Calibration of overtopping roughness factors for concrete armor units in non-breaking conditions using the CLASH database

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1. Introduction

The estimation of wave overtopping on breakwaters is a major design issue because it affects crest elevation and operational conditions. The overtopping rates on a mound breakwater depend on structural and environmental conditions. One of the structural characteristics is the roughness factor, γ_f; the higher the roughness factor, the higher the overtopping rates. The roughness factor, γ_f, takes into account how overtopping is influenced by the armor unit geometry, the number of layers, the packing density, the permeability of the filter and core as well as other structural characteristics. Fig. 1 illustrates the armor roughness of a smooth slope, γ_f=1.00, and a cube-armored slope, γ_f=0.50.

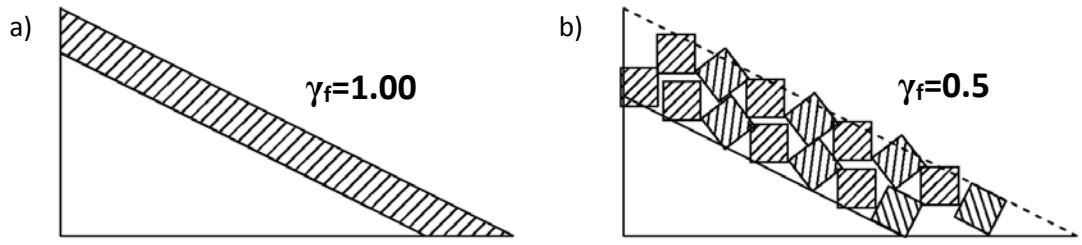

Figure 1. (a) Smooth slope and (b) double-layer randomly-placed cube armored slope.

Table 1 summarizes the roughness factors given by different authors and for different armor units. According to TAW (1974), the first roughness factors based on regular waves and run-up observations were published in Russian manuals. Owen (1980) used the roughness factors (γ_f) to estimate wave overtopping as the ratio between the run-up of a given wave on a rough slope and the run-up of the same wave on a smooth slope. Van der Meer and Janssen (1994) proposed calculating the γ_f for dikes and rock slopes by comparing the run-up of a rough slope with that of a smooth one. Lykke and Burchart (2004) pointed out that γ_f based on run-up measurements may not be adequate to estimate overtopping rates. For rock and cube armor units, Lykke and Burchart (2004) analyzed the correction factor given by Besley (1999) to take into account a permeable crest berm in both Owen's (1980) and Van der Meer and Janssen's (1994) formulas. The correction factor decreased the scatter on the data in both formulas; however, the best corrected formulas required different γ_f for the same armor unit, and in both cases these were different from the roughness factors originally proposed by Owen (1980) and Van der Meer and Janssen (1994).

Hebsgaard et al. (1998) developed an overtopping formula adjusting the coefficients of the formula to obtain the best fit when using a fixed γ_f=0.55 for double-layer rock armors, following the γ_f recommended by other researchers.

As part of the European CLASH Project (2001-2003), a set of γ_f based on overtopping measurements for different armor units was provided by Pearson et al. (2004). Those roughness factors were calibrated considering results from a specific cross-section and using the formula given by Van der Meer and Janssen (1994). Pearson et al. (2004)

factored all the initial γ_f values, the γ_f for the smooth slope being $\gamma_f = 1.00$; as γ_f obtained from smooth slope data was $\gamma_f = 1.05$, a 5% reduction was imposed on all values.

The European CLASH Project collected results from 10,532 overtopping tests corresponding to a variety of coastal structures (see Verhaeghe et al., 2003 and Van der Meer et al., 2009). The CLASH database was created as the foundation for a generic overtopping prediction method based on artificial neural networks (see Van Gent et al., 2007). The CLASH neural network (CLNN) uses the γ_f given by Coeveld et al. (2005), which are slightly different from those derived by Pearson et al. (2004) which were also obtained within the CLASH Project.

The CLNN uses 3 input variables to describe the characteristics of the incident waves and 12 input variables to describe the characteristics of the structure (see Fig. 2).

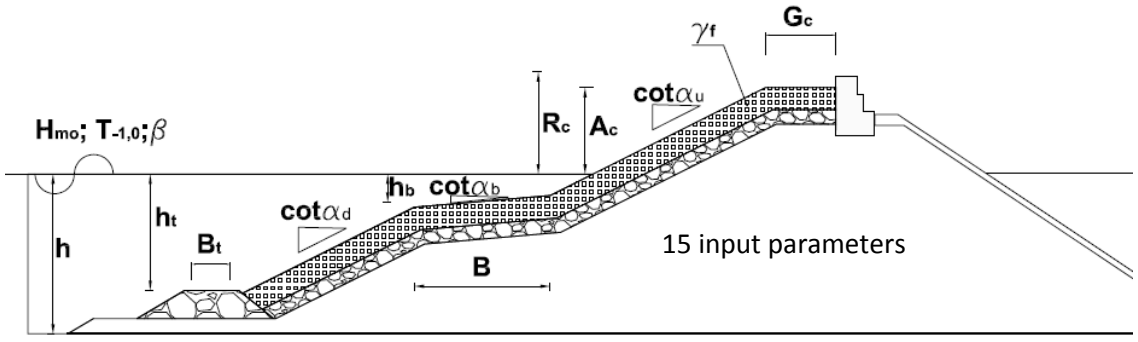

Figure 2. CLASH breakwater cross-section considered for the CLNN.

R_c is the breakwater crest freeboard; A_c is the armor crest freeboard; G_c is the breakwater crest width; cotα_d is the slope of the structure downward from the berm; cotα_u is the slope of the structure upward from the berm; B is the width of the berm; cotα_b is the slope of the berm; h_b is the water depth on the berm; h is the water depth in front of the structure; h_t is the water depth at the toe of the structure; B_t is the width

of the toe berm; β is the angle of wave attack; $H_{m0}=4(m_0)^{0.5}$ is the significant wave height at the toe of the structure; $T_{-1,0}=m_{-1}/m_0$ is the mean spectral wave period at the toe of the structure, being m_n the n^{th} spectral moment, and γ_f is the roughness factor given by Coeveld et al. (2005).

Bruce et al. (2006) reported specific tests and results from Pearson et al. (2004) and listed γ_f for different armor units which were used in the formulas given by EurOtop (2007). Bruce et al. (2009) re-examined the tests reported by Bruce et al. (2006), proposing certain changes in the γ_f and calculating the confidence intervals for each γ_f by analyzing variance. Overtopping rates were measured in specific small-scale tests for mound breakwaters without toe berm (B_t=0); cotα=1:1.5; $R_c=A_c$ and $G_c=3D_n$ (where D_n is the nominal diameter).

Smolka et al. (2009) carried out overtopping tests using cube and Cubipod-armored breakwaters, proposing a new 4-parameter formula (described in section 2). The proposed roughness factors were those which best fitted the results for double-layer cube and single- and double-layer Cubipod armors.

Van der Meer and Bruce (2014) proposed revising EurOtop (2007) formulas in order to account for low and zero crest freeboard (R_c/H_{m0}<0.5-1.00). In this revision, the roughness factors to be used in the new overtopping formula were not specified.

Kortenhaus et al. (2014) obtained the roughness factors for single- and double-layer Haro armors which best fitted their tests using formulas given by Van der Meer and Janssen (1994) and Van der Meer and Bruce (2014). The former resulted in γ_f=0.57 and the latter in γ_f=0.63. Their tested model was similar to that analyzed by Pearson et al. (2004) who proposed γ_f=0.47; Kortenhaus et al. (2014) suggested that the differences in

γ_f values were due to either model or scale effects, and thus the need for a more detailed analysis.

Table 1 shows different sets of roughness factors for mound breakwaters with permeable cores as proposed in the literature for a variety of overtopping prediction formulas. It must be stated that each set of γ_f is reliable only for the overtopping formula given by the corresponding author. The values underlined are estimated by Pearson et al. (2004), Bruce et al. (2006) and Bruce et al. (2009). Pearson et al. (2004), Bruce et al. (2006) and Bruce et al. (2009) gave values of the tested packing densities (all the papers were based on the same tests) in which Dolos armor units were not tested. For Cubipods, packing densities were taken from Smolka et al. (2009).

Type of armor 2L=double-layer 1L=single-layer	Packing density (Φ)	Owen (1980)	Hebsgaard et al. (1998)	Coeveld et al. (2005) CLNN	Pearson et al. (2004) Bruce et al. (2006) EurOtop (2007) Eq.(1) and Eqs.(2)	Smolka et al. (2009) Eq.(3)	Bruce et al. (2009) Eq.(1)	Kortenhaus et al. (2014) Eq.(1) and Eq.(4)
Smooth	-	1.00	-	1.00	1.00	-	1.00	-
Rock (2L)	1.38	0.50-0.60	0.55	0.50	0.40	-	0.40	-
Cube (2L, random)	1.17	-	-	0.50	0.47	0.50	0.47	-
Cube (2L, flat)	1.17	-	-	-	0.47	-	0.47	-
Cube (1L, flat)	0.70	-	-	-	0.50	-	0.49	-
Antifer (2L)	1.17	-	0.65	0.50	0.47	-	0.50	-
Haro^{R} (2L)	-	-	-	0.47	0.47	-	0.47	0.57/0.63
Haro^{R} (1L)	-	-	-	-	-	-	-	0.57/0.63
Tetrapod (2L)	1.04	-	-	0.40	0.38	-	0.38	-
Accropode ^{TM} (1L)	0.62	-	0.55	0.49	0.46	-	0.46	-
Core-Loc^{TM} (1L)	0.56	-	-	0.47	0.44	-	0.44	-

Xbloc^{R} (1L)	0.58	-	-	0.49	0.45	-	0.44	-
Dolos (2L)	-	-	0.45	0.43	0.43	-	0.43	-
Cubipod^{R} (2L)	1.18	-	-	-	-	0.44	-	-
Cubipod^{R} (1L)	0.61	-	-	-	-	0.46	-	-

Table 1. Roughness factors (γ_f) given in the literature.

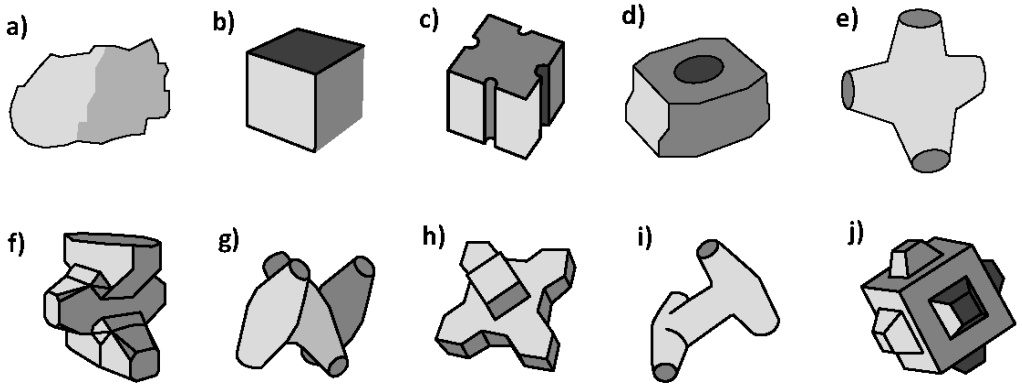

Figure 3. Concrete armor units: (a) rock; (b) cube; (c) Antifer; (d) Haro^{R}; (e) Tetrapod; (f) Accropode^{TM}; (g) Core-loc^{TM}; (h) Xbloc^{R}; (i) Dolos and (j) Cubpod^{R}.

The roughness factor is usually considered a parameter associated with the armor unit geometrical shape; however, γ_f is dependent not only on the armor unit geometry, but also on the packing density, number of layers and other structural characteristics. Furthermore, in this study, γ_f is also considered dependent on the specific empirical formulas in which γ_f is included.

In this paper, an overtopping background is given first. Secondly, the datasets extracted from the CLASH database are described in detail. Thirdly, a methodology to calibrate the armor roughness factors is described. Fourthly, the roughness factors and confidence intervals to be used along with different overtopping formulas are given. Fifthly, the influence of packing density and armor roughness is analyzed. Finally, a sensitivity analysis is provided and conclusions are drawn.

2. Selected overtopping formulas

This study considers some of the most popular overtopping formulas which include the roughness factor as an explicative variable. Nevertheless, the methodology used in this study is applicable to any empirical formula or overtopping prediction tool which includes the roughness factor as an explicative variable.

Eq. (1) is a well-known formula initially proposed by Van der Meer and Janssen (1994) to estimate wave overtopping on dikes in non-breaking conditions.

$$Q_{VMJ} = \frac{q}{\sqrt{g \cdot H_{m0}^3}} = A_1 \cdot \exp\left(- A_2 \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f} \right) \quad (1)$$

where A_1 = 0.2, A_2 = 2.6, and γ_f is used to consider the effect of the slope roughness. EurOtop (2007) suggested using Eq. (1) with the γ_f given by Bruce et al. (2006) and corrected the first estimation with Eqs. (2) proposed by Besley (1999) if G_c>3D_n.

$$Cr = \min\left[1.0; B_1 \cdot \exp\left(- B_2 \cdot \frac{G_c}{H_{m0}} \right) \right] \quad (2a)$$

$$Q_{EurOtop} = \frac{q}{\sqrt{g \cdot H_{m0}^3}} = Cr \cdot Q_{VMJ} \quad (2b)$$

where *Cr* is the reduction factor, B_1 = 3.06, and B_2 = 1.5. If G_c/H_{m0} < 0.75, there is no reduction in wave overtopping (*Cr* = 1). Initially, Eqs. (2) were derived by Besley (1999) to correct the formula given by Owen (1980), valid for rock slopes and R_c=A_c. Besley (1999) reported that Eqs. (2) can conservatively be applied to other permeable structures.

Eq. (1) is a simple and robust formula with only two parameters (A_1 = 0.2 and A_2 = -2.6). The corresponding ranges of application for the slope angle, relative crest freeboard and

Iribarren's number in Eq. (1) are 1.0 < cotα < 4.0, 0.5 < R_c/H_{m0} < 3.5, and Ir_p = T_p/cotα[2πH_{m0}/g]$^{0.5}$ > 2. The reliability of Eq. (1) is expressed by considering B_2 = -2.6, as a normally distributed random variable N(-2.6, 0.35^2).

Van Gent et al. (2007) described the CLASH neural network (CLNN) based on the CLASH database. The CLNN was created using a bootstrapping technique to train 500 artificial neural networks to estimate overtopping rates and confidence intervals. The CLNN gives no prediction when an input variable is out of its application range or when dimensionless overtopping rates are very low, $q/\sqrt{g \cdot H_{m0}^3}$ = Q<10^{-6}. One of the input variables of the CLNN is the γ_f given by Coeveld et al. (2005). In this study, Q_{CLNN} refers to the overtopping discharge estimated using the CLNN.

For cube- and Cubipod-armored breakwaters, Smolka et al. (2009) proposed the following overtopping formula:

$$Q_{SZM} = \frac{q}{\sqrt{g \cdot H_{m0}^3}} = C_1 \cdot \exp\left(C_2 \cdot Irp - C_3 \cdot \frac{A_c}{R_c} - C_4 \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f} \right) \quad (3)$$

where C_1=0.2, C_2=0.53, C_3=3.27, C_4=2.16, Ir_p = T_p/cotα[2πH_{m0}/g]$^{0.5}$, γ_f [cube 2L random] =0.50, γ_f [Cubipod 1L] =0.46, and γ_f [Cubipod 2L] =0.44. Tests by Smolka et al. (2009) were conducted in the ranges of 2.7< Ir_p <7.0, cotα=1.5, 0.70<A_c/R_c [cube 2L random]<1.00, 0.40<A_c/R_c [Cubipod 1L]<0.65, 0.58<A_c/R_c [Cubipod 2L]<0.80, and 1.30<R_c/H_{m0}<2.80. This overtopping formula was selected as an example of a formula which was obtained and calibrated from specific laboratory tests.

Recently, Van der Meer and Bruce (2014) proposed revising the Q_{VMJ} formula to describe overtopping on sloping structures with zero and positive freeboard in non-breaking conditions:

$$Q_{VMB} = \frac{q}{\sqrt{g \cdot H_{m0}^3}} = D_1 \cdot \exp\left(-\left(D_2 \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f} \right)^{D3} \right) \quad (4)$$

where D_1=0.09, D_2= 1.5, and D_3=1.3. Van der Meer and Bruce (2014) pointed out that Eq. (4) gives almost the same overtopping discharge estimations as Eq. (1), but better estimations for low and zero crest freeboards (R_c/H_{m0}<0.5-1.0). The reliability of Eq. (4) is expressed by considering D_1 = 0.09, as a normally distributed random variable N(0.09, 0.013^2) and D_2 = 1.5 as N(1.5, 0.15^2).

3. Datasets from CLASH database

This paper focuses on mound breakwaters with crown wall, corresponding to the cross-section depicted in Fig. 4, and referred to as conventional mound breakwaters. This is the most common typology for mound breakwaters, especially when concrete armor units are used.

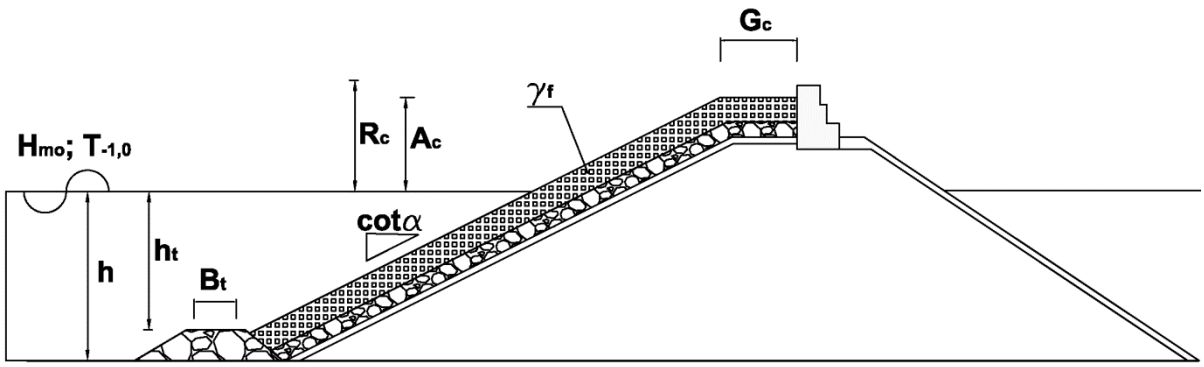

Figure 4. Conventional mound breakwater cross-section.

This study used the overtopping measurements for conventional mound breakwaters included in the CLASH database. For Cubipod-armored breakwaters, the tests conducted by Smolka et al. (2009) were used. The structural characteristics of the tests by Smolka

et al. (2009) were cotα=1.5, G_c[m]=0.12, and B_t[m]=0. Appendix A provides the overtopping results from the small-scale tests reported by Smolka et al. (2009).

To select the data corresponding to conventional mound breakwaters, the following data filters were applied to the CLASH database: β=0, cotα_d=cotα_u=cotα, 1.19 ≤ cotα ≤ 4, B=0, tanα_b=0, h_b=0, RF≤2, CF=1, non-breaking conditions (1.8 H_{m0toe}<$0.8h$ and/or Ir_p= T_{ptoe}/cotα[2πH_{m0toe}/g]$^{0.5}$ >2 to ensure no wave breaking) and Q≥10^{-6}. RF is the Reliability Factor (1≤RF≤4) to account for the quality of the test, and CF is the Complexity Factor (1≤CF≤4) to account for the complexity of the cross section, both defined in Van Gent et al. (2007). Furthermore, tests with remarks and/or without references were removed. The CLASH database (http://www.clash.ugent.be/) identified the armor type using the values of γ_f listed by Bruce et al. (2006). For cases in which one value of γ_f identified two or more armor units, it was necessary to check the reference to correctly identify the tests corresponding to each armor unit. Test data provided by Stewart et al. (2002), corresponding to tightly-packed rock armor, were removed given the divergence between the roughness factor found in the CLASH database, γ_f =0.40, and γ_f =0.75 proposed by Stewart et al. (2002). For smooth slopes, tests with R_c[m]=0 were removed since they are not within the common range of conventional mound breakwaters. For Dolos, only 8 tests with references are available in the database, so all were used. After applying the filter described above, a total of 1,183 of 10,532 tests were selected. Table 3 specifies the characteristics of the overtopping tests extracted from the CLASH database and Smolka et al. (2009). Table 3 also specifies the applicability range of the roughness factors derived in this study. Given a specific armor unit, selecting the same dataset for all the overtopping formulas allows for the direct comparison of the results.

The relative Mean Squared Error (*rMSE*) of log Q, similar to that used in Van Gent et al. (2007), is used here to measure the quality of the overtopping estimator "e" when applied to a group of target or observed data "o" (i=1,2,….,N). The *rMSE* corresponding to overtopping estimator "e" and observations "o" is given by:

$$rMSE_e(o) = \frac{MSE_e(o)}{Var(o)} = \frac{\sum_{i=1}^{N} WF_i \left(\log Qe_i - \log Qo_i\right)^2}{\left(\sum_{i=1}^{N} WF_i\right) \cdot Var\left(\log Qo\right)} \qquad (5)$$

where *N* is the total number of data; *i* is the data index; *WF* is the weight factor given in Table 2 from CLASH (see Van Gent et al., 2007); *Qe* and *Qo* are the estimated and target dimensionless mean overtopping discharges using estimator "e" and target data "o". 0%<$rMSE_e$(o)<100% indicates the proportion of variance of the data not explained by the estimator "e".

RF	***WF***
1	9
2	6

Table 2. Weight Factor dependent on the Reliability Factor.

Armor type	Datasets	No. data	H_{m0} [m]	$T_{-1,0}$ [s]	R_c [m]	A_c [m]	G_c [m]	cot α	h_t [m]	h [m]	B_t [m]
Smooth	30,35,42, 102,103, 218,220, 221,222, 226,227, 703	226	0.027-0.203	0.679-3.647	0.040-0.55	0.040-0.55	0.000	1.19-4.00	0.080-0.720	0.160-0.720	0.000-0.800
Rock (2L)	32,35, 331,510, 701,702, 705,954, 958	555	0.051-0.203	0.800-2.560	0.062-0.370	0.010-0.300	0.000-0.360	1.33-4.00	0.087-0.730	0.138-0.730	0.000-0.140
Cubes (2L, random)	331,510, 702,705	171	0.041-0.177	0.747-2.854	0.070-0.263	0.070-0.240	0.089-0.351	1.33-2.50	0.405-0.722	0.405-0.722	0.000-0.130
Cubes (2L, flat)	510	28	0.044-0.102	0.751-1.542	0.071-0.118	0.071-0.116	0.089	1.50-2.00	0.677-0.724	0.677-0.724	0.000
Cubes (1L, flat)	510	16	0.045-0.097	0.795-1.540	0.071-0.116	0.071-0.116	0.089	1.50	0.678-0.721	0.678-0.721	0.000
Antifer (2L)	379,510	25	0.048-0.136	0.791-2.191	0.079-0.180	0.079-0.180	0.099-0.150	1.50	0.400-0.725	0.400-0.725	0.000
Haro^{R} (2L)	510	15	0.044-0.101	0.751-1.540	0.071-0.118	0.071-0.118	0.078-0.089	1.50	0.678-0.724	0.678-0.724	0.000
Tetrapod (2L)	331,379, 510	86	0.079-0.136	0.952-2.191	0.081-0.024	0.081-0.180	0.105-0.351	1.33-2.00	0.400-0.731	0.400-0.731	0.000
Accropode^{TM} (1L)	510	14	0.069-0.118	0.948-1.640	0.086-0.139	0.086-0.139	0.095	1.50	0.674-0.727	0.674-0.727	0.000
Core-Loc^{TM} (1L)	379,510	27	0.060-0.136	0.951-2.191	0.086-0.181	0.086-0.181	0.089-0.150	1.50	0.400-0.727	0.400-0.727	0.000
Xbloc^{R} (1L)	510	12	0.075-0.115	0.952-1.642	0.090-0.142	0.090-0.142	0.090	1.50	0.673-0.728	0.673-0.728	0.000
Dolos (2L)	702	8	0.122-0.177	1.091-2.000	0.200-0.240	0.110-0.150	0.180	2.50	0.550-0.590	0.550-0.590	0.000
Cubipod^{R} (2L)	Table 6	65	0.089-0.157	1.045-2.780	0.203-0.263	0.150-0.200	0.120	1.50	0.500-0.550	0.500-0.550	0.000
Cubipod^{R} (1L)	Table 7	59	0.075-0.158	0.978-2.683	0.203-0.263	0.110-0.160	0.120	1.50	0.500-0.550	0.500-0.550	0.000

Table 3. Test data extracted from the CLASH database and Smolka et al. (2009).

4. Methodology to estimate the roughness factors (γ_f)

Considering a specific overtopping predictor and a given dataset, *rMSE* (Eq. 5) can be used to estimate the optimum γ_f which minimizes *rMSE*. However, no information is obtained regarding the uncertainty of this γ_f. In order to overcome the uncertainty of

the estimation of the γ_f, a bootstrap resampling technique is used in this study as described by Van Gent et al. (2007). A bootstrap resample is a random selection of N datum taken from the N original dataset, with the probability 1/N that a particular datum is selected each time. As a result, some data are selected once or more than once, while others may be absent in a resample.

In this study, 1000 resamples were made for each type of armor and overtopping predictor. For each resample, the γ_f was varied around the value given by Coeveld et al. (2005) and the *rMSE* was calculated for each γ_f. Thus, 1000 values for the roughness factor which minimized the *rMSE* were obtained and used to statistically characterize the γ_f to be used for each type of armor and overtopping predictor. The γ_f was characterized by the percentiles 10% (γ_{f10}), 50% (γ_{f50}) and 90% (γ_{f90}) of the discrete histogram. The calculated-values of γ_{f10}, $\gamma_{f50}$and γ_{f90} were used in combination with data given in Table 3 to obtain the expected *rMSE* presented in Table 4.

4.1. General method: application to cubes (2L, random)

Once the tests were selected from the CLASH database and the 1000 resamples were created by bootstrapping, each formula was applied to each resample to optimize the roughness factor. Fig. 5 shows the *rMSE* corresponding to different γ_f for three specific resamples using the formula Q_{VMJ} (Eq. 1). Other formulas show similar graphs; each has a different *rMSE* for a different value of γ_f.

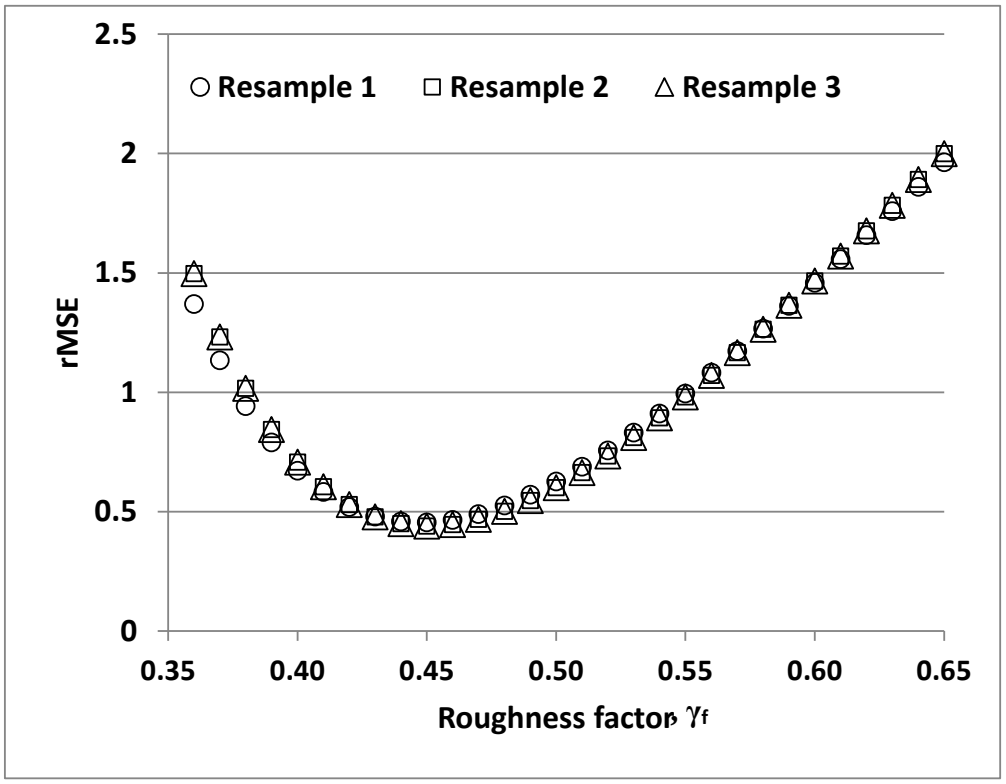

Figure 5. Roughness factor and *rMSE* for cube (2L, random) using Q_{VMJ}.

Considering a specific overtopping predictor, the γ_f which minimized the *rMSE* of each resample was used to define a discrete frequency histogram, characterized by the 10%, 50% and 90% percentiles: γ_{f10}, γ_{f50}, and γ_{f90} (see Fig. 6). The *rMSE* were calculated for at least 30 values of γ_f around the γ_f given by Coeveld et al (2005) in increments of 0.01. In the case of cube (2L, random) and Eq. (1), γ_{f10}=0.44, γ_{f50}=0.45, and γ_{f90}=0.46. Fig. 7 illustrates the cross-validation graph of the estimated overtopping using Q_{VMJ} with γ_{f50}=0.45 in comparison to the measured overtopping.

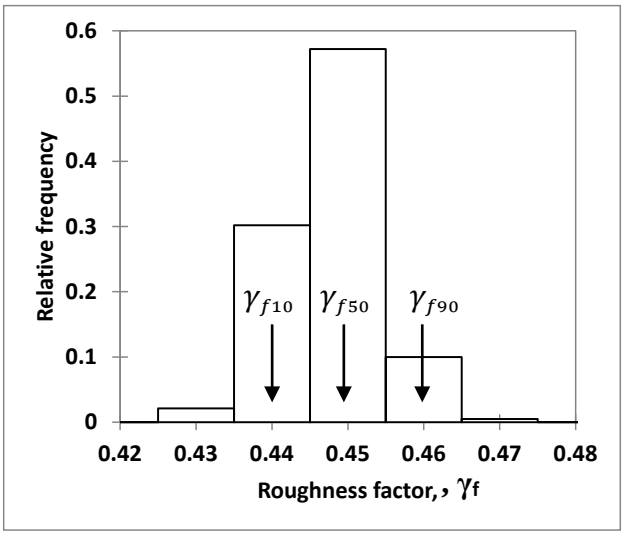

Figure 6. Roughness factor frequency histogram corresponding to cube (2L random) using Eq. (1).

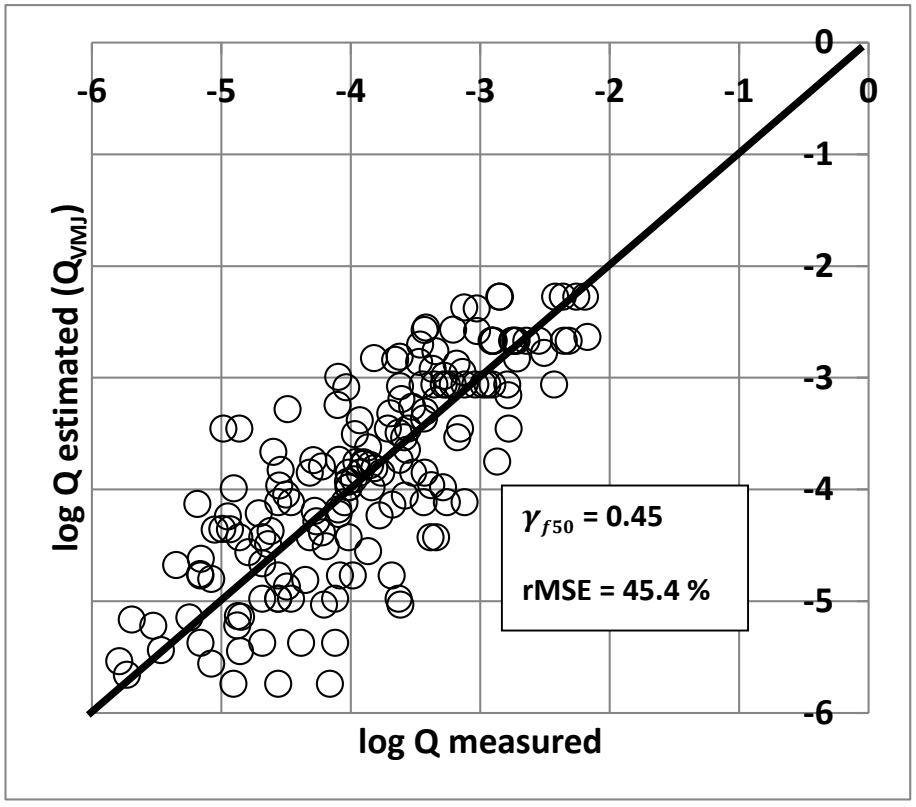

Figure 7. Measured and estimated overtopping rates of cube (2L random) using Eq. (1).

5. Results

Table 4 summarizes the results of γ_{f10}, γ_{f50}, and γ_{f90} as well as the associated rMSE for different armors. The CLNN gave the lowest rMSE for all cases except for Dolos, where a slightly lower *rMSE* for γ_{f50} was given by Smolka et al. (2009). For smooth slopes and estimator Q_{CLNN}, no prediction is given if γ_f>1.00 because the γ_f-value is internally limited by the CLNN to $0.30<\gamma_f\leq1.00$. The first column shows the roughness factors proposed by Coeveld et al. (2005) used for the CLNN and the roughness factors calculated by Smolka et al. (2009) for Cubipod armors. Both studies found γ_f=0.50 for cube armors (2L, random).

Table 4 shows the variability of the optimum roughness factor for each type of armor and formula. There is a range of roughness factors which leads to almost the same *rMSE* (see Fig. 5) for each concrete armor unit. Therefore, the roughness factors shown in Table 4 may change in the future if additional tests are added to the dataset used for calibration.

The selected overtopping formulas clearly improved their prediction when increasing the number of variables, except Eq. (4) which gives less accurate predictions than Eq. (1) in most cases. One should take into consideration that selected CLASH tests for calibration (see Table 3) have $0.5<R_c/H_{m0}<3.5$; therefore, using Eq. (4) does not take advantage of its better performance for zero and low crest freeboard cases.

Armor type Coeveld et al. (2005) Smolka et al. (2009)		Overtopping estimator									
		Q_{CLNN} (2007)		Q_{VMJ} (1994)		$Q_{EurOtop}$ (2007)		Q_{SZM} (2009)		Q_{VMB} (2014)	
				(Eq. 1)		(Eqs. 2)		(Eq. 3)		(Eq. 4)	
γ_f	γ_{fx}	γ_f	rMSE(%)	γ_f	rMSE(%)	γ_f	rMSE(%)	γ_f	rMSE(%)	γ_f	rMSE(%)
Smooth	γ_{f10}	0.99	*5.0*	1.02	*11.1*	1.02	*11.1*	1.18	*16.9*	1.00	*9.9*
	$\boldsymbol{\gamma_{f50}}$	**1.00**	***4.9***	**1.03**	***11.1***	**1.03**	***11.1***	**1.21**	***16.8***	**1.01**	***9.8***
1.00	γ_{f90}	1.00	-	1.05	*11.2*	1.05	*11.2*	1.24	*16.9*	1.03	*9.9*
Rock (2L)	γ_{f10}	0.48	*14.6*	0.45	*59.5*	0.52	*51.9*	0.43	*32.8*	0.46	*80.8*
	$\boldsymbol{\gamma_{f50}}$	**0.49**	***14.4***	**0.45**	***59.5***	**0.53**	***51.5***	**0.44**	***32.6***	**0.47**	***79.9***
0.50	γ_{f90}	0.50	*14.6*	0.46	*59.9*	0.54	*51.8*	0.44	*32.6*	0.48	*80.9*
Cube (2L, random)	γ_{f10}	0.52	*10.2*	0.44	*45.8*	0.52	*37.3*	0.43	*25.2*	0.45	*58.5*
	$\boldsymbol{\gamma_{f50}}$	**0.53**	***10.0***	**0.45**	***45.4***	**0.53**	***36.8***	**0.44**	***24.6***	**0.46**	***57.7***
0.50	γ_{f90}	0.53	*10.0*	0.46	*46.6*	0.54	*37.0*	0.45	*25.1*	0.47	*58.8*
Cube (2L, flat)	γ_{f10}	0.52	*7.5*	0.46	*29.5*	0.52	*17.5*	0.49	*24.0*	0.46	*36.1*
	$\boldsymbol{\gamma_{f50}}$	**0.53**	**6.9**	**0.48**	***27.4***	**0.53**	***16.8***	**0.51**	***22.6***	**0.48**	***32.3***
-	γ_{f90}	0.54	7.1	0.50	*29.6*	0.55	*17.5*	0.53	*23.5*	0.50	*34.3*
Cube (1L, flat)	γ_{f10}	0.53	*3.3*	0.49	*15.2*	0.56	*10.3*	0.50	*12.0*	0.50	*20.8*
	$\boldsymbol{\gamma_{f50}}$	**0.54**	***3.1***	**0.52**	***12.7***	**0.59**	***8.2***	**0.53**	***10.8***	**0.53**	***16.9***
-	γ_{f90}	0.55	*3.3*	0.54	*14.0*	0.62	*9.2*	0.55	*11.8*	0.56	*19.7*
Antifer (2L)	γ_{f10}	0.51	*9.8*	0.48	*34.3*	0.54	*25.9*	0.48	*33.6*	0.48	*38.9*
	$\boldsymbol{\gamma_{f50}}$	**0.52**	***9.3***	**0.50**	***32.2***	**0.57**	***23.7***	**0.51**	***31.6***	**0.50**	***35.8***
0.50	γ_{f90}	0.53	*9.9*	0.52	*33.9*	0.59	*25.1*	0.54	*34.8*	0.52	*37.5*
Haro [R] (2L)	γ_{f10}	0.51	*2.4*	0.47	*19.6*	0.52	*8.5*	0.48	*18.6*	0.47	*21.3*
	$\boldsymbol{\gamma_{f50}}$	**0.52**	***2.3***	**0.49**	***17.6***	**0.54**	***7.8***	**0.50**	***17.4***	**0.49**	***17.9***
0.47	γ_{f90}	0.53	*2.9*	0.52	*20.7*	0.56	*9.3*	0.53	*19.5*	0.52	*21.3*
Tetrapod (2L)	γ_{f10}	0.41	*17.7*	0.42	*28.8*	0.50	*30.1*	0.38	*25.8*	0.43	*37.7*
	$\boldsymbol{\gamma_{f50}}$	**0.42**	***17.5***	**0.43**	***28.5***	**0.52**	***29.2***	**0.39**	***24.9***	**0.43**	***37.7***
0.40	γ_{f90}	0.43	*17.6*	0.43	*28.5*	0.53	*29.8*	0.40	*25.5*	0.44	*37.7*
Accropode [TM] (1L)	γ_{f10}	0.47	*3.9*	0.46	*15.5*	0.50	*10.1*	0.48	*9.9*	0.47	*19.7*
	$\boldsymbol{\gamma_{f50}}$	**0.48**	***3.7***	**0.48**	***13.0***	**0.51**	***9.2***	**0.49**	***9.4***	**0.49**	***16.9***
0.49	γ_{f90}	0.49	*4.7*	0.50	*14.8*	0.53	*10.1*	0.51	*10.4*	0.50	*17.7*
Core-Loc[TM] (1L)	γ_{f10}	0.45	*6.1*	0.44	*23.9*	0.48	*18.4*	0.44	*20.7*	0.45	*24.4*
	$\boldsymbol{\gamma_{f50}}$	**0.46**	***6.0***	**0.46**	***22.2***	**0.49**	***17.8***	**0.46**	***19.6***	**0.46**	***23.2***
0.47	γ_{f90}	0.47	*7.1*	0.47	*23.0*	0.51	*19.1*	0.48	*21.4*	0.48	*25.2*
Xbloc [R] (1L)	γ_{f10}	0.49	*10.6*	0.44	*44.0*	0.46	*33.5*	0.46	*26.7*	0.44	*54.0*
	$\boldsymbol{\gamma_{f50}}$	**0.51**	***8.6***	**0.47**	***37.7***	**0.49**	***27.9***	**0.48**	***24.5***	**0.47**	***44.3***
0.49	γ_{f90}	0.52	*10.1*	0.49	*41.2*	0.51	*30.8*	0.51	*27.7*	0.49	*48.3*
Dolos (2L)	γ_{f10}	0.31	*22.3*	0.39	*37.9*	0.42	*39.4*	0.35	*28.0*	0.41	*33.3*
	$\boldsymbol{\gamma_{f50}}$	**0.32**	***22.3***	**0.41**	***30.0***	**0.45**	***31.8***	**0.37**	***22.0***	**0.43**	***29.1***
0.43	γ_{f90}	0.43	*26.0*	0.43	*35.0*	0.47	*38.0*	0.38	*24.2*	0.44	*33.0*
Cubipod [R] (2L)	γ_{f10}	0.44	*18.5*	0.54	*47.7*	0.56	*46.3*	0.45	*23.7*	0.56	*53.5*
	$\boldsymbol{\gamma_{f50}}$	**0.45**	***18.1***	**0.55**	***46.8***	**0.57**	***44.7***	**0.45**	***23.7***	**0.57**	***52.6***
0.44	γ_{f90}	0.46	*18.3*	0.56	*47.7*	0.59	*46.1*	0.46	*23.8*	0.58	*54.1*
Cubipod [R] (1L)	γ_{f10}	0.47	*15.0*	0.57	*33.4*	0.60	*32.6*	0.45	*18.2*	0.60	*40.4*
	$\boldsymbol{\gamma_{f50}}$	**0.48**	***14.8***	**0.58**	***32.4***	**0.61**	***31.4***	**0.46**	***16.8***	**0.61**	***40.3***
0.46	γ_{f90}	0.50	*15.5*	0.59	*33.2*	0.63	*33.2*	0.47	*18.4*	0.62	*42.3*

Table 4. Roughness factors and rMSE (CLASH database and Tables 6 and 7).

The CLNN shows the minimum *rMSE* in this study and avoids the influence of certain structural variables on the estimation of the roughness factor. Thus, the CLNN is recommended to compare the influence of a given type of armor on overtopping discharges with different cross sections. Simple formulas such as those given by EurOtop (2007) can be applied considering the wave conditions and structural geometry which have been used to obtain the roughness factors.

The armor placement did not significantly influence the overtopping discharges on cube armors. This result is consistent with the conclusions drawn by Bruce et al. (2009), and may change in the future when increasing the number of data for 2L-flat cubes (28 in this study) to be compared with the 171 tests of 2L-random cubes. Cubes and Cubipods were analyzed in single- and double- layer armors. In both cases, the single-layer system presented higher roughness factors, and hence higher overtopping discharges are expected.

Only eight tests using Dolos conducted by Pedersen (1996) were selected from CLASH database ($\cot\alpha$=2.5) with small overtopping discharges. Thus, variations in the roughness factors for Dolos listed in Table 4 are expected when more overtopping data are included.

Single- and double-layer Cubipod^R armors were tested with A_c/R_c<1; therefore, Eq. (1), Eqs. (2) and Eq. (4) which do not include A_c as input variable give unrealistic values of γ_f for Cubipod^R armors compared to those given by CLNN and Eq. (3), which include A_c/R_c as an input variable. Thus, the formula in Smolka et al. (2009) or the CLNN are

recommended to properly estimate wave overtopping on Cubipod[R] armored breakwaters.

Table 5 summarizes the minimum and maximum roughness factors for each type of armor listed in Table 1 and the percentiles 10% and 90% of the calculated-roughness factors in this study to be used in the CLNN. While the ranges of the γ_f extracted from the literature are broad and usually do not reflect the influence on deviations of the γ_f, the ranges of the calculated-γ_f for the CLNN were quantified here using bootstrapping technique. In the case of Dolos, only 8 tests (Pedersen, 1996) were selected from the CLASH database; more data would be useful to increase the representativeness of the γ_f derived in this study.

Type of armor	Taken from Table 1	Q_{CLNN} (2007)
	Min(γ_f)-Max(γ_f)	$\gamma_{f10}, \gamma_{f90}$
Smooth	1.00,1.00	0.99 ,1.00
Rock (2L)	0.40,0.60	0.48,0.50
Cube (2L, random)	0.47,0.50	0.52,0.53
Cube (2L, flat)	0.47	0.52,0.54
Cube (1L, flat)	0.49,0.50	0.53,0.55
Antifer (2L)	0.47,0.65	0.51,0.53
Haro[R] (2L)	0.47,0.63	0.51,0.53
Tetrapod (2L)	0.38,0.40	0.41,0.43
Accropode (1L)	0.44,0.55	0.47,0.49
Core-Loc[TM] (1L)	0.44,0.47	0.45,0.47
Xbloc[R] (1L)	0.44,0.49	0.49,0.52
Dolos (2L)	0.43,0.45	0.31,0.43
Cubipod[R] (2L)	0.44	0.44,0.46

Cubipod^{R} (1L)	0.46	0.47,0.50

Table 5. Range of roughness factors for each type of armor.

5.1 Influence of packing density and armor roughness on overtopping

None of the overtopping formulas given in the literature explicitly introduces armor porosity or packing density as an input variable. In this study, test data reported by Pearson et al. (2004) were selected from the CLASH database for all types of armor except Dolos and Cubipods. Thus, packing densities given by Pearson et al. (2004), which are the same as those considered by Bruce et al. (2006), were assumed here to represent the selected data of the different types of armor. For Dolos armors, Pedersen's (1996) overtopping data were used here but this author did not provide the packing density. For Cubipod tests, packing densities were taken from Smolka et al. (2009).

The γ_{f50}-calibrated roughness factors from the CLNN were used here to study the influence of packing density (ϕ) and armor roughness (γ_f) on overtopping, given that the CLNN showed the lowest *rMSE*. Fig. 8 illustrates the influence of armor porosity (p=1- ϕ/n) on the roughness factor. The armor porosities used here are the recommended values for each type of armor unit. In both single- and double-layer armors, armor units placed with higher porosity tend to have a lower roughness factor. Given an armor unit, an armor porosity above recommended values decreases the concrete consumption but also decreases the hydraulic stability (see Medina et al., 2014), affecting the breakwater performance during lifetime.

The straight line drawn in Fig. 8 represents the influence of armor porosity on the roughness factor without considering the armor unit geometry or number of layers. The

linear model $\gamma_f = 1 - 1.25p$ shown in Fig. 8 fits reasonably well all cases (CV=$|\gamma_f - \gamma_{f50}|/\gamma_f$<15%) except the double-layer rock armor which has a lower than expected roughness factor.

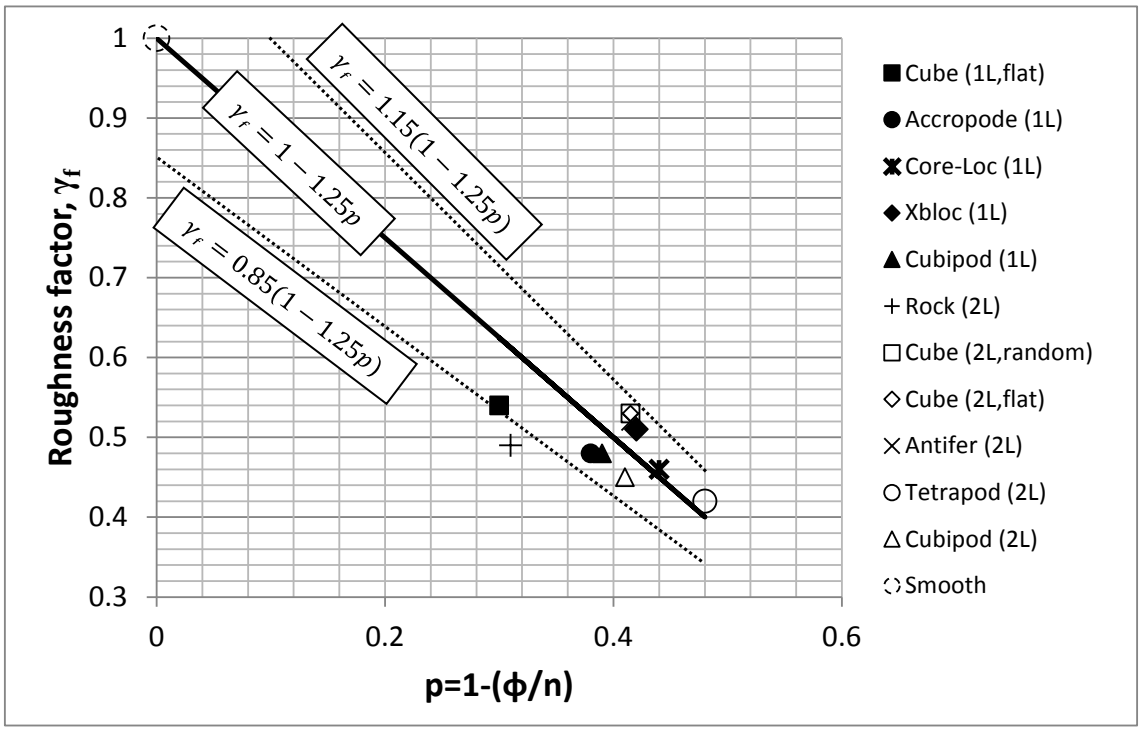

Figure 8. γ_{f50}-calibrated roughness factors of the CLNN and armor porosity.

For practical design applications, the γ_{f50}-calibrated roughness factors given in Table 4 can be used together with their associated formula to estimate wave overtopping discharges on mound breakwaters. The best estimations are given by Q_{CLNN}(2007). Armor porosity affects not only armor roughness and overtopping, but also armor hydraulic stability; recommended packing densities must be followed to avoid changes in porosity during lifetime. Designing an armor with porosity higher than the recommended values may decrease the roughness factors and the economic cost. However, in these cases, significant settlements are expected during lifetime, thus

changing the initial armor porosity affecting the armor stability and increasing estimated overtopping rates.

5.2 Sensitivity of overtopping rates depending on the roughness factor

An analytical study of the influence of small variations of the roughness factor on overtopping is discussed in this section. Only formulas with a topology similar to that of Eq. (1) and Eq. (3) are considered here to analytically compare the different variables involved in the overtopping process. Eq. (6) summarizes the partial derivative of the formulas Q_{VMJ} (Eq. 1) and Q_{SZM} (Eq. 3).

$$\frac{\partial Q_e}{\partial \gamma_f} = -K\left(\frac{R_c}{H_{m0}}\right) Q_e \left(-\frac{1}{\gamma_f^2}\right) \tag{6}$$

where K is a positive constant, and $Q_e = q_e/\sqrt{gH_{m0}^3}$ is the estimated dimensionless overtopping rate. Eq. (6) can be rewritten as:

$$\frac{\partial Q_e}{Q_e} = \left(\frac{\partial \gamma_f}{\gamma_f}\right)\left(\frac{K}{\gamma_f}\right)\left(\frac{R_c}{H_{m0}}\right) \tag{7}$$

Considering Eq. (1) and (7), a slight variation in the roughness factor, say $\Delta\gamma_f/\gamma_f$ = +0.01/0.50 = +2%, generates a 15% increase in the estimated overtopping rates with R_c/H_{m0}=1.5. For lower values of R_c/H_{m0}, overtopping rates are less sensitive to variations in the roughness factor. Thus, the relative crest freeboard, R_c/H_{m0}, affects the sensitivity of overtopping to variations in the roughness factor; the higher the R_c/H_{m0}, the greater the influence of variations in γ_f on the estimated overtopping discharges. The values of γ_{f10}, γ_{f50}, and γ_{f90} shown in Table 4 indicate that overtopping estimations using γ_{f50} may

easily change in the future from 10% to 25% if the dataset is significantly enlarged with additional tests.

The relative increases in overtopping rates, $\Delta Q/Q_e$, are directly proportional to the relative increase in the roughness factor, $\Delta\gamma_f/\gamma_f$, the relative crest freeboard, R_c/H_{m0}, and indirectly proportional to the roughness factor, γ_f.

6. Conclusions

This paper describes a methodology to estimate the optimum value of the roughness factor to be used in a specific overtopping estimator and a given overtopping dataset. This methodology was applied to four empirical formulas and a neural network tool to estimate mean overtopping discharges (Q_{VMJ}, $Q_{EurOtop}$, Q_{SZM} and Q_{CLNN}) of conventional mound breakwaters. The median values of the roughness factor (γ_{f50}) given in Table 4 are suitable to estimate the mean overtopping discharges. The present methodology can be applied to properly estimate the γ_f to be used in new formulas which include the roughness factor as an input variable to estimate wave overtopping.

Simple overtopping formulas with fewer input variables are easy to use but more information is implicitly absorbed by the roughness factor. In the preliminary design stage, formulas with a few variables such that given by Eq. (1) can be applied considering the wave conditions and the structural variables used to obtain the roughness factors. The γ_f is highly dependent on the corresponding formula and the dataset used for calibration. For instance, single- and double-layer Cubipod^R armors (Smolka et al., 2009) were tested with $A_c/R_c<1$; therefore, Eq. (1), Eqs. (2) and Eq. (4), which do not include A_c as input variable, give unrealistic values of γ_f for Cubipod^R armors compared to those

given by CLNN and Eq. (3), which include A_c/R_c as an input variable. The formula proposed by Smolka et al. (2009) or the CLNN are recommended here to estimate overtopping discharges on Cubipod^R armors. Very low and disperse values of roughness factor were obtained for Dolos armors because of the low number of Dolos results in the database; significant changes in Dolos roughness factors are expected when more overtopping data are available to be used for calibration.

The EurOtop (2007) overtopping predictor given by Eqs. (2) requires increasing the roughness factor given by Bruce et al. (2006) to effectively improve the mean overtopping prediction reducing *rMSE*. Generally speaking, the formula by Van der Meer and Bruce (2014) gave slightly higher *rMSE* than Eq. (1) in the range of data used in this study ($0.5<R_c/H_{m0}<3.5$) which do not include zero and low crest freeboard cases.

The roughness factors given in Table 4 correspond to armors with characteristics described in Table 3. Cubes and Cubipods were analyzed in single- and double-layer armors: one layer systems presented higher roughness factors and hence higher overtopping discharges. At first sight, higher armor porosity ($p=1-\phi/n$) leads to a lower roughness factor but also to a lower hydraulic stability and a higher risk of settlements during lifetime. Designing an armor with porosity above the recommended values will tend to generate settlements during lifetime, thus decreasing the initial armor porosity, changing the roughness factor and increasing overtopping rates. Thus, each type of armor must be designed and constructed with its recommended armor porosity and placement technique to maintain the reliability of the overtopping estimations.

The values of γ_{f10}, γ_{f50}, and γ_{f90} given in Table 4 indicate that overtopping estimations using γ_{f50} may easily change in the future from 10% to 25% if the dataset is significantly enlarged with additional tests. The relative crest freeboard (R_c/H_{m0}) affects the sensitivity of overtopping estimations to variations in the roughness factor; the higher the R_c/H_{m0}, the higher the influence of the increase in γ_f on the estimated overtopping discharges.

When comparing the influence of a concrete armor unit on overtopping discharges with different cross sections, estimator Q_{CLNN} is recommended. Q_{CLNN} shows the minimum *rMSE* in this study and eliminates the influence of certain structural variables on the estimation of the roughness factor, not included in other formulas. To avoid misunderstandings, the experimental database and the roughness factor should be clearly specified when new overtopping formulas are published.

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Appendix A. Small-scale tests reported by Smolka et al. (2009)

h [m]	$H_{m0\ toe}$ [m]	T_p[s]	$T_{m-1,0\ toe}$ [s]	h_t [m]	R_c [m]	A_c [m]	*q (m^3/s/m)*
0.550	0.132	2.968	2.628	0.550	0.203	0.150	1.28E-04
0.550	0.135	3.103	2.640	0.550	0.203	0.150	1.23E-04

0.500	0.138	3.103	2.780	0.500	0.253	0.200	1.20E-04
0.550	0.135	3.103	2.647	0.550	0.263	0.150	4.87E-05
0.550	0.125	2.968	2.530	0.550	0.203	0.150	4.63E-05
0.550	0.116	2.968	2.459	0.550	0.203	0.150	3.50E-05
0.550	0.144	2.528	1.942	0.550	0.203	0.150	3.46E-05
0.550	0.130	2.528	2.206	0.550	0.203	0.150	3.44E-05
0.550	0.138	1.932	1.814	0.550	0.203	0.150	3.27E-05
0.550	0.137	2.528	2.321	0.550	0.203	0.150	3.05E-05
0.550	0.137	1.693	1.693	0.550	0.203	0.150	2.53E-05
0.550	0.137	2.028	1.871	0.550	0.203	0.150	2.26E-05
0.500	0.131	3.103	2.555	0.500	0.253	0.200	2.16E-05
0.550	0.116	2.498	2.420	0.550	0.203	0.150	2.10E-05
0.550	0.126	2.528	2.130	0.550	0.203	0.150	1.86E-05
0.550	0.131	1.693	1.693	0.550	0.203	0.150	1.86E-05
0.550	0.155	2.276	2.040	0.550	0.263	0.150	1.69E-05
0.500	0.151	2.276	2.002	0.500	0.253	0.200	1.65E-05
0.550	0.138	1.304	1.305	0.550	0.203	0.150	1.22E-05
0.550	0.128	1.205	1.183	0.550	0.203	0.150	1.21E-05
0.550	0.131	2.028	1.773	0.550	0.203	0.150	1.15E-05
0.550	0.108	2.968	2.320	0.550	0.203	0.150	1.10E-05
0.550	0.157	1.330	1.313	0.550	0.263	0.150	1.06E-05
0.550	0.131	1.796	1.750	0.550	0.203	0.150	9.53E-06
0.550	0.125	1.588	1.588	0.550	0.203	0.150	9.00E-06
0.550	0.125	3.103	2.541	0.550	0.263	0.150	8.48E-06
0.550	0.144	2.090	1.886	0.550	0.263	0.150	8.34E-06
0.550	0.117	1.812	1.617	0.550	0.203	0.150	8.21E-06
0.550	0.135	1.412	1.262	0.550	0.203	0.150	8.08E-06
0.550	0.121	1.812	1.693	0.550	0.203	0.150	5.60E-06
0.550	0.114	1.679	1.581	0.550	0.203	0.150	5.23E-06
0.550	0.114	1.151	1.112	0.550	0.203	0.150	4.48E-06
0.500	0.138	2.090	1.855	0.500	0.253	0.200	4.03E-06
0.550	0.127	1.339	1.236	0.550	0.203	0.150	4.02E-06
0.500	0.142	1.330	1.247	0.500	0.253	0.200	3.89E-06
0.550	0.118	1.495	1.495	0.550	0.203	0.150	3.50E-06
0.500	0.106	2.498	2.342	0.500	0.253	0.200	3.22E-06
0.550	0.146	1.264	1.248	0.550	0.263	0.150	3.19E-06
0.550	0.111	1.495	1.310	0.550	0.203	0.150	2.95E-06
0.550	0.120	1.241	1.197	0.550	0.203	0.150	2.64E-06
0.550	0.131	1.205	1.181	0.550	0.263	0.150	2.29E-06
0.550	0.110	2.498	2.271	0.550	0.263	0.150	2.18E-06
0.500	0.135	1.264	1.221	0.500	0.253	0.200	2.03E-06
0.550	0.114	2.528	2.019	0.550	0.203	0.150	1.50E-06
0.550	0.100	1.484	1.423	0.550	0.203	0.150	1.08E-06
0.550	0.105	1.304	1.248	0.550	0.203	0.150	9.41E-07
0.550	0.117	1.151	1.112	0.550	0.263	0.150	9.24E-07
0.550	0.108	1.131	1.119	0.550	0.203	0.150	9.05E-07
0.550	0.100	1.056	1.048	0.550	0.203	0.150	8.85E-07
0.500	0.123	1.932	1.706	0.500	0.253	0.200	8.46E-07
0.550	0.114	1.157	1.157	0.550	0.203	0.150	8.27E-07
0.550	0.097	1.304	1.197	0.550	0.203	0.150	7.10E-07
0.550	0.110	1.101	1.073	0.550	0.263	0.150	7.04E-07
0.550	0.107	1.693	1.527	0.550	0.203	0.150	6.83E-07
0.550	0.097	2.498	2.183	0.550	0.203	0.150	5.89E-07
0.500	0.122	1.151	1.153	0.500	0.253	0.200	4.69E-07
0.550	0.101	1.061	1.088	0.550	0.203	0.150	4.17E-07
0.550	0.130	1.796	1.757	0.550	0.263	0.150	3.83E-07
0.550	0.107	2.028	1.914	0.550	0.203	0.150	3.83E-07
0.550	0.116	1.679	1.580	0.550	0.263	0.150	3.25E-07
0.500	0.107	1.101	1.081	0.500	0.253	0.200	2.51E-07
0.550	0.099	1.693	1.453	0.550	0.203	0.150	1.80E-07

0.550	0.101	1.484	1.423	0.550	0.263	0.150	1.80E-07
0.550	0.102	1.056	1.045	0.550	0.263	0.150	1.56E-07
0.550	0.089	1.339	1.159	0.550	0.203	0.150	1.40E-07

Table 6. Cubipod 2L small-scale tests by Smolka et al. (2009).

h [m]	$H_{m0\ toe}$ [m]	T_p[s]	$T_{m-1,0\ toe}$ [s]	h_t [m]	R_c [m]	A_c [m]	*q (m^3/s/m)*
0.500	0.100	1.061	1.048	0.500	0.253	0.160	2.60E-07
0.500	0.116	1.131	1.116	0.500	0.253	0.160	5.81E-07
0.500	0.129	1.212	1.191	0.500	0.253	0.160	1.54E-06
0.500	0.133	1.241	1.223	0.500	0.253	0.160	2.38E-06
0.500	0.141	1.304	1.247	0.500	0.253	0.160	5.69E-06
0.500	0.093	1.452	1.372	0.500	0.253	0.160	1.13E-07
0.500	0.107	1.638	1.540	0.500	0.253	0.160	3.35E-07
0.500	0.122	1.879	1.704	0.500	0.253	0.160	1.30E-06
0.500	0.141	2.028	1.858	0.500	0.253	0.160	1.00E-05
0.500	0.152	2.301	1.994	0.500	0.253	0.160	2.51E-05
0.500	0.158	2.301	2.055	0.500	0.253	0.160	3.85E-05
0.500	0.114	2.660	2.330	0.500	0.253	0.160	5.60E-06
0.500	0.132	3.151	2.547	0.500	0.253	0.160	2.61E-05
0.550	0.086	0.962	0.978	0.550	0.203	0.110	1.12E-07
0.550	0.094	0.999	1.010	0.550	0.203	0.110	5.40E-07
0.550	0.099	1.061	1.049	0.550	0.203	0.110	1.56E-06
0.550	0.108	1.084	1.076	0.550	0.203	0.110	2.72E-06
0.550	0.115	1.157	1.114	0.550	0.203	0.110	4.62E-06
0.550	0.091	1.157	1.117	0.550	0.203	0.110	3.75E-07
0.550	0.099	1.212	1.170	0.550	0.203	0.110	1.52E-06
0.550	0.107	1.241	1.218	0.550	0.203	0.110	3.07E-06
0.550	0.113	1.339	1.270	0.550	0.203	0.110	3.51E-06
0.550	0.120	1.412	1.321	0.550	0.203	0.110	1.05E-05
0.550	0.128	1.495	1.375	0.550	0.203	0.110	2.14E-05
0.550	0.135	1.495	1.431	0.550	0.203	0.110	2.97E-05
0.550	0.143	1.588	1.480	0.550	0.203	0.110	4.38E-05
0.550	0.084	1.304	1.275	0.550	0.203	0.110	8.06E-08
0.550	0.094	1.495	1.354	0.550	0.203	0.110	1.22E-06
0.550	0.102	1.495	1.425	0.550	0.203	0.110	1.48E-06
0.550	0.109	1.693	1.509	0.550	0.203	0.110	5.08E-06
0.550	0.116	1.693	1.583	0.550	0.203	0.110	7.82E-06
0.550	0.126	1.693	1.657	0.550	0.203	0.110	7.02E-06
0.550	0.131	1.879	1.743	0.550	0.203	0.110	1.63E-05
0.550	0.138	2.028	1.810	0.550	0.203	0.110	3.10E-05
0.550	0.075	1.588	1.442	0.550	0.203	0.110	7.11E-08
0.550	0.100	1.879	1.769	0.550	0.203	0.110	2.90E-07
0.550	0.107	2.028	1.857	0.550	0.203	0.110	2.30E-06
0.550	0.116	2.028	1.973	0.550	0.203	0.110	9.52E-06
0.550	0.134	2.528	2.191	0.550	0.203	0.110	2.86E-05
0.550	0.099	2.528	2.174	0.550	0.203	0.110	5.02E-06
0.550	0.120	2.528	2.406	0.550	0.203	0.110	5.15E-05
0.550	0.094	0.975	1.008	0.550	0.263	0.110	2.16E-07
0.550	0.101	1.056	1.048	0.550	0.263	0.110	3.65E-07
0.550	0.109	1.101	1.073	0.550	0.263	0.110	8.05E-07
0.550	0.114	1.151	1.117	0.550	0.263	0.110	8.76E-07
0.550	0.114	1.151	1.114	0.550	0.263	0.110	9.73E-07
0.550	0.128	1.205	1.188	0.550	0.263	0.110	2.19E-06
0.550	0.136	1.264	1.210	0.550	0.263	0.110	3.24E-06
0.550	0.149	1.330	1.286	0.550	0.263	0.110	4.07E-06
0.550	0.100	1.484	1.420	0.550	0.263	0.110	1.44E-07
0.550	0.109	1.679	1.505	0.550	0.263	0.110	3.76E-07

0.550	0.116	1.679	1.586	0.550	0.263	0.110	8.77E-07
0.550	0.130	1.796	1.737	0.550	0.263	0.110	1.15E-06
0.550	0.143	2.090	1.886	0.550	0.263	0.110	1.11E-05
0.550	0.156	2.276	2.023	0.550	0.263	0.110	3.11E-05
0.550	0.091	2.276	2.174	0.550	0.263	0.110	1.89E-07
0.550	0.108	2.498	2.390	0.550	0.263	0.110	5.38E-06
0.550	0.127	3.103	2.644	0.550	0.263	0.110	4.26E-05
0.550	0.143	3.531	2.683	0.550	0.263	0.110	1.90E-04

Table 7. Cubipod 1L small-scale tests by Smolka et al. (2009).

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