

AVERAGE AND WAVE-BY-WAVE OVERTOPPING PERFORMANCE OF STEEP LOW-CRESTED STRUCTURES

David Gallach-Sánchez¹, Peter Troch¹ and Andreas Kortenhaus¹

Wave overtopping is a key process in coastal protection. The assessment of the wave overtopping rates is an important aspect in the design of coastal structures. In this paper, the focus is on steep low-crested structures, which include structures with steep slopes up to the limit case with vertical structures, with small relative freeboards up to the case with zero freeboards. This type of structures is of use for coastal protection in the case of sea level rise within climate change process and for overtopping wave energy converters. A literature review of the overtopping knowledge available for steep low-crested structures is carried out, identifying a knowledge gap. To fill this knowledge gap, 2D hydraulic model tests were performed at the wave flume of the Department of Civil Engineering at Ghent University, measuring wave conditions and the overtopping performance. Average and individual wave overtopping were analysed and compared to existing prediction formulae. Inaccuracies in the existing prediction formulae are detected and studied, and enhanced prediction formulae are presented for the average overtopping and the probability distribution of the individual overtopping volumes. The new prediction formulae improve the accuracy of wave overtopping volumes for steep low-crested structures range while maintaining the accuracy for other types of structures. The improved understanding of the overtopping behaviour allows a safer design of coastal structures.

Keywords: coastal structures; wave overtopping; steep low-crested structures; physical modelling; prediction.

INTRODUCTION

Wave overtopping is a key process in coastal protection. The assessment of the wave overtopping rates is an important aspect in the design of coastal structures. Overtopping events can result in threat to human lives, damage of property and infrastructure and economic losses if the sea defence structure is not correctly designed. Traditionally the average wave overtopping rate was the only overtopping parameter considered in the design, although recent insight reveals that individual wave overtopping should be considered also as a key design parameter of sea defence structures. A good knowledge of the physics behind wave overtopping is therefore necessary to improve the safety of coastal structures and to minimize the potential risks.

Wave overtopping prediction formulae are widely available in scientific literature for various structural and wave conditions. Extensive research was done in the CLASH project (De Rouck et al., 2009) which consisted of physical model tests and field measurements of wave overtopping for rubble mound breakwaters and smooth slopes with various foreshore geometries, for both regular and irregular sea states. The CLASH project resulted in a very detailed database of wave overtopping results for the aforementioned conditions, and the development of neural networks on wave overtopping (e.g., Verhaeghe et al. 2008).

Despite the huge amount of overtopping data collected with the CLASH project, there were still various data ranges that were not covered by the project. One of those ranges was for steep and very steep slopes with small, very small and zero relative freeboards: the so called steep low-crested structures, formed by structures with slope angles $2 \geq \cot \alpha \geq 0$ and relative crest freeboards $0.8 > R_c/H_{m0} \geq 0$.

Experiments carried out in Ghent University (Belgium) within the PhD research of Victor (2012) covered partially the steep low-crested structures knowledge gap of the CLASH database, forming the so called 'UG10' dataset. However, not the whole range of slope angles and relative crest freeboards was covered by the UG10 dataset. As a result, there are still knowledge gaps in the scientific literature on wave overtopping for very steep slopes and vertical walls, with very small and zero freeboards, which cover useful geometries for coastal structures.

The definition ranges of slope angle α and relative crest freeboard R_c/H_{m0} that are used in this paper are shown in Table 1 and Table 2, respectively.

¹ Dept. of Civil Engineering, Ghent University, 904 Technologiepark, Zwijnaarde, 9052, Belgium

Table 1. Range definition of slope angle α .

	cot α (-)
Mild slopes	$\cot \alpha > 1.5$
Steep slopes	$1.5 > \cot \alpha > 0.27$
Very steep slopes	$0.27 \geq \cot \alpha > 0$
Vertical walls	$\cot \alpha = 0$

Table 2. Range definition of relative crest freeboard R_c/H_{m0} .

	Relative crest freeboard R_c/H_{m0} (-)
Large relative crest freeboard	$R_c/H_{m0} \geq 0.8$
Small relative crest freeboard	$0.8 > R_c/H_{m0} \geq 0.1$
Very small relative crest freeboard	$0.1 > R_c/H_{m0} > 0$
Zero crest freeboard	$R_c/H_{m0} = 0$

The second section of this paper presents an overview of the existing knowledge in literature on wave overtopping, both average overtopping and individual, focusing on the most recent overtopping prediction formulae for the limit case of very steep slopes to vertical walls and the limit case of very small crest freeboards to zero crest freeboard. The third section explains the physical model tests performed in the wave flume of Ghent University, describing both the test setup and the experimental programme for the UG13, UG14 and UG15 datasets. The fourth section presents an updated average overtopping prediction for steep low-crested structures based on the Ghent University overtopping datasets and the CLASH database. The fifth section presents an updated shape factor B and probability of overtopping P_{ow} prediction for steep low-crested structures based. Finally, the last section presents the conclusions of this research.

LITERATURE REVIEW FOR STEEP LOW-CRESTED STRUCTURES

The scientific literature available on wave overtopping prediction is very extensive. This section summarizes the literature about wave overtopping for steep low-crested structures, including the overtopping prediction formulae available. The focus is both on average and individual overtopping.

Average wave overtopping prediction formulae

During the PhD research of Victor (2012) on overtopping wave energy converters (OWECs) a new wave overtopping prediction formula was needed which included the operational conditions of these devices that behave as steep low-crested structures. Victor & Troch (2012) developed new average overtopping prediction formulae based on the dataset UG10, and the subsets 106, 107 and 402 of the CLASH database (all of them for plain vertical walls under non-impulsive conditions with a relative crest freeboards $R_c/H_{m0} < 0.8$). The formulae are divided into 4 different zones (Z1, Z2, Z3, Z4) depending on the values of slope angle α and relative crest freeboard R_c/H_{m0} . The formulae give a high physical insight of wave overtopping based on this classification in 4 zones, allowing a clear visualization of the physical meaning of the formulae and leading to a better understanding of the dependence of wave overtopping on the slope angle α and relative crest freeboard R_c/H_{m0} .

Eq. 1 shows the formula to predict the dimensionless average overtopping rate $q/\sqrt{gH_{m0}^3}$ and Table 3 shows the expressions for the a and b coefficients as a function of the slope angle α and relative crest freeboard R_c/H_{m0} . The formula in Eq. 1 maintains the shape of the EurOtop (2007) formula for non-breaking conditions, with the relative crest freeboard R_c/H_{m0} as governing parameter of the wave overtopping prediction.

$$\frac{q}{\sqrt{gH_{m0}^3}} = a_{\text{Victor}} \cdot \exp \left[-b_{\text{Victor}} \cdot \frac{R_c}{H_{m0}} \right] \quad 1$$

Table 3. Coefficients of Victor and Troch (Victor & Troch, 2012) formulae (Eq. 1) as a function of the slope angle α and relative crest freeboard R_c/H_{m0} .

		Relative crest freeboard R_c/H_{m0}	
Slope $\cot \alpha$		$0 \leq R_c/H_{m0} \leq 0.8$	$0.8 \leq R_c/H_{m0} \leq 2$
	$0 \leq \cot \alpha \leq 1.5$	Z1 $a_{\text{Victor}}=0.033 \cdot \cot \alpha + 0.062$ $b_{\text{Victor}}=3.45 - 1.08 \cdot \cot \alpha$	Z2 $a_{\text{Victor}}=0.2$ $b_{\text{Victor}}=4.88 - 1.57 \cdot \cot \alpha$
	$1.5 \leq \cot \alpha \leq 2.75$	Z3 $a_{\text{Victor}}=0.11$ $b_{\text{Victor}}=1.85$	Z4 $a_{\text{Victor}}=0.2$ $b_{\text{Victor}}=2.6$

The existing EurOtop (2007) overtopping prediction formula for non-breaking conditions was reviewed and improved by the overtopping prediction formulae (mean value approach) presented by Van der Meer & Bruce (2014) (Eq. 2) in the shape of a Weibull-type function. These formulae extend the range of application of the EurOtop (2007) prediction towards steep, very steep slopes and vertical walls with very small and zero freeboard, with a range of application $\cot \alpha \geq 0$ and $R_c/H_{m0} \geq 0$. On the updated EurOtop (2016) these overtopping prediction formulae are prescribed to be used for the range from steep slopes to vertical walls, and from large to zero relative crest freeboards. The expression for the $a_{\text{van der Meer}}$ and $b_{\text{van der Meer}}$ coefficients of Eq. 2 was fitted by Van der Meer & Bruce (2014) using wave overtopping results for specific slope angles α and relative crest freeboards R_c/H_{m0} from different sources (Figure 1).

$$\frac{q}{\sqrt{gH_{m0}^3}} = a_{\text{van der Meer}} \cdot \exp \left(- \left(b_{\text{van der Meer}} \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta} \right)^{c_{\text{van der Meer}}} \right) \quad 2$$

with the following expressions for the coefficients a , b and c :

$$a_{\text{van der Meer}} = 0.09 - 0.01 (2 - \cot \alpha)^{2.1} \text{ for } \cot \alpha \leq 2$$

$$\text{and } a_{\text{van der Meer}} = 0.09 \text{ for } \cot \alpha > 2$$

$$b_{\text{van der Meer}} = 1.5 + 0.42 (2 - \cot \alpha)^{1.5} \text{ for } \cot \alpha \leq 2,$$

$$\text{with a maximum of } b_{\text{van der Meer}} = 2.35;$$

$$\text{and } b_{\text{van der Meer}} = 1.5 \text{ for } \cot \alpha > 2$$

$$c_{\text{van der Meer}} = 1.3$$

The Van der Meer & Bruce (2014) formulae for non-breaking conditions (Eq. 2) add a power inside the exponential function (coefficient $c_{\text{van der Meer}} = 1.3$) and two coefficients $a_{\text{van der Meer}}$ and $b_{\text{van der Meer}}$ which are a function of the slope angle α . The coefficient $a_{\text{van der Meer}}$ determines the overtopping value when the value of the x-axis is equal to zero (therefore, in the case of zero relative crest freeboards $R_c=0$). The coefficient $b_{\text{van der Meer}}$ determines the shape of the equation for the entire range of R_c/H_{m0} . The coefficient $c_{\text{van der Meer}} = 1.3$ was obtained as a best fit for both breaking and non-breaking wave conditions in order to have a common value for both prediction formulae (Van der Meer et al., 2013), while the best fit for the non-breaking conditions prediction formulae is lower than the suggested value.

The reliability of Eq. 2 is described in the EurOtop (2016) by a coefficient of variation $\sigma' = \sigma/\mu$ (being σ the standard deviation and μ the average value of normally distributed stochastic parameters) for the coefficients $a_{\text{van der Meer}}$ and $b_{\text{van der Meer}}$, being $\sigma'(a_{\text{van der Meer}}) = 0.15$ and $\sigma'(b_{\text{van der Meer}}) = 0.10$.

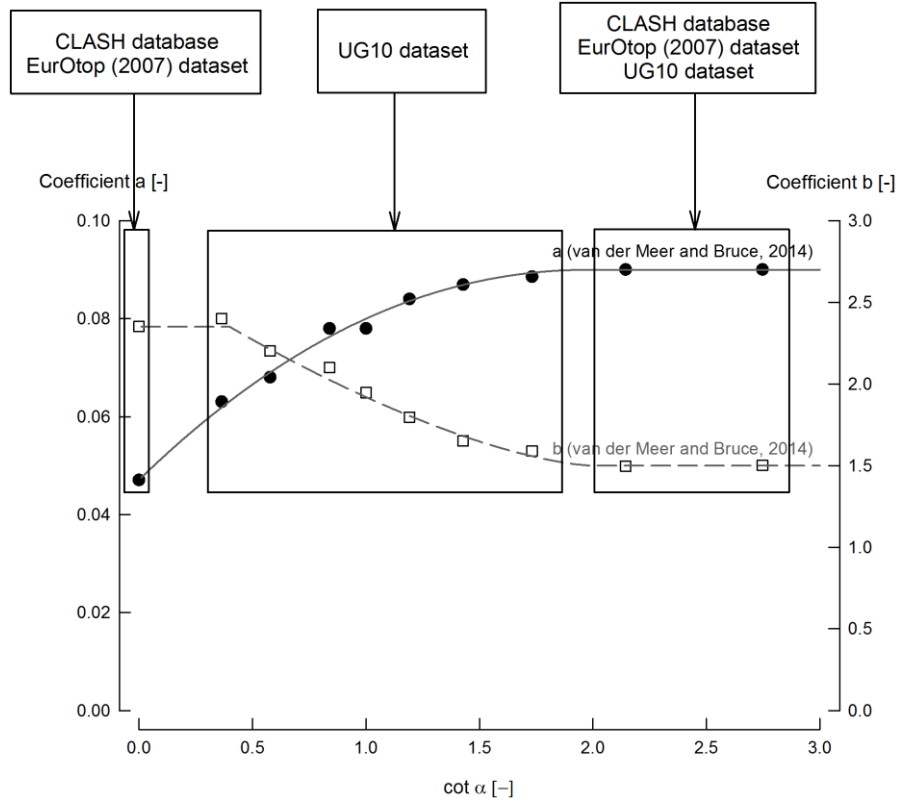


Figure 1. Best fit per slope angle α of the a and b coefficients for the selected tests of the UG10 dataset, EurOtop (2007) dataset and CLASH database, with the Van der Meer & Bruce (2014) formulae (Eq. 2) expressions for a and b .

Individual wave overtopping prediction formulae

The individual overtopping volumes are distributed following a two-parameter Weibull distribution (Franco et al., 1994; van der Meer & Janssen, 1994). The exceedance probability P_v of each overtopping volume V is described by Eq. 3, where A is the scale factor and B is the shape factor.

$$P_v = P[V_i \geq V] = \exp\left(-\left(\frac{V}{A}\right)^B\right) \quad 3$$

The scale factor A is proportional to the average overtopping discharge per wave. Larger values of individual volumes V_i correspond to larger values of the factor A . The shape factor B determines the shape of the probability distribution. A constant shape factor $B=0.75$ is suggested as an average value both for smooth and rubble mound structures by different publications summarized in the EurOtop (2007) manual.

Victor et al. (2012) suggested a new prediction formula (Eq. 4) for the shape factor B fitted through all the best fit B values of each UG10 test. As opposed to the constant B value suggested by EurOtop (2007), the Victor et al. (2012) shape factor B formula depends both on the relative crest freeboard R_c/H_{m0} and the slope angle α . The reliability of Eq. 4 is expressed by applying a RMSE value of 0.10.

$$B = \exp\left(-2.0 \frac{R_c}{H_{m0}}\right) + (0.56 + 0.15 \cdot \cot \alpha) \quad 4$$

Hughes et al. (2012) used the same data from the UG10 dataset (364 tests) to fit a new shape factor B prediction formula, also adding new individual overtopping data with negative freeboard (27 tests) from Hughes & Nadal (2009) and with very large relative crest freeboards (14 tests) from van der Meer & Janssen (1995). The suggested formula (Eq. 5) is only depending on the relative crest freeboard R_c/H_{m0} and is valid for a range of R_c/H_{m0} from negative up to $R_c/H_{m0} \leq 4$.

$$B = \left[\exp \left(-0.6 \frac{R_c}{H_{m0}} \right) \right]^{1.8} + 0.64 \quad 5$$

The probability of overtopping P_{ow} (Eq. 6) is the ratio between the number of overtopping wave N_{ow} and the number of incident waves N_w at the toe of the structure. Van der Meer & Janssen (1994) and Franco et al. (1994) assume that the run-up heights distribution follows a Rayleigh distribution, giving the theoretical probability of overtopping P_{ow} described by Eq. 7, where the coefficient χ is related to the relative 2% run-up height. The limit values of the probability of overtopping P_{ow} are 1 for the case of zero freeboard (all waves overtop the crest of the structure) and 0 for the case of very large relative crest freeboards (no waves overtop the structure).

$$P_{ow} = \frac{N_{ow}}{N_w} \quad 6$$

$$P_{ow} = \exp \left(- \left(\frac{1}{\chi} \cdot \frac{R_c}{H_{m0}} \right)^2 \right) \quad 7$$

Van der Meer & Janssen (1994) proposed a value of the $1/\chi$ coefficient of Eq. 7 equal to 0.65 valid for mild slopes with non-breaking waves. For vertical walls the probability of overtopping P_{ow} is related to the theoretical value of the relative 2% run-up height, being the value of the coefficient $1/\chi = 1.4$. Victor et al. (2012) proposed a new prediction formula for the probability of overtopping P_{ow} also depending on the slope angle α (Eq. 8).

$$P_{ow} = \exp \left[- \left((1.4 - 0.3 \cdot \cot \alpha) \frac{R_c}{H_{m0}} \right)^2 \right] \quad 8$$

WAVE OVERTOPPING PHYSICAL MODEL TESTS

The UG13, UG14 and UG15 datasets consist in total of 939 tests. Unlike the UG10 dataset, the new datasets contain overtopping data for the full range of slope angles (from mild slopes to vertical walls) and of relative crest freeboards (from large to zero). This section presents the test setup and the wave and structural parameters of the UG13, UG14 and UG15 datasets.

Experimental setup in the wave flume

The experiments were performed in the wave flume of the Department of Civil Engineering at Ghent University (Belgium) which has a length of 30 m, a width of 1 m and a height of 1.2 m. The wave flume is equipped with a piston type wave paddle with a maximum stroke length of 1.5 m. The experimental setup of the UG13 dataset (Gallach-Sánchez et al., 2018) consists of a horizontal foreshore (Figure 2, top). For the UG14 dataset (Gallach-Sánchez et al., 2014) and the UG15 dataset (Gallach-Sánchez et al., 2016) it consists of a mild 1:100 foreshore slope over 15 m. The influence of the foreshore slope on the average overtopping rates is considered negligible for all the datasets as the foreshore does not influence the wave transformation processes taking place in the wave flume.

The model structure in the experimental setup consisted of a smooth impermeable plywood panel forming a given slope angle α with the foreshore. Behind the structure the overtopping flow was captured by a so-called overtopping box that measures overtopping using the weigh cell technique (Figure 2, bottom). The overtopping box was developed by Victor & Troch (2010) and it was specifically designed to measure individual wave overtopping volumes with high accuracy. The average overtopping rate q and the individual wave overtopping volumes V_i are measured for each test of the UG13, UG14 and UG15 datasets. After processing the data with a MATLAB™ script, both the average overtopping rates and the individual overtopping volumes are obtained.

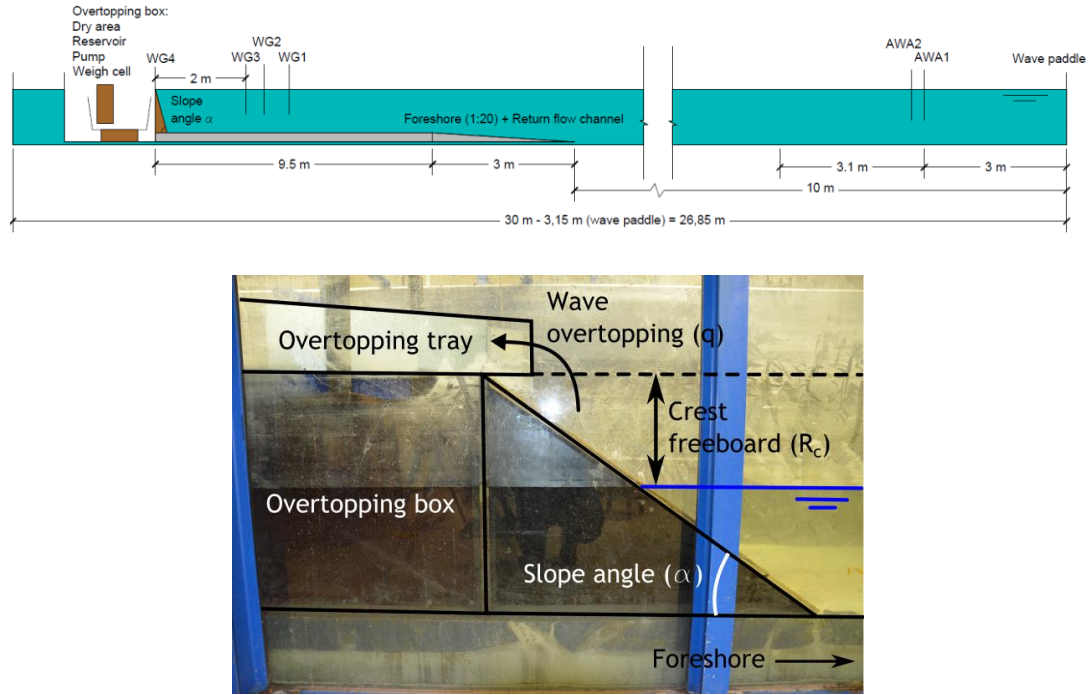


Figure 2. Test setup for the UG13 model tests (top), and model structure with the overtopping box used to measure the overtopping rates behind it (bottom).

Experimental programme

The experiments were performed using the setups described in Section “Experimental setup in the wave flume” for various structural parameters (slope angle α , crest freeboard R_c) and wave parameters at the toe of the structure (local water depth at the toe of the structure h , incident spectral wave height H_{m0} , incident peak wave period T_p and incident wave period $T_{m-1,0}$).

Table 4 shows an overview of the ranges of the parameters tested in the UG10, UG13 and UG14 datasets, and Figure 3 shows a plot of the various slope angles ($\cot \alpha$) and relative crest freeboards R_c/H_{m0} tested on the three datasets obtained at Ghent University. These datasets are considered entirely in the non-breaking waves region as the surf similarity parameter is $\xi_{m-1,0} > 2$ for every test.

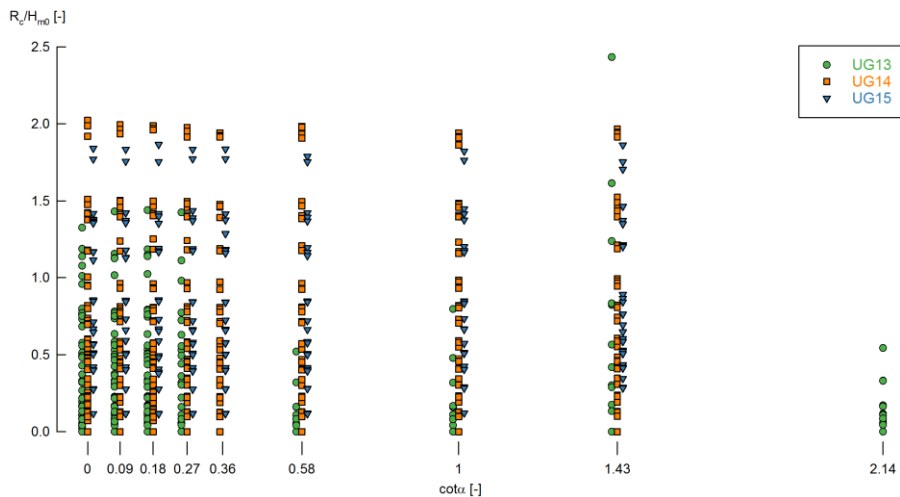


Figure 3. Slope angle ($\cot \alpha$) and relative crest freeboard R_c/H_{m0} values tested on the UG13 (green circles), UG14 (orange squares) and UG15 (blue triangles) datasets. The values on the $\cot \alpha$ axis have been artificially shifted for clarity.

Table 4. Overview of UG10, UG13, UG14 and UG15 datasets.

	UG10	UG13	UG14	UG15
Slope angle α (°)	20, 25, 30, 35, 40, 45, 50, 60, 70	25, 35, 45, 60, 75, 80, 85, 90	35, 45, 60, 70, 75, 80, 85, 90	35, 45, 60, 70, 75, 80, 85, 90
cot α (-)	2.75, 2.14, 1.73, 1.43, 1.19, 1.00, 0.84, 0.58, 0.36	2.14, 1.43, 1.00, 0.58, 0.27, 0.18, 0.09, 0	1.43, 1.00, 0.58, 0.36, 0.27, 0.18, 0.09, 0	1.43, 1.00, 0.58, 0.36, 0.27, 0.18, 0.09, 0
Crest freeboard R_c (m)	0.020, 0.045, 0.070	0, 0.005, 0.01, 0.02, 0.045, 0.07	0, 0.02, 0.045, 0.076, 0.12, 0.2	0, 0.02, 0.045, 0.076, 0.12, 0.2
Incident spectral wave height at the toe H_{m0} (m)	0.023 – 0.19	0.018 – 0.16	0.061 – 0.225	0.107 – 0.22
Relative crest freeboard R_c/H_{m0} (-)	0.1 – 1.69	0 – 2.43	0 – 2.92	0.11 – 1.87
Target peak wave period $T_{p,target}$ (s)	1.000 – 2.000	1.022 – 2.045	1.022, 1.534, 2.045	1.534, 2.045, 2.534
Relative wave height H_{m0}/h (-)	0.04 – 0.38	0.03 – 0.33	0.20, 0.30, 0.40, 0.50	0.30, 0.40, 0.50
Wave steepness $s_{m-1,0}$ (-)	0.016 – 0.056	0.014 – 0.047	0.012 – 0.062	0.01 – 0.05
Surf similarity parameter $\xi_{m-1,0}$ (-)	2 – 21.5	2.28 – 95	2.8 - 90	3.3 - 82

As seen on Section “LITERATURE REVIEW FOR STEEP LOW-CRESTED STRUCTURES”, the overtopping prediction formulae presented by Victor & Troch (2012) (Eq. 1 and Table 3) and by Van der Meer & Bruce (2014) formulae (Eq. 2) were not fitted through very steep slopes, while for very small and zero relative freeboards they were fitted only through the very limited overtopping data available on the CLASH database. However, these two ranges of slope angle α and relative crest freeboard R_c/H_{m0} are included within the range of application of the formulae, urging a validation of the accuracy of the overtopping prediction for these conditions. To this effects, the UG13, UG14 and UG15 datasets are suitable to study the accuracy of Eq. 2 for steep low-crested structures.

AVERAGE WAVE OVERTOPPING

From the recently presented overtopping prediction formulae the most used ones are the Van der Meer & Bruce (2014) formulae (Eq. 2), included also in the EurOtop (2016) manual. After a study of the prediction accuracy of these formulae, updated a, b and c coefficients maintaining the same Weibull-type shape as Eq. 2 will be proposed in this section to improve the average overtopping prediction of steep low-crested structures.

Update of the average overtopping prediction formula

An update of the coefficients of Eq. 2 that improves the accuracy of the prediction is possible by adding the UG13, UG14 and UG15 datasets to the fitting datasets that were used by Van der Meer & Bruce (2014) (Eq. 2), besides UG10 and selected subsets of the CLASH database. By adding UG13, UG14 and UG15 the prediction would be improved in three different ranges of slope angles and relative crest freeboards:

- vertical walls (cot $\alpha = 0$), which can be added to the existing CLASH data increasing the number of tests available for the fitting of the coefficients;
- very steep slopes ($0 < \cot \alpha \leq 0.27$), which was not previously considered in the fitting of the coefficients; and
- very small and zero crest freeboard ($0 \geq R_c/H_{m0} > 0.11$), which only had a very limited of tests included in the previous fitting from a CLASH subset.

The average overtopping prediction formula for non-breaking conditions is the Weibull-type seen in Eq. 2 and used by Van der Meer & Bruce (2014), with a , b and c coefficients with the same physical meaning as explained in Section “Average wave overtopping prediction formulae”. A nonlinear regression is made with the software SPSS to find the best fit of the coefficients by minimizing the residual sum of squares and using a sequential quadratic programming algorithm as the iterative method. The best fit of the coefficients is found for 1410 average overtopping data of the UG10, UG13, UG14 and UG15 datasets, the CLASH database and the EurOtop (2007) dataset. The updated average overtopping prediction is presented in Eq. 9:

$$\frac{q}{\sqrt{gH_{m0}^3}} = a \cdot \exp\left(-\left(b \cdot \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)^c\right) \quad 9$$

with the following expressions for the coefficients a , b and c :

$$\begin{aligned} a &= 0.102 - 0.028 \cdot (1.5 - \cot \alpha) \text{ for } \cot \alpha \leq 1.5 \text{ and } a = 0.102 \text{ for } \cot \alpha > 1.5 \\ b &= 2 + 0.56 (1.5 - \cot \alpha)^{1.95} \text{ for } \cot \alpha \leq 1.5 \text{ and } b = 2 \text{ for } \cot \alpha > 1.5 \\ c &= 1.1 \end{aligned}$$

The uncertainty related to a is defined by a standard error of the estimate $\sigma_{est}(a) = 0.01$, and the uncertainty related to b is defined by a standard error of the estimate $\sigma_{est}(b) = 0.66$. The range of application of the formula is for slope angles $0 \leq \cot \alpha \leq 4$ and relative crest freeboards $R_c \geq 0$ under non-breaking conditions.

As a first step, the best fit for the c coefficient is found. The resulting value is $c = 1.1$ and no influence of the slope angle α on c is found. This coefficient is different than the one suggested by Van der Meer & Bruce (2014) $c_{\text{van der Meer}} = 1.3$ (Eq. 2). The obtained values of c for each slope angle also suggest that the shape of overtopping data for the complete range of relative crest freeboards is closer to a line in a log-linear plot than estimated by Van der Meer et al. (2013) and Van der Meer & Bruce (2014). This inaccurate estimation is maybe due to lack of a significant number of overtopping data available for zero and very small freeboards at the time of both publications. This close to linear shape was already observed in the data when comparing UG13, UG14 and UG15 with Eq. 2 (Gallach-Sánchez et al., 2014, 2016, 2018). The value selected for c in the update of the coefficients $c = 1.1$ yields a prediction trend close to a straight line in a log-linear plot, matching better the shape of the data. To obtain the coefficients a and b , the value of $c = 1.1$ is fixed.

The best fit of the a coefficient is found among the zero freeboard data ($R_c = 0$) to assure the most accurate prediction for these conditions. The a coefficient shows a dependence on the slope angle, although only for values $\cot \alpha < 1.5$. This limit differs from Van der Meer & Bruce (2014) who found a limit on $\cot \alpha = 2$ but is the same value found by Victor & Troch (2012). The updated a coefficient has a similar expression to Eq. 2 although with a linear shape, reaching a constant value at $\cot \alpha = 1.5$. The resulting expression for a is larger for the updated prediction than for Van der Meer & Bruce (2014).

A linearisation is applied to the data by calculating the natural logarithm $\ln$ of both sides of Eq. 9. On this step, the values of c and a are fixed. The best fit power law for b maintaining the same shape as $b_{\text{van der Meer}}$ with a limit on $\cot \alpha = 1.5$ is calculated through the linearised b values per slope angle. Compared to Eq. 2, Eq. 9 does not have a constant maximum value of b for very steep slopes as the data show increasing values of b at this range of slopes.

One of the objectives of updating the prediction is to improve the accuracy of the prediction by Van der Meer & Bruce (2014) for the zero freeboard case ($R_c = 0$), which was underpredicting consistently for all the slope angles the average overtopping rates for this case. Figure 4 shows the updated prediction compared to the Van der Meer & Bruce (2014) for the zero freeboard case. The updated prediction shows a great improve of the accuracy of the prediction, as it adapts better than the Van der Meer & Bruce (2014) prediction to the data.

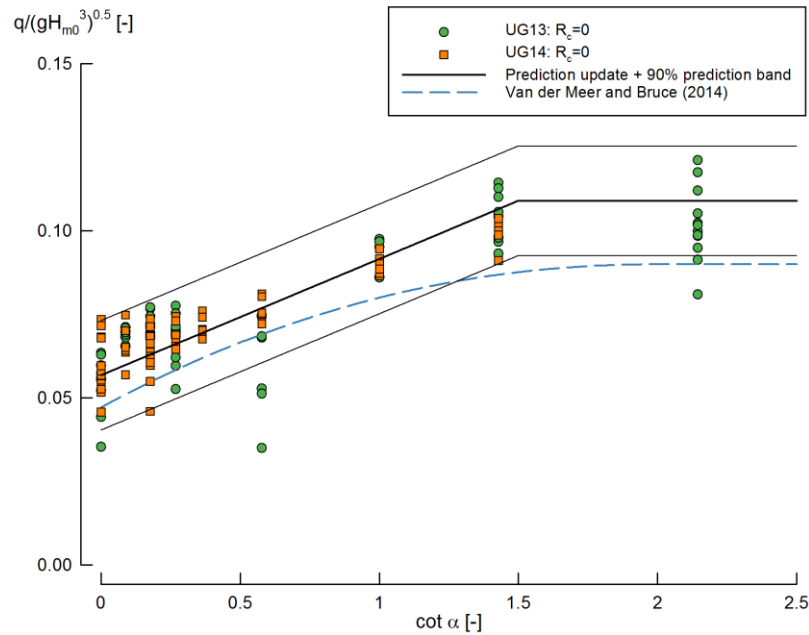


Figure 4. Zero freeboard (R_c) overtopping data compared to the updated average overtopping prediction formula (black) with its 90% prediction interval and Van der Meer & Bruce (2014) (blue).

INDIVIDUAL WAVE OVERTOPPING

The individual overtopping is characterized and analysed in this chapter for the new datasets UG13, UG14 and UG15. The scale factor A and the shape factor B determine the probability distribution of the individual overtopping volumes, and the probability of overtopping P_{ow} determines the number of waves that overtop a coastal structure. These coefficients are analysed with respect to various wave and structural parameters and compared with prediction formulae on the literature. New prediction formulae for B and P_{ow} are suggested based on the new datasets.

New prediction formula for the shape factor B

The Hughes et al. (2012) prediction does not fully adapt to the shape of the data (Gallach-Sánchez et al., 2015) as it does not consider the slope angle α as an influence parameter of the B values. This results in an overprediction of the data for very steep slopes and vertical structures. Victor et al. (2012) prediction considers α as an influencing parameter of B . However, the predicted B values for zero freeboards and large relative freeboards are not predicted with accuracy, with B being overpredicted in both formulae. Moreover, for large relative freeboards the formula assumes that B is influenced by the slope angle α , although the data show that B for this range of relative freeboards is constant and not dependent on α .

The datasets UG13, UG14 and UG15 fill the gap for zero and very small relative freeboards, and very steep and vertical structures that the UG10 dataset had. As both Hughes et al. (2012) and Victor et al. (2012) predictions were fitted through UG10, it is possible to improve the accuracy of both predictions for the range of relative freeboards and slope angles where UG10 lacks of overtopping data.

The set of tests selected to fit the new shape factor B prediction formula is formed by tests of the UG10, UG13, UG14 and UG15 datasets, covering from mild slopes to vertical structures with relative crest freeboards from large to zero. The tests also cover the range from relatively deep to relatively shallow water conditions. The total number of tests through which the new B prediction formula is fitted is 1223. This number compares to the 364 tests of the UG10 dataset used by Victor et al. (2012) and the 405 tests from UG10 and other sources used by Hughes et al. (2012) to fit the predictions, which is a factor three increase.

Using a nonlinear regression analysis, the best fit of B is found by minimizing the residual sum of squares and using a sequential quadratic programming algorithm as iterative method. The new prediction

of the shape factor B is formed by the coefficients $w = 0.59 + 0.23 \cdot \cot \alpha$, $x = 2.2$ and $y = 0.83$, resulting in Eq. 10. The reliability of Eq. 10 is expressed by the root mean square error $\text{RMSE} = 0.217$.

$$B = (0.59 + 0.23 \cdot \cot \alpha) \cdot \exp(-2.2 \frac{R_c}{H_{m0}}) + 0.83 \quad 10$$

Figure 5 shows the data of the UG13, UG14 and UG15 for very steep slopes ($0.27 \geq \cot \alpha > 0$) compared to the new prediction (Eq. 10). The B prediction for zero freeboards of the new formula is higher than the prediction by Victor et al. (2012) and depends on the slope angle as a result of the new coefficient w , which adapts better to the average of the values for this conditions. Also for large relative freeboards the new prediction is lower, however it does not depend on the slope angle α , as the coefficient y was found not to be dependent on the slope angle of the structure. The prediction for this range of relative freeboards is slightly higher than $B = 0.75$, indicating that the EurOtop (2007) B value is still valid for large relative freeboards and all slope angles.

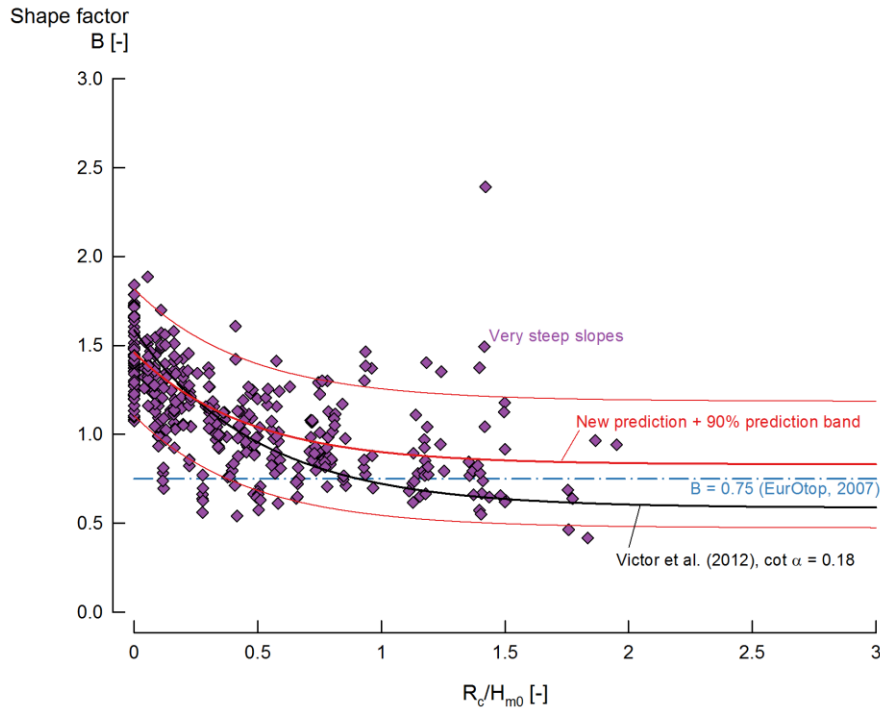


Figure 5. Shape factor B as a function of the relative crest freeboard R_c/H_{m0} for very steep slopes of the datasets UG13, UG14 and UG15, compared to Victor et al. (2012) (Eq. 4), $B = 0.75$ (EurOtop, 2007) and the new B prediction (Eq. 10) with its 90% prediction band.

New prediction formula for the probability of overtopping P_{ow}

An improvement on the P_{ow} prediction accuracy is possible for mild slopes, as the prediction by Van der Meer & Janssen (1994) (which is also the limit case for mild slopes of Victor et al. (2012) prediction) is overpredicting the results (Gallach-Sánchez et al., 2015). For vertical structures, both the theoretical value and the prediction by Franco et al. (1994) are underpredicting the results. For zero freeboards, the predictions are theoretically $P_{ow} = 1$, while for very small relative freeboards is close to that value. However, the P_{ow} results of the UG13, UG14 and UG15 datasets are lower.

It is possible to fit a new P_{ow} prediction formula by adding the UG13, UG14 and UG15 datasets to the UG10 dataset. This new prediction formula will improve the accuracy of Victor et al. (2012) for the slope angle and relative crest freeboards ranges with prediction inaccuracies. The total number of tests through which the new P_{ow} prediction formula is fitted is 1163, which compares to the 364 tests of the UG10 dataset used by Victor et al. (2012) (a factor three increase).

The new P_{ow} prediction is presented in Eq. 11, with a coefficient $p = 0.8 + 0.24 \cdot (2 - \cot \alpha)$. The reliability of Eq. 11 can be expressed with a root mean square error $RMSE = 0.126$. The value of p decreases linearly for increasing $\cot \alpha$ (milder slopes) until reaching an approximately constant value for $\cot \alpha \geq 2$.

$$P_{ow} = \exp \left[- \left([0.8 + 0.24 \cdot (2 - \cot \alpha)] \frac{R_c}{H_{m0}} \right)^2 \right] \quad 11$$

$$\text{with } P_{ow} = \exp \left[- \left(0.8 \frac{R_c}{H_{m0}} \right)^2 \right] \text{ for } \cot \alpha \geq 2$$

Figure 6 compares the new P_{ow} prediction to the vertical structures data of the datasets UG13, UG14 and UG15. The new prediction is closer to the Franco et al. (1994) prediction than to the theoretical prediction. The new prediction adapts better to the shape of the data, and predicts the P_{ow} values with more accuracy, except for the case of zero and very small relative freeboards where the P_{ow} prediction is 1.

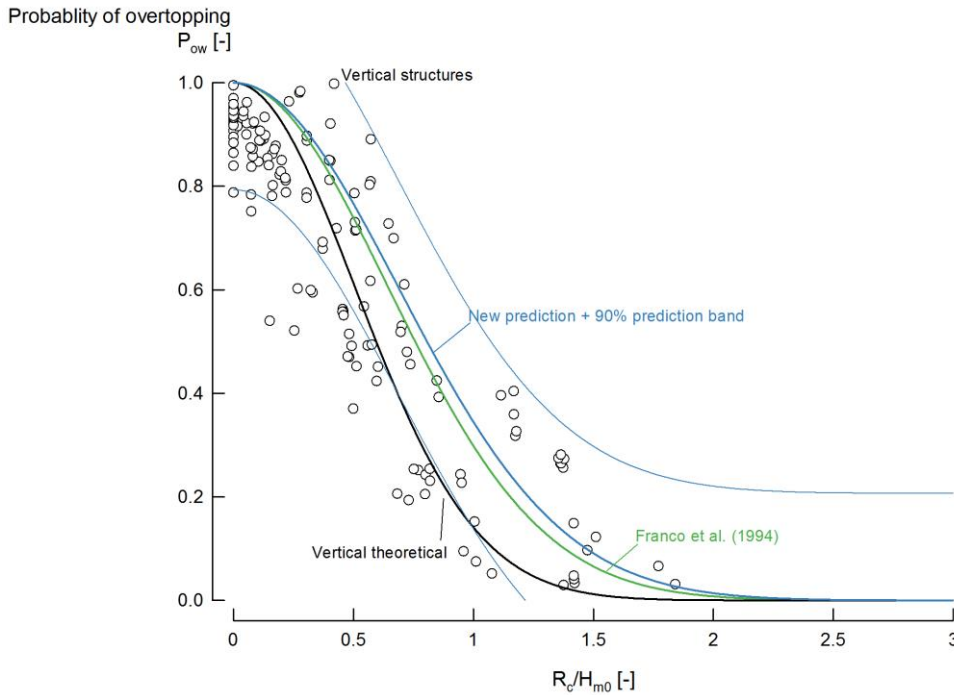


Figure 6. Probability of overtopping (P_{ow}) as a function of the relative crest freeboard R_c/H_{m0} for vertical structures of the datasets UG13, UG14 and UG15, compared to the theoretical prediction for vertical structures, Franco et al. (1994) and the new prediction (Eq. 11) with its 90% prediction band.

CONCLUSIONS

The main objectives of this research are (i) to increase the knowledge of wave overtopping for steep low-crested structures, (ii) with an analysis of the average overtopping rates and (iii) the individual overtopping volumes in order to (iv) improve the accuracy of the overtopping prediction formulae. To meet these objectives, 2D hydraulic model tests are performed in the wave flume at Ghent University, measuring wave conditions and the overtopping. In total, 1211 overtopping tests are performed, with the data divided in four different datasets: UG13, UG14, UG15 and UG16.

The existing average wave overtopping prediction formulae show an underprediction of the results for very small relative freeboards and the zero freeboard case, while for very steep slopes there is an underprediction for large relative freeboards. To solve the inaccuracies of the existing predictions, a new average overtopping prediction formula is suggested (Eq. 9). This formula is fitted through existing overtopping data and the new data obtained in this research. The new prediction improves the accuracy for very steep slopes and the zero freeboard case while maintaining the accuracy for the rest of ranges.

Regarding individual wave overtopping, a relation between the shape factor B and the slope angle α is found for very small and zero relative freeboards, while for large relative freeboards the B values are constant for all the slope angles considered. The existing B prediction formulae are underpredicting the values for very small and zero relative freeboards. The probability of overtopping P_{ow} for the zero freeboard case is theoretically 1 (all the incident waves are overtopping). However, the data show that these values are ranging from 0.8 to 1 due to the interaction between the incident and reflected waves. The P_{ow} values decrease for larger relative freeboards and for steeper slopes. New prediction formulae for B (Eq. 10) and P_{ow} (Eq. 11) are presented, fitted through the datasets obtained in this research and the UG10 dataset. The new prediction formulae for B and P_{ow} solve the inaccuracies of the existing formulae.

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