple rough slopes. For simple smooth slopes the results of several investigators are presented in Table 3 and it is observed that Equation 10 provides consistent results with a=1.0 and b varying over a small band of 4.8 to 6.2, covering slopes of 1:1.33 to 1:2.5.

Simple rough slopes will reflect less wave energy than the equivalent smooth slope due to the additional energy dissipation resulting from the protrusion of the roughness elements. Any reduction measured in model tests has proved to be small and there are no reliable general data available on the reflection performance of such slopes. It is therefore recommended that if the roughness of the slope does not generate a sufficiently porous slope which could contribute to the energy dissipation process, the value of Cr used should be that corresponding to a smooth slope.

4.3 Armoured porous slopes

Armoured porous slopes can be broadly classified into rock armoured and concrete armoured rough slopes. Porous trapezoidal structures and porous sloping protection to vertical walls also have a similar configuration.

4.3.1 Rock armoured slopes

Allsop and Channel (1989) conducted detailed tests on a range of rock armoured slopes including that for a single layer of armour. Usually armoured rock is laid in two layer thickness for which design methods have been developed. However there are instances where only a single layer of armour has been used. Although such a form of design and construction is not recommended it has been considered useful to have an assessment made of the reflection performance of such structures. The results of Allsop and Channel (1989) using Equation 10 are presented in Table 3. The table also presents the results of Postma (1989) who analysed the data measured by Van der Meer (1988) on simple armoured slopes as well as the data measured by Allsop and Channel (1989) on rock armoured slopes. Postma observed that a simple curve as given by Equation 8 gave a good fit to the data.

4.3.2 Concrete armoured slopes

Concrete armoured structures will exhibit reflection characteristics similar to that of the equivalent rock armoured slope. Breakwater designers have developed various shapes of concrete armour units in order to obtain high hydraulic stability and performance at a relatively small armour block weight.

The different types of artificial armour units used in practice can be broadly classified into four types,

1) Double layer bulky units
2) Double layer interlocking units
3) Single layer interlocking units
4) Single layer hollow block units

Armour units belonging to the bulky type and the interlocking type are normally placed in two layers and at random although there are instances when these units are placed in a predetermined layout. Therefore the void dimensions and shapes which influence the dissipation of wave energy are generated between the armour units in a random manner and for all practical purposes, this is also valid when slender interlocking type of armour units are placed in a predetermined manner. The same applies to single layer armour units of the interlocking type.

The single layer hollow block type of armour units are somewhat different to the other two types in that the voids are built into the individual units in the required form. Armour units belonging to this type are always placed in a pre-determined manner and the resulting voids matrix of the primary armour is geometrically well-defined and not generated randomly. Thus the geometry of the voids within the confined boundaries of an individual armour or a group of armour units is controlled to produce a cost-effective primary armour layer which has a high overall porosity and is very efficient with respect to wave energy dissipation.

From the above discussion it is evident that some types of concrete armour units are more open and permeable to wave action than rock armouring and that it is also possible to incorporate a pre-determined voids matrix for greater wave energy dissipation. Therefore reduced reflections may be expected under these conditions. Conversely, on certain occasions bulky armour units such as concrete cubes have been placed in a tight packing, generating an armour layer of low porosity leading to higher reflections than might be predicted.

Table 3 presents the empirical equations for the reflection performance of a range of concrete armour units. It is noted that the investigations of Oumeraci and Partenscky (1990) and Murray, Oumeraci, Zimmerman and Partenscky (1992) have been conducted on trapezoidal breakwater cross-sections as opposed to simple armoured slopes.

Comparison of different investigations provided important information on the use of prediction equations. Allsop and Hettiarachchi (1989) analysed the reflection studies of Stickland (1969) on Cob armour units using regular waves. Stickland used units of side length 5.9 cm on slopes of 1:1.33 to 1:2.5 for wave periods 1.2 to 1.8 secs using a constant water depth of 38.1 cm. Equation 10 provided a good fit for the data, which exceeded 50 values, with the coefficients being a=0.50 and b=6.54 for the range $4.5 \geq Ir_o \geq 1.5$. Hettiarachchi and Holmes (1988) conducted investigations on a range of single layer hollow block armour units, including Cobs, Sheds and Seabees using regular waves. All armour units were approximately of the same external size of 4.2 cm on a slope 1:1.33 for wave periods 1.0 to 2.0 secs using a constant water depth of 25 cm. Equation 10 provided a good fit for the data, which exceeded 50 values, with the coefficients being a=0.41 and b=22.2 for the range $16 \geq Ir_s \geq 4$.

The above comparison clearly shows that the expressions given by the two equations should only be used to predict the reflection coefficients for values of Ir which lie within the range used to determine empirical constants in the respective equations. This discussion also recognises in general the importance of obtaining experimental data over a wide range so that more generalised formulae can be obtained. Some of the differences observed in the two expressions for the reflection coefficient, may be due to scale effects, the model armour units being of different sizes. This appears to be the major difference in the two experimental studies and clearly implies that Equation 10 is inadequate in representing scale effects.

4.4 Porous sloping protection to vertical walls

From previous studies on vertical or steep seawalls it has been noted that a step or berm placed at, or close to, the design water level will often improve the hydraulic performance considerably. There are many instances where seawalls have been built into or at the back of a sloping beach resulting in energy dissipation due to breaking of waves before reaching the wall. Increased wave activity due to reflection at the wall will contribute to local scour, lowering the beach level and allowing waves of greater height to reach the wall. This will in turn increase wave reflection resulting in higher velocities at the sea bed leading to greater scour and sediment transport. It is in this context that sloping protection in front of vertical non-porous seawalls can be used effectively to improve its overall hydraulic performance and stability. Similarly a step or berm placed in the region of the design water level will contribute to an improvement in the hydraulic performance.

An example of protection to an existing seawall by the use of rock armour placed against it was presented by Henton (1986). The results of this study were analysed by Allsop and Hettiarachchi (1989). The reflection performance of three sections, namely, the existing section and the alternatives are presented in Figure 1, measurements having taken for three water levels.

The existing seawall (section 1) has high reflections approaching 0.9 at the higher water levels. At lower water levels the reflections are reduced to around 0.65 due to wave breaking in front of the seawall, illustrating the influence of the smooth slope. For alternative sections 2 and 3, the reflection performance varies with the water level, and in particular with the relative position of the berm formed by the crest level of the rock protection. For these water levels close to the crest level reflections are very low within the range 0.2 -0.3, illustrating clearly the influence of a berm type of structure. The reflection coefficients increase to around 0.4 when waves reflect from the armour slope.

From investigations on berm structures it is observed that Iribarren Number is not the best parameter to study the influence of berm slopes. The berm length to wave length (B/L) is found to be an appropriate parameter for such structures. The slope angle of the berm and its length are two parameters which influence the reflection performance. Influence of these parameters has to be investigated by conducting a well formulated series of experiments with the variables being the berm length, slope angle, the water level and the incident wave climate.

4.5 Armoured porous trapezoidal structures

Most investigations of wave reflection on porous sloping structures have concentrated on two dimensional cross-sections which simulate revetment type of structural forms. Very few investigations have been conducted on porous trapezoidal cross sections which not only reflect waves but also transmit waves through their porous bodies. In addition to the principal use as breakwaters in harbours, this type of structure is used as offshore breakwaters in coast protection and in the construction of nearshore causeways. In analysing wave action on these structures it is important to consider both wave reflection and transmission performance in order to assess the wave energy dissipation.

Results from investigations on rock armoured porous trapezoidal structures conducted by Sollitt and Cross (1972), Sulisz (1985) were analysed by Hettiarachchi and Mirihagalla 1997). In both studies reflection and transmission have been measured for at least five wave periods varying from 0.7 to 2.5 secs. Although there is a certain scatter in the data, it is clearly possible to identify the general trend of the variation of the respective coefficients with the Iribarren number and the wave period. In general the wave reflection increased with increasing period and in particular for wave period of the order of 2 secs the reflection coefficients were comparatively high. The transmission coefficients too increased with wave period. Comparison of results indicate the influence of the material used in reducing permeability characteristics of the structure and the possible influence of air entrainment in the porous media which will contribute towards a decrease in transmission and increase in reflection.

As part of this investigation the experimental results of Gunbak (1979), Sollitt and Cross (1972) and Sulisz (1986) were further analysed and prediction equations were derived. All these rock armoured structures consisted of primary armour, secondary armour and the core. The seaward face of the structures covered slopes of 1:1.5 and 1:2.5. In addition the results of an investigation on a porous trapezoidal structure assembled with hollow square blocks (model COB armour units) having a front slope of 1:1 was analysed. This structural configuration had a high volumetric porosity of the order of 60%. Although wave reflections for this structure is lower it will exhibit significant transmission coefficients due to the high porosity of the structure. The respective empirical coefficients for Equation 10 which gave a good fit for the data are given in Table 3.

4.6 Field investigations on wave reflection

In comparison with laboratory investigations very few field studies have been conducted on prototype structures. Thornton and Calhoun (1972) conducted a pioneering study on wave reflection and transmission for a rubble mound breakwater in California. It was observed that reflection and transmission coefficients displayed a dependence on wave frequency, tidal stage and the incident wave amplitude.

Davidson, Bird Bullock and Huntley (1994) presented the results of an extensive field investigation on wave reflection on an offshore breakwater and a berm breakwater on the south coast of England. Results of the investigations are presented in Table 4.

The raw data showed a general trend of a decrease in wave reflection with an increase in frequency. Wave breaking on the natural beach resulted in almost negligible reflected wave energy, of the order of 4%, with no clear trend with frequency. There was a trend for wave reflection to increase with the gradient of the shoreface.

In the case of the offshore breakwater, the considerably higher values of the Iribarren Number than those reported in most laboratory experiments are mainly due to low amplitude waves acting on a relatively steep gradient of the structure (1:1.1). The results do illustrate well the trend of the data at the extreme range with the upper saturation value of the order of 0.6 to 0.65. In view of the scatter of data due to the possible influence of local water depth (tidal variations), the equations have been fitted for different depth bands.

The variation of the reflection coefficient versus the Iribarren Number for the berm breakwater displayed a similar trend to that of the offshore breakwater. The Iribarren numbers were lower due to the high energy of the incident waves and the shallower sloping shoreface. The reflection performance were dependent on the water depth over the berm. For low water depths over the berm the reflection coefficient was low and could not be related to the Iribarren number. The reflection estimates for the berm breakwater were consistently less than those obtained for the steeper offshore breakwater. More dissipative nature of the structure including the shallower shoreface slope, the dissipating effect of the berm, the positioning of concrete blocks on the berm and the influence of wave transmission over the structure near high tide would have contributed to lower reflection.

5. Conclusions and Recommendations

This study has examined the hydraulic performance of a range of coastal structures with respect to energy transformation processes. In particular attention is focused on wave reflection performance mainly due to the fact that the structures examined refer to coast protection works of the revetment/seawall type for which external transmission is not very relevant. Since low crest structures were not considered in detail, wave overtopping was not included in the analysis.

This study has reviewed the reflection performance of a wide range of structures. Types of prediction methods for wave reflection are discussed and an assessment is made of the predictive equations. The Iribarren Number is identified as a relevant variable in quantifying wave reflection on simple sloping structures. The predictive equation $Cr=a.Ir^2/(b+Ir^2)$ was found to be acceptable to describe the variation of Cr with Ir for a range of coastal structures and the degree of fitness was very satisfactory. Where possible all results have been presented within a uniform framework in which the Iribarren Number was the principal variable. However it was observed that this number was not the best parameter to study the influence of berm slopes and sloping protection to vertical walls.

From the study of the performance of porous armoured trapezoidal structures it was evident that Iribarren Number could also be used to describe the external transmission coefficients. It is recommended that further investigations be carried out in this respect.

The analysis of results from field studies have strengthened the findings of the hydraulic model studies. The recent work of Davidson, Bird, Bullock and Huntley (1994) has contributed to improved understanding of reflection performance of prototype structures and established a positive link between experimental and field results.

This study has presented reliable predictive equations for wave reflection for a range of structures used in practice. The relevance of scale effects and the influence of extrapolation outside the experimentally measured range of Ir are clearly identified. These observations recognised the importance of conducting large scale experiments in order to obtain reliable experimental data covering a wide range leading to the development of generalized formulae. Such formulae will be representative over a wide range of input parameters.

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TABLE 1 DAMAGE REPORTED TO SEAWALLS (Thomas and Hall 1992)

Damage reported to seawall	Number of occurrences	As percentage of all seawalls reported
Erosion of toe	63	12.3
Partial crest failure	26	5.1
Collapse/breach	16	3.1
Removal of revetment armour	19	3.7
Abrasion	16	3.0
Wash-out of fill material behind seawall	10	1.9
Concrete disintegration	9	1.7
Structural member failure	5	1.0
Landslip	5	1.0
Corrosion	3	0.6
Outflanking	3	0.6
Uplift of armouring	3	0.6
Settlement	2	0.4
Spalling of concrete	2	0.4
Damage to promenade	4	0.8
Concrete cracking	2	0.4
Total	188	36.6%

TABLE 2 STRUCTURAL CONFIGURATIONS INVESTIGATED

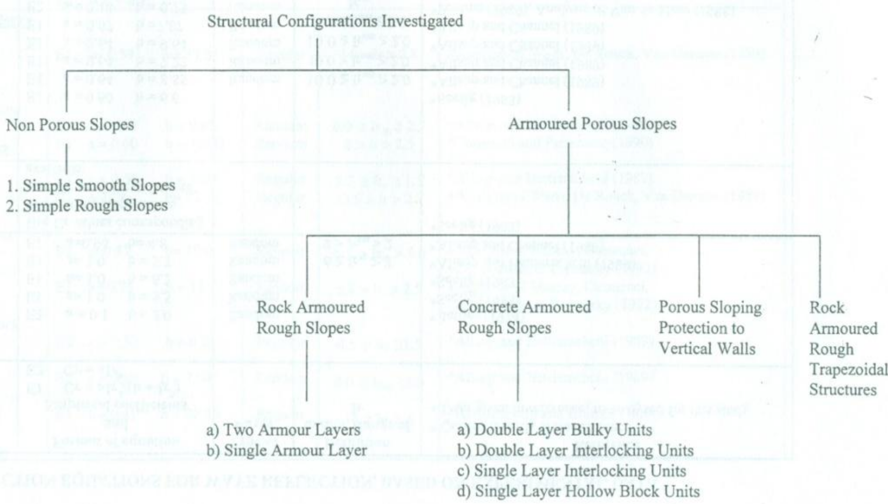

TABLE 3 PREDICTION EQUATIONS FOR WAVE REFLECTION, BASED ON EXPERIMENTAL DATA

Type of structure	Format of equation and Empirical coefficients E1 $Cr = aIr^2/(b + Ir^2)$ E2 $Cr = aIr^b$	Type of waves	Definition and/or Range of Ir	Reference * Quoted directly from reference + Data given in reference, re-analysed for this study
NON POROUS SLOPES				
<u>Simple smooth slopes</u>	E2 a = 0.1 b = 2.0	Random		*Battjes (1974)
	E1 a= 1.0 b = 5.5	Random		*Seelig (1983)
	E1 a= 1.0 b = 6.2	Random		*Seelig (1983)
	E1 a= 1.0 b = 5.7	Random	$6 \geq Ir_{op} \geq 3$	*Allsop and Hettiarachchi (1989)
	E1 a=0.96 b= 4.8	Random	$9 > Ir_{om} > 2$	*Allsop and Channel (1989)
<u>Simple rough slopes</u>	Use Cr values corresponding to a smooth slope unless specific model test data are available			*Seelig (1983)
ARMOURED POROUS SLOPES				
<u>Rock armoured slopes</u>				
Preliminary estimate	E1 a = 0.60 b = 6.6			*Seelig (1983)
Rock armour (2 layer)	E1 a = 0.64 b = 8.85	Random	$10.0 \geq Ir_{om} \geq 2.0$	*Allsop and Channel (1989)
Rock armour (1 layer)	E1 a = 0.64 b = 7.22	Random	$10.0 \geq Ir_{om} \geq 2.0$	*Allsop and Channel (1989)
Large rock (2 layer)	E1 a = 0.64 b = 9.64	Random	$10.0 \geq Ir_{om} \geq 2.0$	*Allsop and Channel (1989)
Large rock (1 layer)	E1 a = 0.67 b =7.87	Random	$10.0 \geq Ir_{om} \geq 2.0$	*Allsop and Channel (1989)
Rock armour	E2 a = 0.14 b = 0.73	Random	Ir_{op}	*Postma (1989), Analysis of Van de Meer (1988)
Rock armour	E2 a = 0.125 b = 0.73	Random	$9 > Ir_{op} > 2$	*Postma(1989), Analysis of Allsop and Channel (1989)

TABLE 3 contd....

Type of structure	Format of equation and Empirical coefficients E1 $Cr = aIr^2/(b + Ir^2)$ E2 $Cr = aIr^b$	Type of waves	Definition and/or Range of Ir	Reference * Quoted directly from reference + Data given in reference, re-analysed for this study
<u>Concrete armoured slopes</u>				
Double layer bulky				
Haro and Cube	E1 a= 0.59 b = 17.21	Regular	$14 > Ir > 2.8$	+Analysis of Wens, De Rouck, Van Damme (1989)
Double layer interlocking				
Tetrapod and Stabits	E1 a = 0.48 b = 9.62	Random	$6.0 \geq Ir_{op} \geq 2.5$	*Allsop and Hettiarachchi (1989)
Tetrapod	E1 a = 0.60 b = 12.00	Random	$8 > Ir > 2.5$	*Oumeraci and Partenscky(1990)
Dolos	E1 a = 0.56 b = 10.0	Regular	$5.5 \geq Ir_o \geq 1.5$	*Allsop and Hettiarachchi (1989)
Tetrapods and Dolos	E1 a=0.56 b= 22.32	Regular	$13.8 > Ir > 2.7$	+Analysis of Wens, De Rouck, Van Damme (1989)
Single layer interlocking				
Accropode	E1 a=0.82 b= 10.0	Regular	$6.1 > Ir_{sp} > 3.0$	+Analysis of Murray, Oumeraci, Zimmerman & Partensky (1992)
Accropode	E1 a= 0.79 b = 11.37	Random	$6.4 > Ir_s > 2.5$	+Analysis of Murray, Oumeraci, Zimmerman & Partensky (1992)
Single layer hollow block				
Cob	E1 a = 0.50 b = 6.54	Regular	$4.5 \geq Ir_o \geq 1.5$	*Allsop and Hettiarachchi (1989)
Shed and Diode	E1 a = 0.49 b = 7.94	Random	$6.0 \geq Ir_{op} \geq 3.0$	*Allsop and Hettiarachchi (1989)
Cob, Shed, Seabee and Hollow Block	E1 a = 0.41 b = 22.20	Regular	$16 \geq Ir_s \geq 4$	*Hettiarachchi and Holmes (1988)

TABLE 3 contd....

Type of structure	Format of equation And Empirical coefficients E1 $Cr = aIr^2/(b + Ir^2)$ E2 $Cr = aIr^b$	Type of waves	Definition and/or Range of Ir	Reference * Quoted directly from reference + Data given in reference, re-analysed for this study
ARMOURED POROUS TRAPEZOIAL STRUCTURES <u>Rock armoured structures</u>				
	E1 a = 0.57 b = 9.15	Regular	7 > Ir > 1.2	+Analysis of Gunbak (1979)
	E1 a = 0.40 b = 11.60	Regular	16 > Ir > 2	+Analysis of Sollit and Cross(1972)
	E1 a = 0.62 b = 21.71	Regular	9.5 > Ir >2.5	+Analysis of Sulisz (1985)
	E1 a = 0.65 b = 10.06	Regular	5 > Ir > 2	+Analysis of Hettiarachchi and Mirihagalla (1998)
<u>Porous trapezoid consisting of hollow square blocks (Cobs)</u>	E1 a = 0.40 b = 18.23	Regular	15 > Ir > 5.2	+Analysis of Hettiarachchi (1987)

TABLE 4 PREDICTION EQUATIONS FOR WAVE REFLECTION, BASED ON FIELD INVESTIGATIONS

Type of structure	Format of equation and empirical coefficients E1 $Cr = aIr^2/(b + Ir^2)$ E2 $Cr = aIr^b$	Type of waves	Depth range	Range of Ir	Reference
Rock armoured offshore breakwaters *(Gradient of the seaward face of the structure 1:1.1 fronted by a shallow sloping beach 1:50)*	E1 a = 0.65 b = 25 E1 a= 0.60 b = 35 E1 a= 0.64 b = 80	Random	d > 3.25 m 3.1 m ≥d ≥ 2.5 m 2.5 m > d	35 > Ir > 8 35 > Ir > 8 50 > Ir > 8	*Davidson,Bird, Bullock and Huntley (1994)
Berm breakwater *(Energy dissipation taking place on smooth impermeable slope of granite blocks (1:6) stretching seawards to a horizontal berm)*	E1 a = 0.42 b = 2.0	Random	d > 3.0 m	4.2 > Ir > 0.8	*Davidson, Bird, Bullock and Huntley (1994)

Note: * Quoted directly from reference
+ Data given in reference, re-analysed for this study

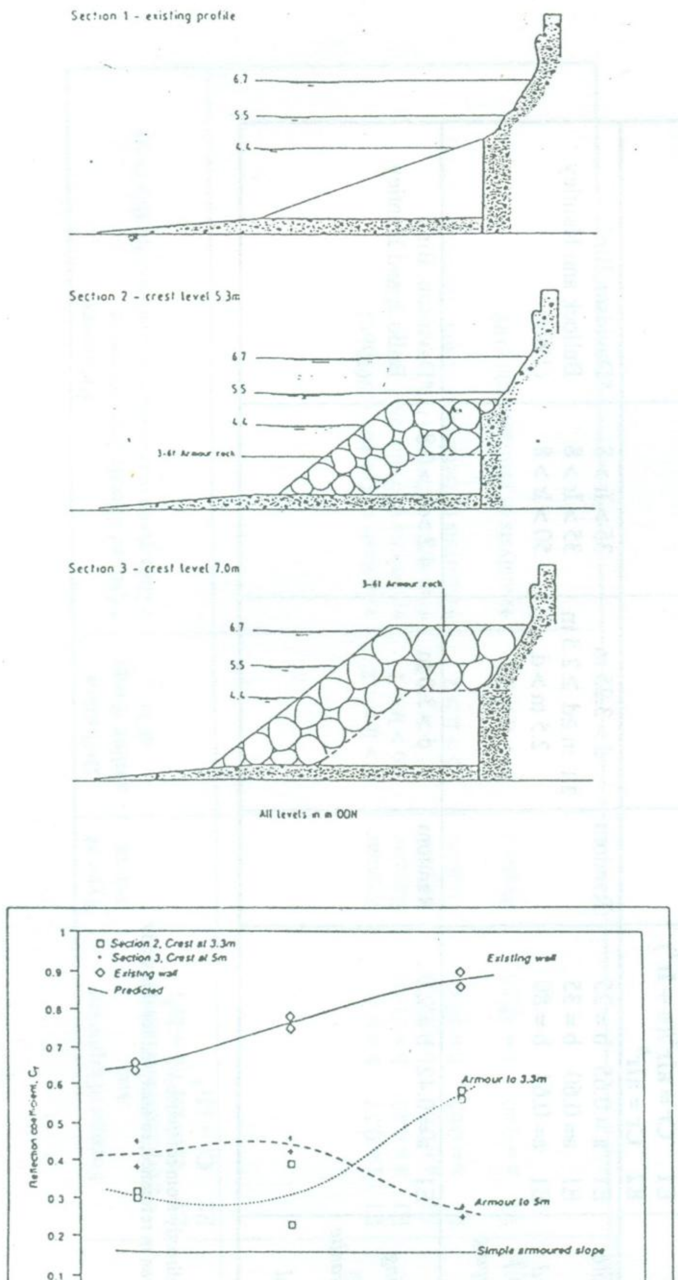

FIGURE 1
Reflection performance of rock protection to existing seawall

Allsop and Hettiarachchi (1989)