WAVE REFLECTION FROM COASTAL STRUCTURES

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This paper analyses wave reflection for various type of structures, such as smooth and rock (permeable and impermeable core) slopes and slopes with all kind of artificial armour units. A database was prepared, based on existing databases for wave transmission and overtopping. A new formula was developed, whose shape fits all kind of straight slopes in design conditions by changing two calibration coefficients. Since reflection and overtopping performance are strongly related, it has been hypothesized and verified that these coefficients depend only on the roughness factor in the overtopping discharge formula. As the roughness factor is available for a wide variety of materials, the extension of the formula to different slopes is straightforward. A preliminary analysis on the effect of a low crest has been performed for rock permeable slopes only, showing that the developed formula can be applied also in this case with the introduction of a proper function of the relative crest height.

INTRODUCTION

The problems associated with reflection of incoming waves from coastal structures and natural coasts are well recognized and include dangerous sea states close to harbors entrances, influence on ship navigation in entrance channels and intensified sediment scour, which can lead to dramatic loss in beach material and structure destabilization. Moreover, numerical models for calculation of wave penetration need a good estimation of the reflection coefficients for all kind of structures. Due to the adverse effects of wave reflection, coastal engineers require design criteria which enable cost effective structures to be built with acceptable reflection performances.

Research dedicated to wave reflection from coastal structures only is fairly limited. Very often reflection is a byproduct of research on structure stability, wave overtopping or wave transmission. It means that a huge amount of data on reflection is available, but has only been used to establish the incident wave height in the model facility and has not been analyzed on its own. The EU-projects DELOS (on wave transmission) and CLASH (on wave overtopping) generated large sets of tests on all kind of structures, where for large parts of the data sets the reflection coefficient K_r is available.

The aim of this work is to analyze the reflection behaviour for various type of structures, such as smooth structures, rock slopes (permeable and impermeable core), slopes with all kind of artificial armour units, berm breakwaters, vertical structures and all kind of combinations. The analysis

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includes many of the existing formulae, like Battjes (1974) and Seelig and Ahrens (1981) for smooth slopes, Postma (1989) and Davidson et al. (1996) for rock slopes and Allsop and Hettiarachchi (1989) for armour units.

A more specific objective is to describe the influence of a low-crest. A first attempt on this topic was made within DELOS, leading to a tentative description, but the scatter was still so large that more data and a full analysis on all aspects are required (Van der Meer et al., 2005). A detailed investigation of the reflection behaviour of smooth and permeable low-crested structures (LCSs) in presence of oblique waves has been performed by Wang et al. (2005).

To achieve these aims, an extensive and homogeneous database on wave reflection has been prepared. The format and also a part of the homogeneous database of CLASH (Steendam et al., 2004) is the starting point, where all kind of coastal structures (slopes, vertical, smooth, rough, combinations, etc.) have been described by structure parameters. The database on wave transmission from DELOS (Briganti et al., 2003), which includes many LCSs, has also been used.

EXISTING FORMULAE FOR THE REFLECTION COEFFICIENT

For smooth impermeable slopes, Miche (1951) empirically determined the reflection coefficient K_r for monochromatic waves breaking on a plane beach. Battjes (1974) redefined Miche's hypothesis in terms of the Iribarren number or breaker parameter ξ. Ursell et al. (1960) and Seelig and Ahrens (1981) indicated that Miche's equation significantly overestimated the reflection of both regular and irregular waves and presented an improved estimate of K_r.

For rough permeable slopes, Numata (1976) suggested an empirical equation for K_r based on the breakwater width to armour diameter ratio. Losada and Gimenez-Curto (1981) developed an exponential model for K_r based on ξ; Seelig and Ahrens (1981) postulated that wave reflection from porous structures is also a function of the toe depth, the offshore seabed slope, the armour characteristic and the number of armour layers. Postma (1989) analysis revealed a strong dependence of K_r on ξ and negligible correlations with spectral form and toe depth. Van der Meer (1992) improved Postma's analysis through a multiple regression method to separate the effects of wave height and period, structure permeability and slope. Davidson et al. (1996) developed a new prediction scheme based on the identification of a non-dimensional parameter that weights the contributions of wave length, wave height, toe water depth, structure slope and armour diameter.

For tetrapods, sheds and diodes, Allsop and Hiettrarchi (1989) provided proper values for the two coefficients in Seelig & Ahrens formula.

All the formulae presented in the work mentioned above, with the exception of Numata (1976), Van der Meer (1992) and Davidson et al. (1996), relate K_r to ξ only and adopt for ξ the peak wave period at the structure toe ξ_{op} with the exception of Allsop and Hiettrarchi (1989) who use the mean wave period.

THE ANALYSIS

The data

The database includes part of the DELOS wave transmission database (Van der Meer et al., 2005), part of the CLASH wave overtopping database (general presentation in Steendam et al, 2004; armour unit data in Bruce et al., 2006), data acquired from model testing in European facilities, field measurements (at Elmer, UK, see Davidson et al., 1996), new tests on LCSs (Cappietti et al., 2006), for a total of about 6000 data.

Preliminary analysis

The analysis has been organized in the following steps: first, comparison of the data, set by set, with existing formulae; then, if necessary, refitting of existing formulae and finally development of a new formula.

Based on results from CLASH, the wave period adopted is the spectral period at the structure toe

$$\xi_o = \frac{\tan\alpha}{\sqrt{(2\pi H_{m0})/(gT_{m-1,0}^2)}} \tag{1}$$

where $T_{m-1,0}=m_{-1}/m_0$. The parameter ξ_o is useful for representing bi-modal spectra or shallow water with flat spectra. For single-peak spectra, $T_{m-1,0}=T_p/1.1$. From the work by Postma (1989) it is known that the wave period has more influence than the wave height on the reflection behaviour, so the use of ξ_o introduces some scatter, but it also allows to incorporate different slopes.

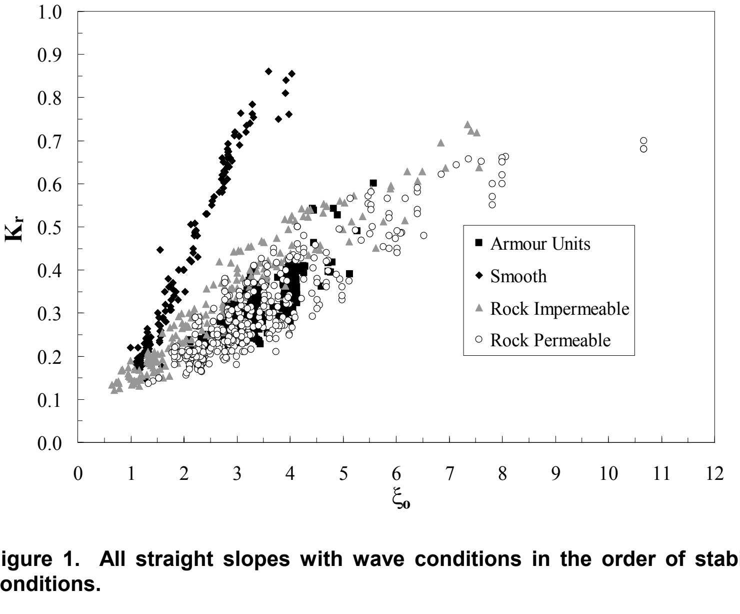

Figure 1. All straight slopes with wave conditions in the order of stability design conditions.

This analysis so far was restricted to straight slope data under design conditions ($R_c/H_{si} \geq 0.5$, $H_{m0}/D_{50} \geq 1.0$, $s_o \geq 0.01$), under perpendicular wave attack, for a total of about 600 data (shown in Fig. 1). From Fig. 1 the presence of four "families" of data is evident: rock with a permeable core, rock with an impermeable core, smooth slopes and slopes with armour units. Armour units fall inside the rock permeable data cloud.

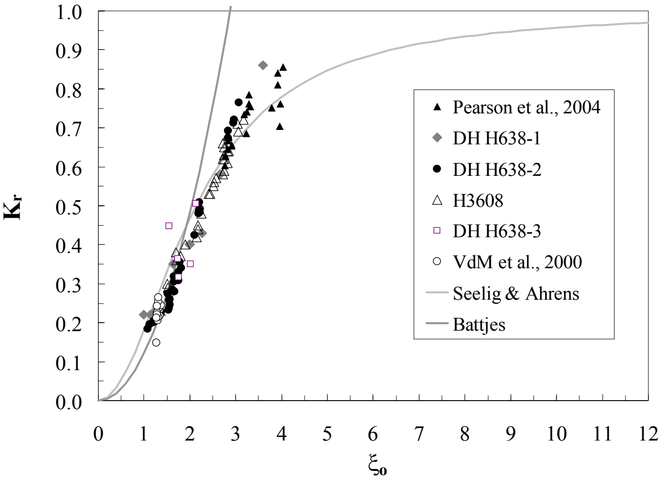

Figure 2. Comparison of smooth slopes with Battjes and Seelig & Ahrens curves.

All the smooth slope data are well approximated by the existing formulae (Fig. 2). Rock impermeable data are fairly well represented by the Postma curve, but the curve does not have a physical limit; rock permeable data were fitted by the Seelig & Ahrens curve, but this performs only for ξ_o in the range 2-4 (Fig. 3). There are different empirical formulae, but with the exception of Seelig & Ahrens for smooth slopes, other formulae for rocks and armour units show quite a lot of scatter.

New fits are thus needed to adequately represent K_r at least for rock and armour units. Since rock with a permeable core and armour units show a similar reflection behaviour, a simple curve for data fitting has been developed

$$K_r = \min\left(0.089 \cdot \xi_o; \quad 0.65\right) \tag{2}$$

For rock impermeable slopes, the best fit is given by

$$K_r = 0.17 \cdot \xi_o^{\;0.7} \tag{3}$$

These curves provide a very fine fit, but only for a specific 'family' of data, whereas it would be nice to have just one shape of formula that can be adapted to all data types by simply changing coefficients.

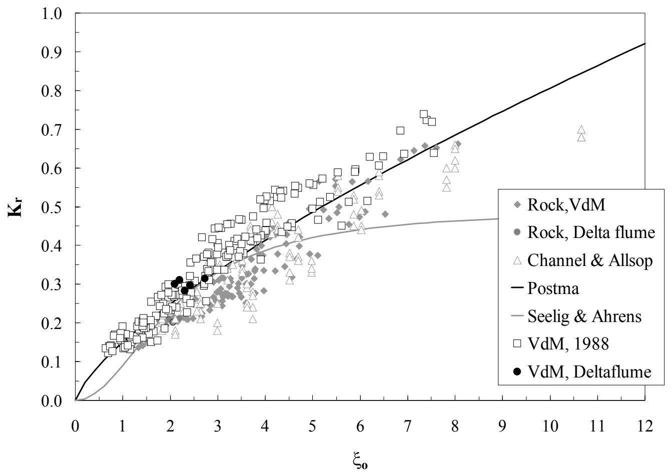

Figure 3. Comparison of rock straight slopes, permeable (grey, grey/white points) and impermeable (black, black/white points) core, with Postma and Seelig & Ahrens curves.

The first attempt can be the refit of Seelig & Ahrens formula, since it already provides a good approximation for smooth data (Fig. 2). For convenience the formula by Seelig & Ahrens is recalled below

$$K_r = \frac{a_1 \cdot \xi_o^{\ 2}}{\xi_o^{\ 2} + b_1} \tag{4}$$

The values of the coefficients a_1, b_1 that have been refitted for armour units, rock permeable and impermeable slopes are reported in Table. 1.

Table 1. Coefficients a_1, b_1 to be included in formula (4). Values for smooth slopes are not refitted.

Data Type	*a_1*	*b_1*
Rock permeable; Armour units	0.75	15
Rock impermeable	0.80	10
Smooth	1.00	4.54

The refit of Seelig & Ahrens formula showed:

- that rock impermeable data are overestimated for ξ_o <2 and ξ_o >4, whereas they fit well for ξ_o =2-4 (Fig. 4);
- that rock permeable data and armour units are underestimated for ξ_o <2 and are fairly well approximated for ξ_o >2 (Fig. 5).

In conclusion, this formula results inadequate for a proper fitting of all data types.

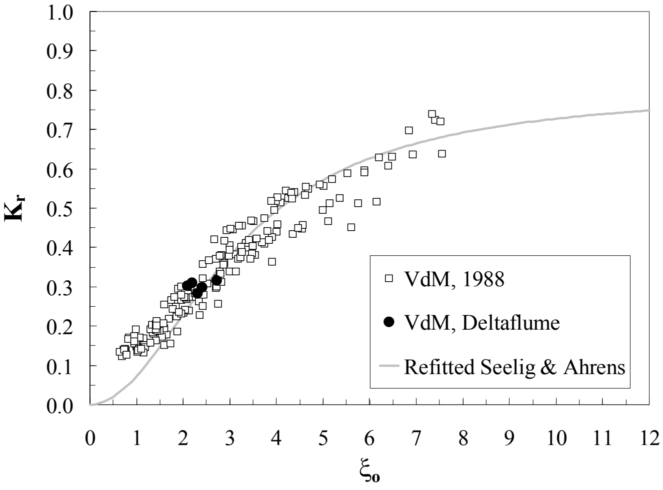

Figure 4. Comparison of rock impermeable slopes with Seelig & Ahrens formula (4) refitted with coefficients a_1, b_1 in Table 1.

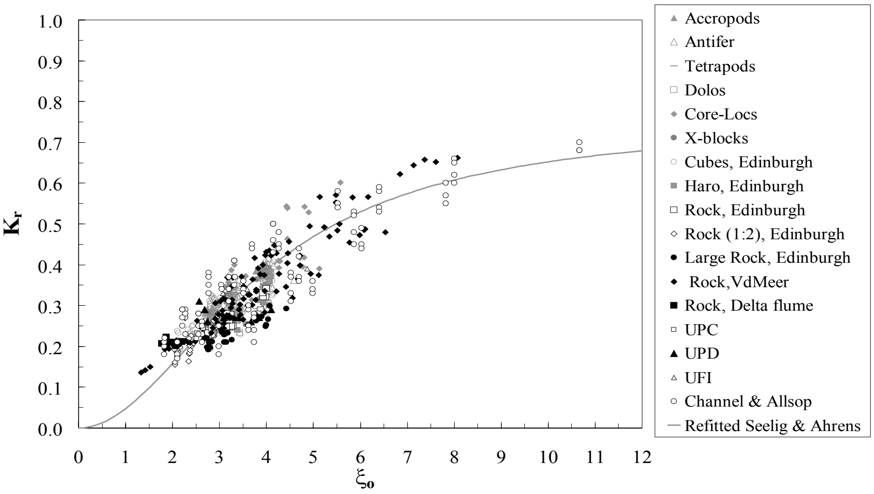

Figure 5. Comparison of rock permeable (black points) and armour unit (grey points) slopes with Seelig & Ahrens formula (4) refitted with coefficients a_1, b_1 in Table 1.

THE NEW FORMULA

The basic concept is to develop a new formula that satisfies all the following requirements:

- its shape can reproduce all different slope types;
- it represents physical bounds;
- it gives a relationship with the roughness factor γ_f in the wave overtopping discharge formula.

This last particular requirement relates the overtopping and reflection performance of different armour units or slopes with different roughness. Since γ_f has been measured or determined for a lot of materials or structures roughness (see TAW, 2002), the dependence on this parameter, if confirmed, may allow to extend the new reflection formula to a wide variety of slopes.

The new formula is given by

$$K_r = \tanh\left(a \cdot \xi_o^{\ b}\right) \tag{5}$$

where the calibrated values of the coefficients *a* and *b* are reported in Table 2. This formula and these values for *a* and *b* have been obtained by analyzing average values of K_r by groups of ξ_o.

Table 2. Coefficients *a*, *b* to be included in formula (5).

	a	*b*	γ_f
Rock permeable	0.12	0.87	0.40
Armour units	0.12	0.87	Various
Rock impermeable	0.14	0.90	0.55
Smooth	0.16	1.43	1.00

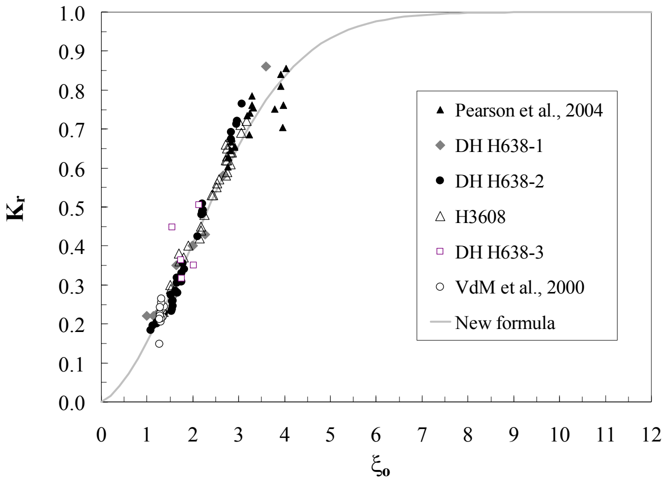

Figure 6. Smooth slopes (points) and the new formula (5), coefficients in Table 2.

The agreement amongst measured data and formula (5) with coefficients given in Table 2 is particularly good for smooth and rock impermeable slopes (Figures 6 and 7 respectively). Formula (5) slightly overestimates K_r for armour units and rock permeable slopes for ξ_o <4 (Fig. 8).

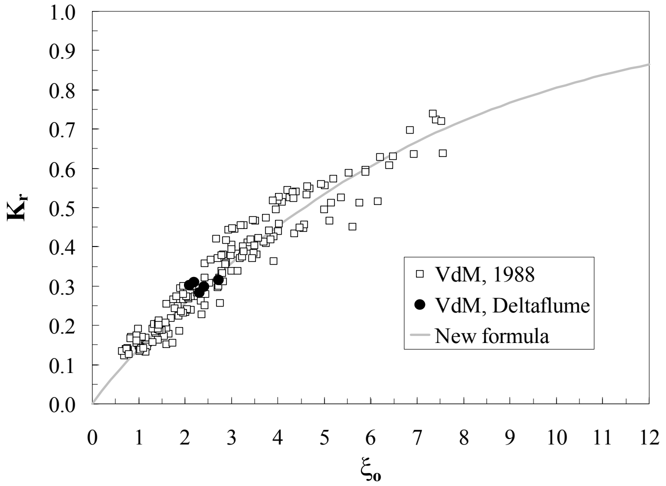

Figure 7. Rock impermeable slopes (points) and the new formula (5), coefficients in Table 2.

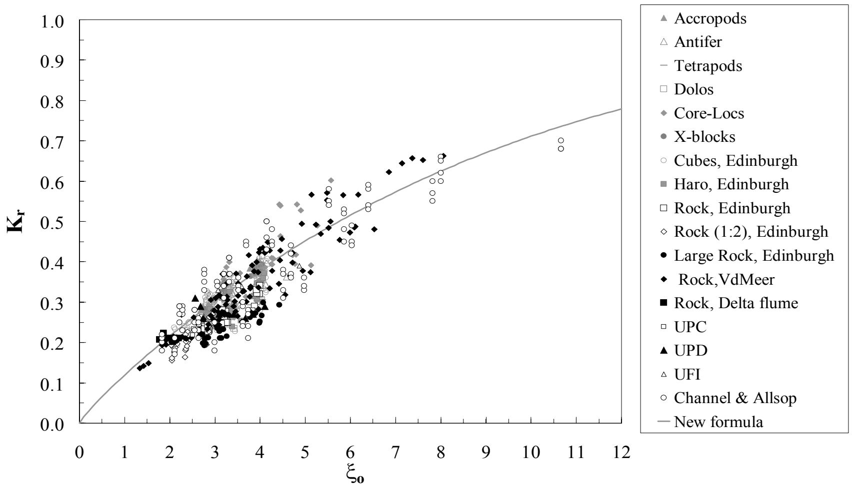

Figure 8. Rock permeable (black points) and armour unit slopes (grey points) and the new formula (5), coefficients in Table 2.

RELATIONSHIP BETWEEN REFLECTION AND WAVE OVERTOPPING

Reflection and overtopping performance of coastal structures are strongly related: large roughness and permeability, give low overtopping and low reflection, due to more dissipation. And visa versa, smooth slopes give more overtopping and higher reflection.

The first step of the analysis carried out in the following is to look for a direct dependence of the coefficients *a* and *b* in (5) on the roughness factor γ_f in the formula to estimate the overtopping discharge. By fitting the three values we have for *a*, *b* and γ_f (Table 2; rock permeable, rock impermeable and smooth slopes) the following expressions for *a* and *b* can be derived

$$a = 0.167 \cdot \lfloor 1 - \exp(-3.2 \cdot \gamma_f) \rfloor,\ b = 1.49 \cdot (\gamma_f - 0.38)^2 + 0.86 \qquad (6)$$

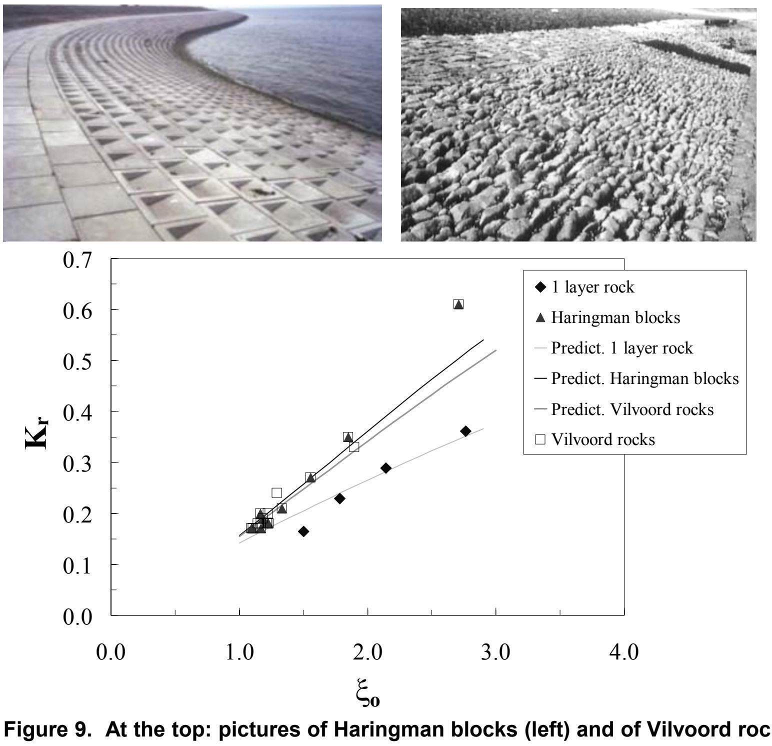

Figure 9. At the top: pictures of Haringman blocks (left) and of Vilvoord rocks (right). At the bottom, comparison amongst measured values (points) and predictions (lines) of K_r for Haringman blocks (γ_f=0.90; *a*=0.157; *b*=1.263), Vilvoord rock (γ_f=0.85; *a*=0.156; *b*=1.189) and one-layer rock (γ_f=0.60; *a*=0.142; *b*=0.932).

The second step is to verify by independent data if formula (5) with the introduction of this dependence (6) for *a* and *b* fits also different kind of slopes with varying γ_f. First, a few slopes characterized by a γ_f in the range 0.55-1 have been analyzed and these data were taken from TAW (2002), where many revetment types are characterized by a γ_f. Reflection data were available for: one layer of rock (γ_f =0.60), Vilvoord rocks (γ_f =0.85) and Haringman blocks (γ_f =0.90). Based on the given γ_f a fair prediction of K_r is obtained from equations (5) and (6), see Fig. 9.

In a second attempt, the attention has been concentrated on γ_f in the range 0.35-0.55, in which all the armour unit slopes are present and the coefficient *b* is almost constant (Fig. 10, eq. (6)). The available dataset is given by Bruce et al. (2006) and consists of different types of armour units that covered in one or two layers the same structure, characterized by 1:1.5 slope and permeable rocky core. In these cases, the comparison among the measured values of K_r for each kind of armour unit and the prediction that formula (5) gives by adopting the constant values of *a*, *b* in Table 2 doesn't give an approximation good enough.

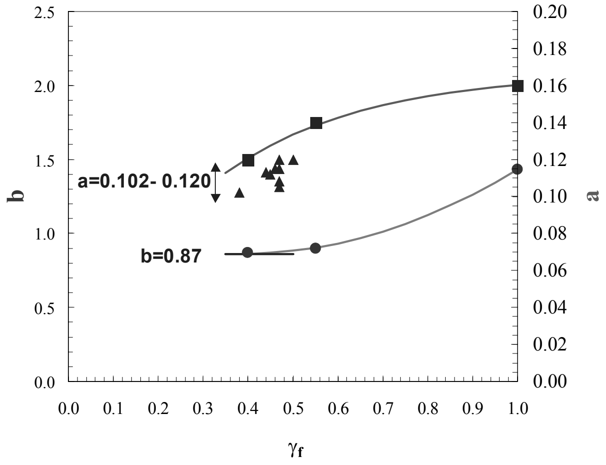

Figure 10. Solid lines represent curves (6) for *a* (upper) and *b* (lower) as functions of γ_f; square points are the couples *a*-γ_f in Table 2; round points are the couples *b*-γ_f in Table 2; triangle points are the couples *a*-γ_f in Table 3: the range of the calibrated values of *a* keeping *b* constant (straight segment and value) are reported.

Table 3. Coefficient *a*, derived by directly fitting formula (5) on the armour units in Edinburgh dataset; for each unit the measured γ_f is included; *b* is constant, 0.87.

Armour unit	γ_f	*a*
Tetrapod, 2 layers	0.38	0.102
Core-Loc, 1 layer	0.44	0.113
Xbloc, 1 layer	0.45	0.112
Accropod, 1 layer	0.46	0.115
Antifer, 2 layers	0.47	0.115
Cube, 2 layers	0.47	0.108
flat	0.47	0.120
(1:2), rough	0.47	0.105
Cube, 1 layer	0.50	0.120

Although the trend 'the larger the γ_f, the larger K_r' is present, there is for some, not understood reason, a bias. The value of *a* has thus been calibrated by keeping *b* constant; the best calibration of *a* for each kind of armour units is reported in Table 3. As expected from Figure 8, all the best values of *a* are slightly lower than the average 0.12 proposed in Table 2 (Fig. 10). Therefore,for armour units the indication is to use equation (5) with constant *b*=0.87 and the values of *a* in Table 3.

One layer cubes and flat cubes are perfectly approximated by (5) without any adjustment for *a*, showing that cubes flat and one layer cubes behave similarly and give greater reflection than all the other armour units.

More tests on armour units, in particular on structures with different slopes, are needed to say something more conclusive regarding the performance of equation (5); so far the formula can be regarded as a very close but cautious prediction for these kinds of slopes.

EFFECT OF A LOW-CREST

The effect of a low-crest has been examined so far for rock permeable slopes only. Also for LCSs, the analysis was limited to design conditions (R_c/H_{si}≥-1.0, H_{m0}/D_{50}≥1.0, s_o≥0.01), under perpendicular wave attack. The corresponding data have been identified in Fig. 11, where the measured K_r to ξ_o ratio is presented as function only of the relative crest height R_c/H_{si}, which is expected to have the most significant effect on wave reflection: the lower the crest, the greater the overtopping and the lower the reflection.

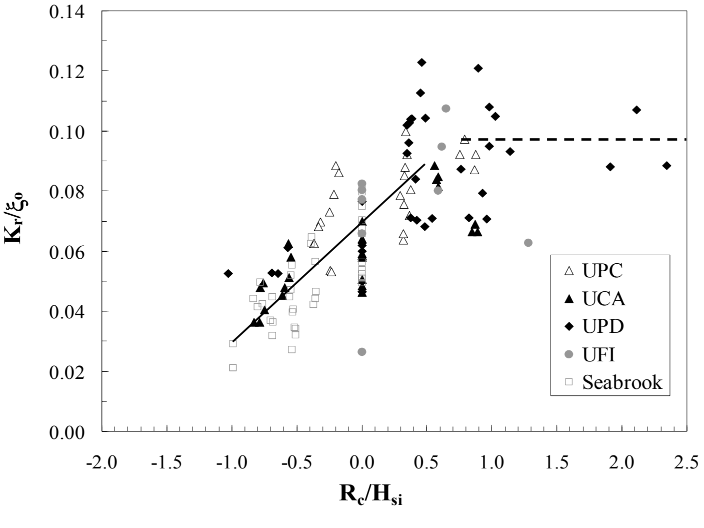

Figure 11. Measured K_r to ξ_o ratio as function of the relative crest height R_c/H_{si} for rock permeable LCss in design conditions.

The high positive values of R_c/H_{si} in Fig. 11 are due to low wave heights for slightly emerged structures; in these conditions of rare overtopping, the K_r/ξ_o tends to the value 0.089 already found for the best linear fit (2) for emerged structures. When $1 \le R_c/H_{si} \le 0.5$, K_r decreases almost linearly with R_c/H_{si}. The K_r for LCSs can be thus approximated by the formula (5) for emerged structures when $R_c/H_{si} \ge 0.5$ and a proper function has to be included to account for the progressive reduction of K_r with R_c/H_{si} when $-1 \le R_c/H_{si} < 0.5$. The formula

$$K_r = K_r(5) \cdot \left(0.67 + 0.37\frac{R_c}{H_{si}}\right),\ -1 \le \frac{R_c}{H_{si}} \le 0.5 \qquad (6)$$

leads to a fair estimate of the measured values.

CONCLUSIONS

A homogeneous database on wave reflection was prepared. Four ‘families’ of data can be distinguished: rock permeable, rock impermeable, armour units and smooth slopes. Only for smooth data a proper fitting formula exists (Seelig and Ahrens, 1981).

In order to approximate rock permeable, impermeable and armour unit slopes by one formula, a simple refitting of Seelig & Ahrens formula is insufficient.

A new formula was proposed to predict the reflection coefficient K_r for rock permeable, rock impermeable, armour unit and smooth slopes. This formula relates K_r to ξ_o, has a physical limit and depends on two parameters, which can be expressed as function only of the roughness factor γ_f in the overtopping discharge formula. This formula was validated with reflection data for slopes with other roughness factors.

The new formula gives a reasonable prediction of K_r also for rock permeable LCSs, if it is corrected by introducing a proper linear dependence on the relative crest height R_c/H_{si}.

Further research is needed to study the effects of wave obliquity, of a composite slope (Andersen and Burcharth, 2006), of a low crest. Another interesting issue can be the use of $k \cdot h$ instead of ξ_o, as proposed by Muttray et al., 2006. Moreover, it may be useful to adopt 2D VOF numerical models to check these effects in a more controlled environment, obtaining information also on wave spectra.

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