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Wave reflection from coastal structures in design conditions

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Abstract

Based on an extensive database of more than 4000 data, this paper analyses wave reflection for various types of coastal structures in design conditions, such as smooth, rock and armour unit slopes. A new simple formula has been developed that relates the reflection coefficient to the breaker parameter and seems to fit all kinds of revetment materials by changing two coefficients. These coefficients depend only on the correct roughness factor, provided by recent research on overtopping discharges. The effects on reflection due to composite slopes and to low crests are also examined and proper extensions of the formula are provided.

Keywords: Wave reflection; Coastal structures; Database; Berm; Low-crest

1. 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 harbours 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 coefficient 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 and very often reflection is a by-product of research on structure stability, wave overtopping or wave transmission. So far several empirical formulae for the prediction of the reflection coefficient K_r are available, but these have been validated against restricted datasets only.

For smooth impermeable slopes, first Miche (1951) determined K_r for monochromatic breaking waves; then Battjes (1974) in his formula for regular waves 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 under both regular and irregular waves and presented an improved estimate of K_r for irregular waves.

For rubble mound structures, 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 characteristics and the number of armour layers. Postma's (1989) analysis on rock slopes revealed a strong dependence of K_r on ξ and negligible correlations with spectral form and toe depth. Starting from Postma's work, Van der Meer (1992) provided a multiple regression method to separate the effects of wave height and period, structure permeability and slope. For rubble mound breakwaters under irregular wave attack, Davidson et al. (1996) developed a 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 a vertical, permeable, non-overtopped breakwater comprised of artificial armour blocks, Numata (1976) suggested

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Table 1
Overview of the database

Tests type	#
A—Rock permeable straight slopes (of which LCSs)	1449 (831)
B—Rock Impermeable straight slopes	198
C—Armour Unit straight slopes	1765
D—Smooth straight slopes	230
E—Structures with combined slopes	430
F—Vertical structures	236
Total	4308

an empirical equation for K_r based on the breakwater width to armour diameter ratio. For tetrapods, sheds and diodes, Allsop and Hiettrarchi (1989) provided proper values for the two coefficients in Seelig and Ahrens (1981) formula.

The EU-projects DELOS (www.delos.unibo.it) and CLASH (www.clash-eu.org) generated wide sets of tests on all kind of structures, where for large parts of the data sets K_r is available. Based most on these research projects, an extensive and homogeneous database on wave reflection has been prepared (Zanuttigh and Van der Meer, 2006).

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) and slopes with all kind of artificial armour units. More specific objectives are:

- to develop a formula for the prediction of K_r from straight slopes, suitable for all kind of materials;
- to determine a proper evaluation of the breaker parameter for composite slopes and berms, for which limited information is available in the literature (Lykke Andersen, 2006);
- to describe the influence of a low-crest, based on the first attempt made within DELOS (Van der Meer et al., 2005).

2. Analysis of wave reflection

2.1. The wave reflection database

The wave reflection database (Zanuttigh and Van der Meer, 2006) 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 (among the others, Lissev, 1993), field measurements (at Elmer, UK, see Davidson et al., 1996), recent tests on low-crested structures (Cappietti et al., 2006) for a total of more than 4000 data. A synthesis of data type and quantity is given in Table 1.

The process for preparing the homogeneous database followed precisely the work already done within CLASH for the wave overtopping database and for the representation of complex structure geometries (see in the next Fig. 11). For almost all datasets the computed values of K_r and not the measured data at the wave gauges were available, so that it was impossible to perform directly a homogeneous spectral wave analysis over the whole database. The methods to derive K_r differ from dataset to dataset, the most widely adopted being by Mansard and Funke (1987), Zelt and Skjelbreya (1992) and Hughes (1993). In some cases incident and reflected waves were derived from wave directional analysis, that can produce quite different results depending on the chosen method (BDM or others), on the selected parameters and on the signal quality (see for instance Martinelli et al., 2003).

2.2. Existing formulae for the reflection coefficient

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 on overtopping prediction and on the belief that overtopping and reflection performance are strictly related (as it will be proven next), the wave period adopted for the analysis is the spectral period at the structure toe

$$\xi_0 = \frac{\tan\alpha}{\sqrt{(2\pi H_{m_0t})/\left(gT^2_{m-1,0}\right)}} \qquad (1)$$

where H_{m_0t} is the significant wave height at the structure toe and $T_{m-1,0} = m_{-1}/m_0$.

Preliminary investigations on the opportunity of the use of ξ_0 in the reflection analysis were carried out by Van der Meer (2005) and recently also by Dekker et al. (in press). The parameter ξ_0 is useful for representing bi-modal spectra or shallow water with flat spectra, where for instance a peak period is not well defined. For single-peak spectra, it is approximately $T_{m-1,0} = T_p/1.1$.

From the work by Postma (1989) it is known that the wave period has more influence on the reflection behaviour than the wave height. So the use of ξ_0 introduces some scatter, but it also allows to incorporate different slopes in a simple way.

Table 2
Range of most relevant parameters for the straight slopes dataset

Slope type		cotα	h, m	H_{m_0t}/h	R_c/H_{m_0t}	ξ_0	G_c/H_{m_0t}	s_0	H_{m_0t}/D_{n50}	#
Rock permeable	min	1.5	0.45	0.07	0.62	1.33	0.00	0.01	1.28	366
	max	3.0	0.80	1.56	7.59	10.67	4.34	0.07	5.62	
Armour unit	min	1.5	0.30	0.05	0.00	2.06	0.00	0.01	1.37	274
	max	2.0	0.73	0.54	4.20	5.57	1.50	0.08	3.95	
Rock impermeable	min	2.0	0.80	0.06	1.36	0.65	0.78	0.01	1.29	194
	max	6.0		1.06	7.54	7.56	4.31	0.06	7.15	
Smooth	min	1.5	0.19	0.07	0.58	1.08	0.00	0.01	–	134
	max	4.0	0.75	0.60	4.49	4.13		0.06	–	

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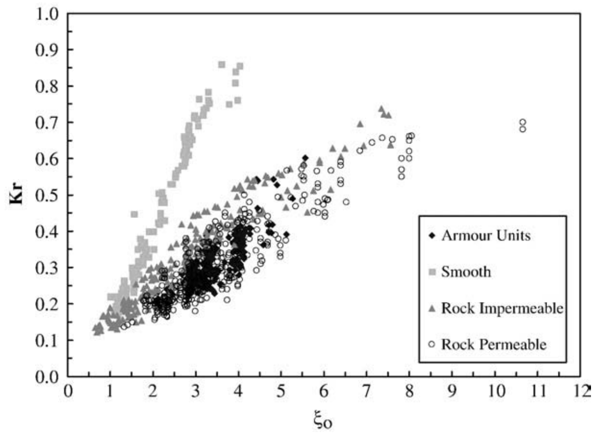

Fig. 1. All straight slopes under design conditions ($R_c/H_{m_0t} \geq 0.5$, $H_{m_0t}/D_{n50} \geq 1.0$, $s_0 \geq 0.01$) and perpendicular wave attack.

This analysis is first restricted to straight slope data in design conditions under perpendicular wave attack. Design conditions mean

- not too much wave transmission, $R_c/H_{m_0t} \geq 0.5$ (where R_c is the structure freeboard);
- not too low waves, $H_{m_0t}/D_{n50} \geq 1.0$ (where D_{n50} is the nominal armour diameter);
- not too long waves, $s_0 \geq 0.01$ (where s_0 is wave steepness related to $T_{m-1,0}$).

In total, there are about 1000 available tests, for which the ranges of the most relevant parameters are summarized in Table 2. All the corresponding data are shown in Fig. 1, where the presence of four "families" of data is evident:

- rock with a permeable core (e.g. breakwater),
- rock with an impermeable core (e.g. seawall),
- smooth slopes,
- slopes with armour units.

Armour units fall inside the rock permeable data cloud.

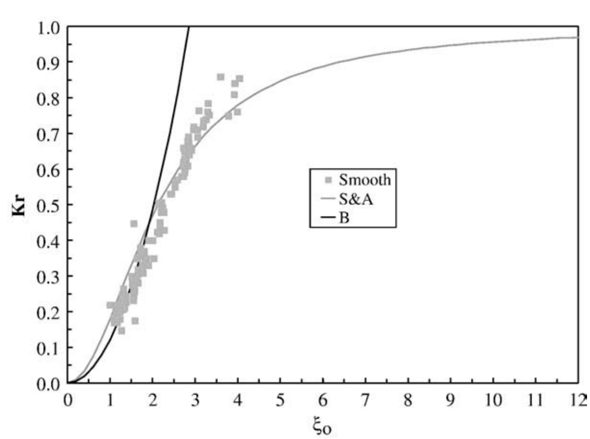

Fig. 2. Comparison of straight smooth slopes with Battjes (B, black line) and Seelig and Ahrens (S&A, grey line) curves, given by Eqs. (3) and (2) respectively.

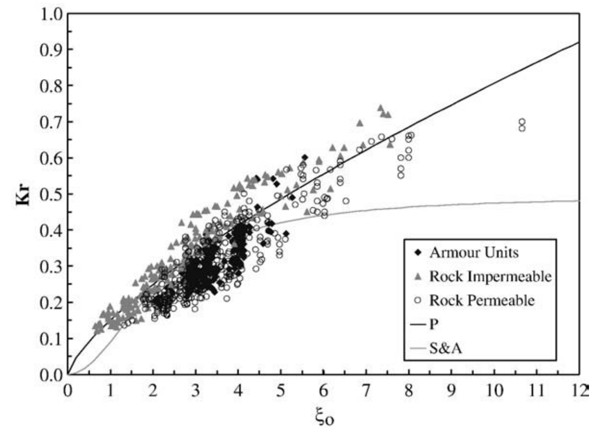

Fig. 3. Comparison of rock straight slopes, with permeable and impermeable core, and armour units with the curves by Postma (P, grey line) and Seelig and Ahrens (S&A, black line), given by Eqs. (4) and (2) respectively.

All the smooth slope data are well approximated, see Fig. 2, by the existing formulae by Seelig and Ahrens (1981)

$$K_r = \frac{a_1 \cdot \xi_0^2}{\xi_0^2 + b_1} \tag{2}$$

where $a_1 = 1.0$ and $b_1 = 5.0$, and by Battjes (1974) in a more restricted range (plunging waves or mild slopes only)

$$K_r = 0.12 \cdot \xi_0^2 \tag{3}$$

Fig. 3 shows that rock impermeable data are well represented by the Postma's (1989) curve

$$K_r = 0.15_0^{0.73} \tag{4}$$

and that rock permeable data can be represented only for $\xi_0 = 2–4$ by the Seelig and Ahrens curve with $a_1 = 0.49$ and $b_1 = 5.456$.

The rms-errors obtained by using these existing formulations are

- 7.09% for rocks with Seelig and Ahrens' Eq. (2),
- 4.63% for impermeable rocks with Postma's Eq. (4),
- 5.82% for smooth slopes with Seelig and Ahrens' Eq. (2).

It should be stressed that no general formula exists for armour units, with the exception of the work by Allsop and Hiettrarchi (1989), who refitted Eq. (2) for shed, diodes and tetrapods by calibrating the values a_1, b_1.

New fits are thus needed to adequately represent K_r at least for rock and armour units and preferable combined in one shape of formula that can be adapted to all types of coastal structures by simply changing coefficients.

Table 3
Coefficients a_1, b_1 to be included in Seelig and Ahrens (1981), given by Eq. (2)

Data type	a_1	b_1
Rock permeable; armour units	0.75	15
Rock impermeable	0.80	10
Smooth	1.00	4.54

Values for smooth slopes are not refitted.

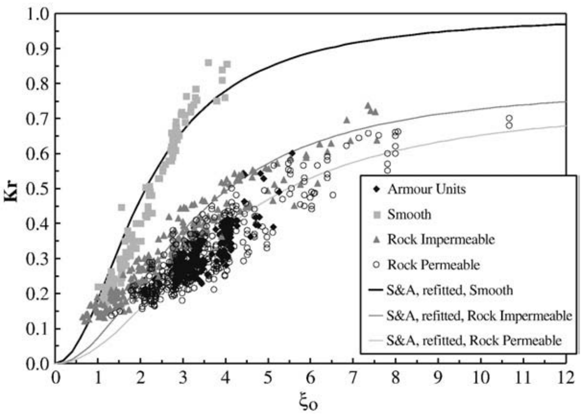

Fig. 4. Comparison of straight slopes with refitted Seelig and Ahrens (S&A), i.e. Eq. (2) refitted with coefficients a_1, b_1 in Table 2.

Since it already provides a good approximation for smooth data, the first attempt can be the refit of Seelig and Ahrens (1981) formula, Eq. (2). The values of the coefficients a_1, b_1 obtained by the calibration performed on the new datasets are reported in Table 3 for armour units, rock permeable and impermeable slopes.

The results obtained by refitting Eq. (2) are shown in Fig. 4:

- rock impermeable data are overestimated for $\xi_0<2$ and $\xi_0>4$, whereas they are well fitted for $\xi_0=2$–4;
- rock permeable data and armour units are underestimated for $\xi_0<2$ and are fairly well approximated for $\xi_0>2$.

The rms-errors obtained by the refitting Eq. (2) are:

- 4.33% for rocks with a permeable core,
- 3.70% for armour units,
- 5.56% for rocks with an impermeable core, and
- 5.82% as above for smooth slopes (with non-refitted coefficients).

In conclusion, this refitted formula allows a quite good approximation of the measured values of K_r but improvements can be done to obtain a better fitting of all types of coastal structures.

2.3. The new formula

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

- its shape can reproduce all different types of coastal structures;
- it represents physical bounds;
- it gives a relationship with the roughness factor γ_f as obtained for wave overtopping.

Table 4
Coefficients a, b to be included in the new formula, given by Eq. (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

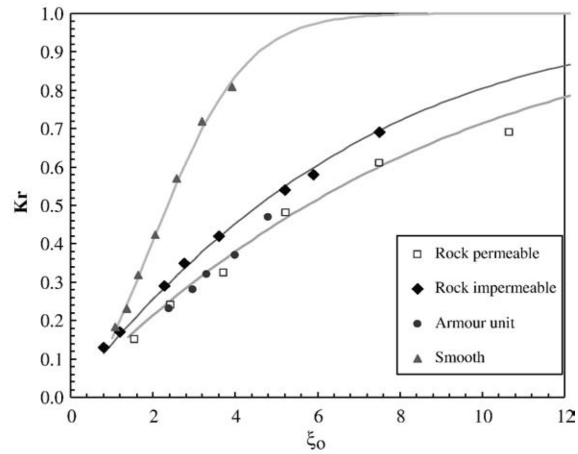

Fig. 5. Average values of K_r and derivation of Eq. (5) for all kind of slopes.

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 revetment materials or structure roughness (see TAW, 2002; Overtopping Manual, 2007), the dependence on this parameter, if confirmed, may allow to extend the new reflection formula to a wide variety of slopes.

The new formula (Zanuttigh and Van der Meer, 2006 is given by

$$K_r = \tanh\left(a \cdot \xi_0^b\right) \quad (5)$$

where the calibrated values of the coefficients a and b are reported in Table 4.

This formula and these values for a and b have been obtained by analyzing average values of K_r by groups of ξ_0, see Fig. 5. This is done, instead of straightforward fitting by a least square method, in order to give similar weight to data along the whole range of ξ_0 covered by the datasets.

The agreement amongst measured data and Eq. (5), with coefficients reported in Table 4, is shown in Fig. 6. K_r seems to be particularly well predicted for smooth and rock impermeable slopes, whereas it is slightly overestimated for armour units and rock permeable slopes when $\xi_0<4$.

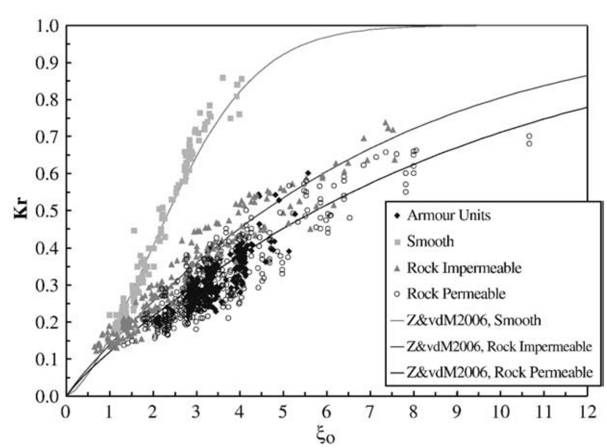

Fig. 6. Overall comparison of the new formula (Z&vdM2006) given by Eq. (5) with all data of straight slopes.

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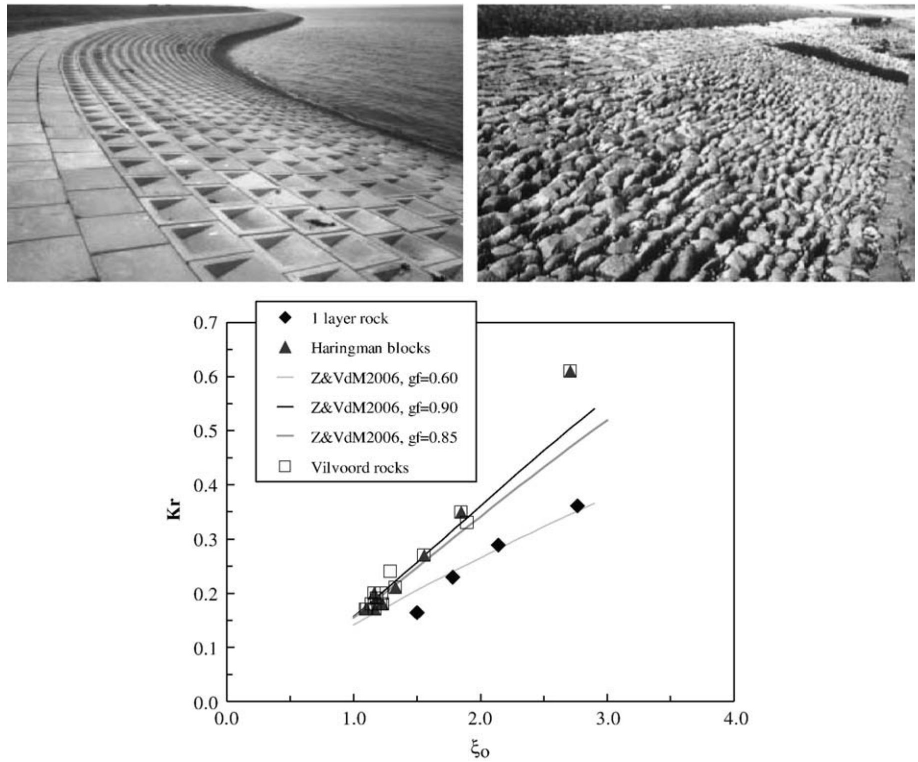

Fig. 7. At the top: pictures of Haringman blocks (left) and of Vilvoord rocks (right). At the bottom, comparison amongst measured values (points) and predictions (lines) of K_r for Haringman blocks (γ_f=0.90; a=0.157; b=1.263), Vilvoord rock (γ_f=0.85; a=0.156; b=1.189) and one-layer rock (γ_f=0.60; a=0.142; b=0.932).

The rms-errors obtained by the new formula are:

- 3.93% for rock with a permeable core,
- 3.74% for armour units,
- 3.71% for rocks with an impermeable core, and
- 4.04% for smooth slopes.

These rms-errors show a global improvement, especially for impermeable rock slopes and smooth structures, with respect to

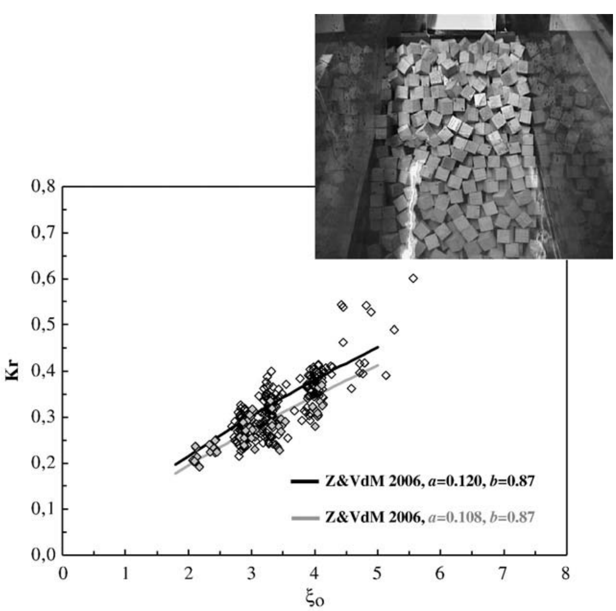

Fig. 8. Armour unit data fitting for two layers of rough cubes. All the armour unit data from Bruce et al. (2006) are identified by black open diamonds, grey diamonds are the cubes rough data. Both lines correspond to Eq. (5): the black one is obtained without refitting a and b (values as in Table 4) and the grey line is obtained by refitting values of a and b (values as in Table 5).

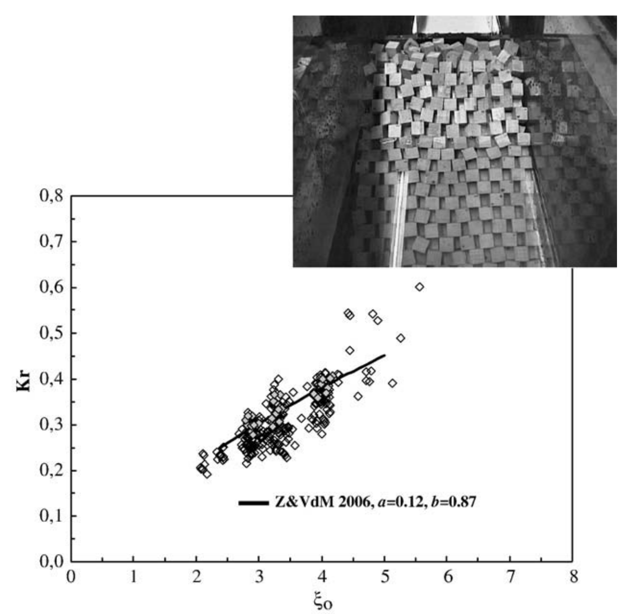

Fig. 9. Armour unit data fitting for single and flat cubes. All the armour unit data from Bruce et al. (2006) are identified by black open diamonds, grey diamonds are the data of single and flat cubes. The black line is Eq. (5) with a and b values as in Table 4.

Table 5
Values of the coefficients a, derived by directly fitting Eq. (5) on the armour units of the Edinburgh dataset (Bruce et al., 2006); 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

the results obtained by refitting Eq. (2). It is worth to highlight that the dataset used for impermeable rock slopes is exactly the same one adopted by Postma (1989) and that the 230 data of smooth slopes include the 97 values obtained from Seelig and Ahrens (1981) dataset. This assures that the comparison among the rms-errors obtained with the new formula and with the existing ones are not biased towards the new formula due to the dataset adopted, at least for rock impermeable slopes.

2.4. Relationship between wave reflection and 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. Thus 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 Eq. (5) on the roughness factor γ_f as estimated for overtopping research (Van der Meer, 1992; TAW, 2002 and most recently Overtopping Manual, 2007). By fitting the three well-known values of a, b and γ_f for rock permeable, rock impermeable and smooth slopes (Table 4), the following expressions for a and b can be derived

$$a = 0.167 \cdot \left[1 - \exp\left(-3.2 \cdot \gamma_f\right)\right], \qquad (6)$$
$$b = 1.49 \cdot \left(\gamma_f - 0.38\right)^2 + 0.86.$$

The second step is to verify Eq. (6) with independent data, different from the four “families” as described above.

First, a few slopes characterized by a γ_f in the range 0.55–1 have been analyzed. These data were taken from TAW (2002), where many revetment types are characterized by a γ_f. Reflection data were also available for a few structures: 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 Eqs. (5) and (6) without any refitting, see Fig. 7.

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 included and the coefficient b is almost constant, see Fig. 10 where Eqs. (5) and (6) are shown. 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 core. In these cases, the comparison among the measured values of K_r for each kind of armour unit and the prediction obtained by Eq. (5) with the constant values of a, b in Table 4 does not give a good enough approximation. Although the trend “the larger the γ_f, the larger K_r” is present, there is for some, not understood reason, a bias.

The case of two layers of rough cubes is presented as an example in Fig. 8, together with the whole dataset of armour units tested in Edinburgh. Eq. (5) with the values of a and b given in Table 4 appears to overestimate on average the whole dataset (as already concluded on the basis of Fig. 6), and certainly overestimates in particular the rough cubes data. By carrying out a calibration process on the value of a it is shown that a better agreement can be achieved among the data and Eq. (5).

One layer cubes and flat cubes are perfectly approximated by Eqs. (5) and (6) without any adjustment of a, showing that flat cubes and one layer of cubes behave similarly and give greater reflection than all the other armour units, see Fig. 9.

The value of a has thus been calibrated by keeping b constant and the best calibration of a for each kind of armour units is reported in Table 5. As it can be expected from Fig. 6, all the best values of a are slightly lower than the average 0.12 proposed in Table 4, see Fig. 10.

3. Reflection from structures with composite slopes

The structures in the reflection database are schematized as in the CLASH overtopping database (Fig. 11), where four possible different structure slopes are included based on the observation that for overtopping the most relevant processes occur in the run-down/up area defined as $\pm 1.5 H_{m_0 t}$ with respect to still water level (SWL):

- the downstream slope α_d, which is the structure slope below the berm if present;
- the average structure slope in the run-down/up area α_{incl} which includes a possible berm;

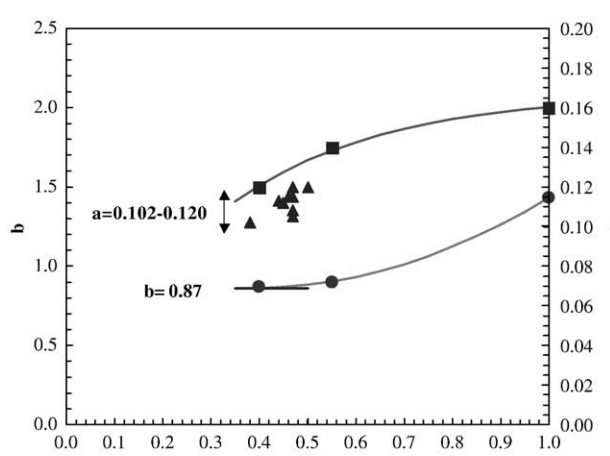

Fig. 10. Solid lines represent Eq. (6) for a (upper) and b (lower) as functions of γ_f; square points are the couples a–γ_f in Table 4; round points are the couples b–γ_f in Table 4; triangle points are the couples a–γ_f in Table 5: the range of the calibrated values of a keeping b constant (straight segment and value) are reported.

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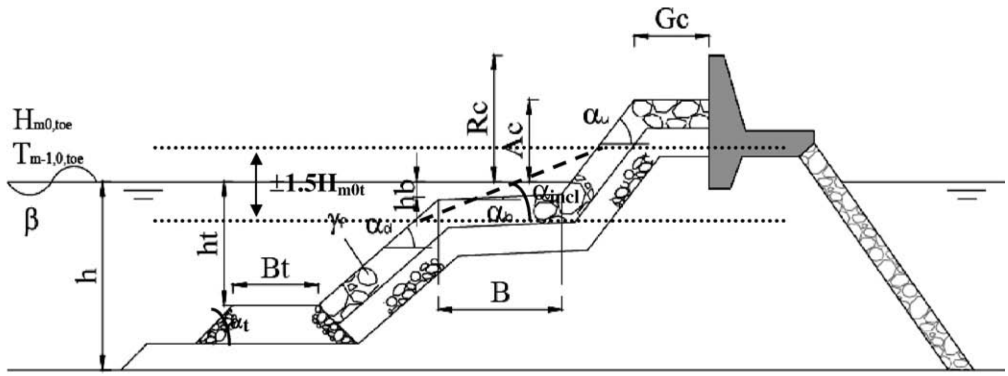

Fig. 11. Structure parameters in the reflection database, based on CLASH. Scheme redrawn from Van der Meer et al. (2005).

- the berm slope α_b with respect to the horizontal;
- the upstream structure slope above the run-down/up area α_u.

The characteristics of the combined slope dataset to which the analysis performed in the following is applied are summarized in Table 6.

Limited information on wave reflection from composite slopes is available in the literature. Lykke Andersen (2006) observed that for a reshaping berm breakwater the slope and hence the surf similarity parameter vary along the slope so that it is difficult to represent the breaking on the structure and the phase lag between reflections from different parts of the structure with a single value of ξ. By analyzing his wide database, he concluded that the slope above SWL is less important for reflection and he found a reasonable correlation between K_r and the Iribarren parameter at the structure toe based on peak wave period ξ_{op} when the breakwater slope is calculated as the average slope between SWL and $1.5H_{m_0t}$ below SWL. By introducing the notations adopted in Fig. 11, the resulting expression of ξ_0 based on the average berm breakwater slope is

$$\xi_0 = \frac{[\tan\alpha_d(1.5 \cdot H_{m_0t} - h_b) + \tan\alpha_b h_b]/(1.5 \cdot H_{m_0t})}{\sqrt{H_{m_0t}/L_0}}. \quad (7)$$

Eq. (7) is not applicable when the berm is at SWL and does not presuppose any effect of the berm when it is emerged or deeply submerged (more than $1.5H_{m_0t}$). For submerged berms located between SWL and $1.5H_{m_0t}$, good estimations of K_r were obtained by including this average slope in Postma's formula, Eq. (4).

Starting from the work by Lykke Andersen (2006) the main points of the present analysis can be summarized as follows:

- what reflects is the slope below SWL;
- for combined slopes an average slope has to be included in the evaluation of the Iribarren parameter;
- reflection is influenced by wave breaking and run-up. The lower the run-up the greater the reflection, and the greater the energy dissipation by breaking on the berm/toe, the lower the reflection. The presence of a toe and/or a berm should thus be accounted for whenever it may affect these processes, more specifically also when the berm is placed in the run-up area $+1.5H_{m_0t}$.

In the attempt to consider the presence of the berm even when it is at SWL or above it, it is suggested to use the following average of the structure slope:

$$\xi_0 = \frac{[\tan\alpha_d \cdot (h - 1.5H_{m_0t}) + \tan\alpha_{inc} \cdot 1.5 \cdot H_{m_0t}]/h}{\sqrt{H_{m_0t}/L_0}} \text{ if } h > 1.5H_{m_0t}$$
$$\xi_0 = \frac{\tan\alpha_{incl}}{\sqrt{H_{m_0t}/L_0}} \text{ if } h \le 1.5H_{m_0t}. \quad (8)$$

The weighted average slope in Eq. (8)

- is performed over the water depth at the structure toe h;
- makes use of the average slope in the whole run-up/down including the berm α_{incl}.

The performance of the two Eqs. (7) and (8) is shown against the same dataset in Fig. 12. To allow the comparison, the data consist only of the 69 tests by Lissev (1993) on reshaping breakwaters with submerged berms always located in the run-

Table 6
Range of most relevant parameters for the dataset of combined slopes

Slope type		$\cot\alpha_d$	$\cot\alpha_{inc}$	h, m	R_c/H_{m_0t}	H_{m_0t}/h	H_{m_0t}/h_t	H_{m_0t}/h_b	B_t/H_{m_0t}	B/H_{m_0}	G_c/H_{m_0t}	s_0	H_{m_0t}/D_{n50}	#
Rock permeable	min	1.3	2.3	0.06	0.50	0.06	0.13	–	0.00	0.00	0.68	0.01	1.31	192
	max	7.0	8.5	0.79	6.22	1.11	1.87		5.39	7.05	6.67	0.06	8.63	
Smooth	min	2.0	2.0	0.09	0.96	0.10	0.10	−4.05	–	0.00	0.00	0.01	–	194
	max	7.0	8.3	0.80	9.59	0.92	0.92	2.99	–	0.51	7.77	0.05		

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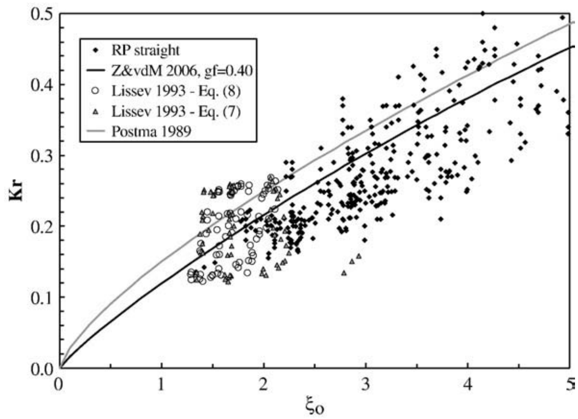

Fig. 12. Reflection data for a reshaping breakwater (Lissev, 1993) with submerged berm ($h_b>0$). The average slope is evaluated following the approximation proposed by Eq. (7) and by Eq. (8). The data of straight rock slopes are represented by black diamonds; Eq. (5), Z&vdM2006, by a solid black line; Eq. (2), Postma (1989), by a solid grey line.

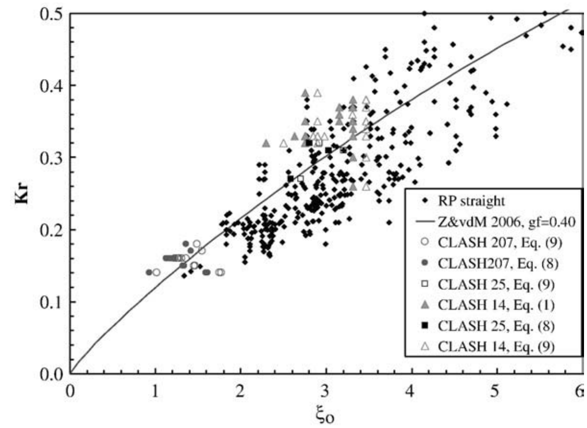

Fig. 14. Rock permeable structures with toe and berm where ξ_0 is evaluated following Eq. (9) or Eq. (8). Data of straight rock permeable slopes are represented by black diamonds and Eq. (5), Z&vdM2006, by a solid black line.

down zone. The prediction obtained by including the slope given by Eq. (8) in Eq. (5) is slightly better than the estimation derived from Eqs. (2) and (7), with rms-errors respectively equal to 4.11% and 6.92%.

As a consequence of the promising result obtained for submerged berms, Eq. (8) is applied to a smooth structure with berm characterized by different submergence in the run-down/up zone (Fig. 13). It can be seen that a fair agreement of the measured data with Eq. (5) is obtained when the berm is submerged (rms-error equal to 3.52%), whereas emerged berms give much more reflection than predicted (rms-error equal to 12.19%) and berms at SWL show still high scatter (rms-error equal to 6.84%).

From this preliminary analysis it can be concluded that Eq. (8), as Eq. (7), can be used to represent only submerged berms and more extensive research is needed for emerged cases.

The presence of a toe protection seems to have small effect on wave reflection limitedly to the available data (Table 6). In

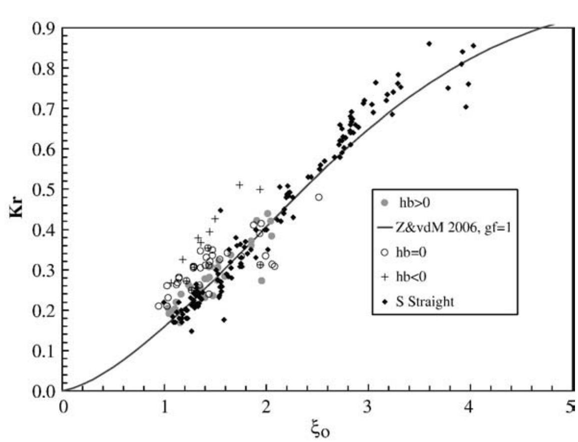

Fig. 13. Reflection data for a smooth structure with a flat berm where ξ_0 is evaluated following Eq. (8). Data of straight smooth slopes are represented by black diamonds and Eq. (5), Z&vdM2006, by a solid black line. The berm position with respect to SWL is indicated by h_b (submerged when positive).

attempt to represent the toe contribution, the following weighted average along the toe water depth h is proposed (slopes in Fig. 11):

$$\xi_0 = \frac{[\tan\alpha_t(h-h_t) + \tan\alpha_d(h_t 1.5H_{m0t}) + \tan\alpha_{\text{incl}} \cdot 1.5H_{m0t}]/h}{\sqrt{H_{m0t}/L_0}} \quad \text{if } h_t > 1.5H_{m0t}$$
$$\xi_0 = \frac{[\tan\alpha_t(h-h_t) + \tan\alpha_{\text{incl}} \cdot h_t]/h}{\sqrt{H_{m0t}/L_0}} \quad \text{if } h \le 1.5H_{m0t}. \qquad (9)$$

The α_t slope is always based on a toe structure which is close to the actual water depth h, only ignoring thin extending layers. When the toe is not coupled with a berm, the slope α_{incl} in Eq. (9) is equal to the structure downstream slope α_d.

Fig. 14 shows some rock permeable slopes with a toe (CLASH 14) and with both toe and submerged berm (CLASH 2O7, CLASH 25). The figure compares the same data where ξ_0 is calculated from Eq. (9) or by neglecting the presence of the toe, i.e. from Eq. (8) for the structures with berm and from Eq. (1) with $\alpha=\alpha_d$ for the structure with toe. It can be seen that the effect of the toe is small and that the data are already well approximated by Eq. (5), but anyway the use in Eq. (5) allows a slightly better agreement with the prediction, leading to a rms-error equal to 3.42% instead of 4.08%.

4. Effect of a low crest

The effect of a low-crest has been examined so far for rock permeable slopes only. Also for low-crested structures, the analysis was limited to design conditions (defined in this case as: $R_c/H_{m_0t} \ge -1.0$, $H_{m_0}/D_{n50} \ge 1.0$, $s_0 \ge 0.01$), under perpendicular wave attack. For this dataset, Table 7 summarizes the ranges of the most relevant parameters; as it can be seen, also the data by Seabrook and Hall (1998) characterized by steeper off-shore slopes and narrower crest widths (i.e. the structures that can still be considered as low-crested ones rather than reefs) have been included in the analysis.

Fig. 15 shows the measured K_r over the one derived from Eq. (5) as function only of the relative crest height R_c/H_{m_0t}. This ratio is expected to have the most significant effect on wave

Table 7
Range of most relevant parameters for the low-crested structures dataset

Label		cotα	h, m	H_{m_0t}/h	R_c/H_{m_0t}	ξ_0	G_c/H_{m_0t}	s_0	H_{m_0t}/D_{n50}	#	References
UPC	min	2.0	1.26	0.17	−0.37	2.51	2.66	0.03	2.65	24	Kramer et al. (2005)
	max		1.68	0.33	0.88	3.23	8.39	0.05	4.36		
UCA	min	2.0	0.25	0.17	−0.83	3.04	2.73	0.01	1.44	25	Kramer et al. (2005)
	max		0.35	0.36	0.89	7.08	17.41	0.04	2.35		
UPD	min	2.0	0.10	0.13	−1.03	2.31	1.39	0.01	1.02	36	Ruol and Faedo (2002)
	max		0.20	0.72	2.34	4.76	7.63	0.06	2.89		Ruol et al. (2004)
UFI	min	2.0	0.20	0.16	−0.55	2.42	0.65	0.01	1.01	26	Cappietti et al. (2006)
	max		0.26	0.51	1.28	4.87	9.90	0.06	5.80		
Seabrook	min	0.9	0.25	0.29	−1.00	2.43	1.61	0.02	1.56	87	Seabrook and Hall (1998)
	max	1.5	0.40	0.58	0.00	7.19	19.89	0.10	3.17		

reflection: the lower the crest, the greater the overtopping and the lower the reflection.

The high positive values of R_c/H_{m_0t} in Fig. 15 are due to low wave heights for slightly emerged structures. In these conditions of rare overtopping, the measured K_r tends to the predicted value for traditional emerged structures.

When $-1 \leq R_c/H_{m_0t} \leq 0.5$, the measured to predicted K_r decreases almost linearly with R_c/H_{m_0t}. For emerged low-crested structures ($R_c/H_{m_0t} \geq 0.5$), K_r can be thus approximated by Eq. (5), whereas a proper function has to be included to account for the progressive reduction of K_r with R_c/H_{m_0t} when $-1 \leq R_c/H_{m_0t} < 0.5$. The following Eq. (10) leads to a fair estimate of the measured values with a rms-error of 4.74%

$$K_r = K_{r\mathrm{Eq.}(5)} \cdot \left(0.67 + 0.37\frac{R_c}{H_{m_0t}}\right), -1 \leq \frac{R_c}{H_{m_0t}} \leq 0.5. \quad (10)$$

More data are needed to allow a proper check and improvement of Eq. (10).

5. Conclusions

Based on earlier datasets obtained in CLASH and DELOS projects, a homogeneous database on wave reflection was prepared. From the database, four 'families' of slopes can be distinguished: rock permeable, rock impermeable, armour units and smooth slopes. Only for smooth structures a proper formula (Seelig and Ahrens, 1981) exists to predict the reflection coefficient K_r over the full range of the breaker parameter ξ_0.

In order to approximate reflection for all kind of slopes by using one predictive formula, the refitting of Seelig and Ahrens (1981) curve is insufficient.

A new simple formula has been proposed to predict K_r for rock permeable, rock impermeable, armour unit and smooth slopes. This formula, given by Eq. (5), relates K_r to ξ_0, has a physical limit and depends on two parameters, which can be expressed as function only of the roughness factor γ_f as found in overtopping research. This formula has been validated against reflection data for slopes characterized by various roughness factors.

In order to extend the formula developed for straight slopes to combined slopes, the way to compute the slope for estimating the breaker parameter has been analysed.

Reflection occurs from the whole slope below SWL and is strictly related to run-up and breaking process.

In presence of a berm, the average structure slope can be computed as a weighted average over the toe water depth h between the downstream slope α_d and the slope in the run-down/up area α_{incl} ($\pm 1.5H_{m_0t}$), Eq. (8). When the berm is at SWL or emerged, this kind of estimation is still too rough and further analysis is needed.

The presence of a toe leads to a small effect on wave reflection, at least limitedly to the available data for rock permeable slopes. Anyway, the weighted average structure slope over the toe water depth h among the toe slope α_t, the structure downstream slope α_d and the slope in the run-down/up area α_{incl}, Eq. (9), seems to improve the agreement among measurements and predictions.

For rock permeable low crested structures, the new formula gives a reasonable prediction of K_r if it is corrected by introducing a proper linear dependence on the relative crest height R_c/H_{m_0t}, Eq. (10).

Further research will be carried out on this topic, by using an alternative predictive method as for instance a Neural Network, as already done in DELOS and CLASH for wave transmission and overtopping respectively (Panizzo and Briganti, 2007; van Gent et al., 2007).

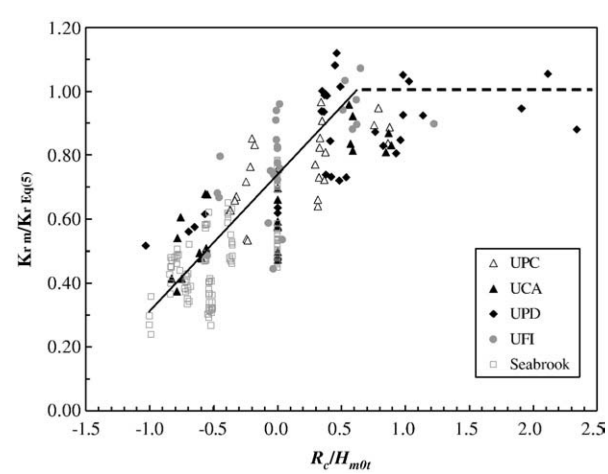

Fig. 15. Measured K_r to calculated K_r ratio as function of the relative crest height R_c/H_{m_0t} for rock permeable LCSs in design conditions ($R_c/H_{m_0t} \geq -1.0$, $H_{mt_0}/D_{n50} \geq 1.0$, $s_0 \geq 0.01$).

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Notations

a	Coefficient depending on γ_f. in the new formula, see Eqs. (5) and (6)
B	Berm width
B_t	Toe width
b	Coefficient depending on γ_f. in the new formula, see Eqs. (5) and (6)
D_{n50}	Nominal rock diameter or typical armour unit size
G_c	Structure crest width
g	Acceleration due to gravity
H_{m_0t}	Significant incident wave height at the structure toe
h	Water depth at the structure toe
h_b	Berm position with respect to SWL (positive if submerged)
h_t	Water depth above the structure toe
K_r	Reflection coefficient, i.e. the reflected to incident significant wave height ratio at the structure toe H_{m_0r}/H_{m_0t}
L_0	Wave length based on spectral wave period at the structure toe
R_c	Structure freeboard (negative if the structure is submerged) SWL still water level
s_0	Wave steepness based on spectral wave at the structure toe
$T_{m-1,0}$	Spectral wave period at the structure toe
α	Off-shore slope for structures with a single slope
α_b	Berm slope with respect to the horizontal
α_d	Structure slope below the berm
α_{incl}	Average structure slope including the berm in the run-down/up area, i.e. $\pm 1.5 H_{m_0t}$
α_t	Toe slope
γ_f	Roughness factor as found in overtopping research
ξ_0	Breaker parameter based on spectral wave period at the structure toe

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