EurOtop revisited. Part 1: sloping structures

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Summary

The European Manual for the Assessment of Wave Overtopping ("EurOtop") was issued free on the internet in 2007 and is now used worldwide. The accompanying Neural Network is the governing prediction tool and the Manual itself gives guidance on all aspects of wave overtopping. It was the result of synthesis of existing Dutch, UK and German guidance with new research findings arising out of projects such as the EC FP7 "CLASH" project. During and since writing, the manual team has identified gaps and areas in which other improvements and clarifications could be made. This paper presents a summary of new analysis of existing data on wave overtopping at low and zero freeboards for sloping structures (dikes, levees, revetments). A companion paper revisits vertical structures (Bruce et al., 2013).

Data on zero freeboard overtopping show that such a situation will be largely over-predicted by the usual exponential-type equations. It appears that theory developed by Battjes in 1974 and used in Dutch guidelines works extremely well for prediction of overtopping using a curved line on a log-linear graph. For easy application, a curved Weibull-type equation has been used in this paper to describe wave overtopping for slopes for all positive freeboards. Next, vertical walls at relatively deep water and steep slopes can be described by a similar Weibull-type formula (Bruce et al., 2013). This enables the description of overtopping at very steep slopes (roughly between vertical and 1:1.5), together with vertical walls and steep slopes, by just one formula, taking the slope angle as the governing parameter. All new formulae are described including their reliability. They give enhanced insight in the relation on wave overtopping between various types of sloping and vertical structure, but for more complicated structures one should continue to consider the Neural Network tool for prediction.

Introduction

The following topics were treated in the EurOtop Manual (2007), but were not explored as fully as would have been desirable and are therefore key drivers for this and the companion paper:

- Wave overtopping at low and zero freeboards for sloping structures. Existing (old) theory and available data sets show lower wave overtopping than predicted by the exponential type of formulae used in the EurOtop Manual. This topic has been treated first in this paper.
- Overtopping response at very steep slopes with geometries lying between the fully-vertical and more familiar milder slopes, i.e. for slopes approximately in the range 5:1 (i.e. 5V:1H) down to 1:1. The second part of this paper describes the analysis on this topic.
- Physical explanation of the relationship between the formulae for vertical breakwaters and seawalls, for "non-impulsive" (or "pulsating") waves and for "impulsive" (breaking) wave overtopping, described by exponential and power-law formulae, respectively (EurOtop, 2007,

Chapter 7). This applies also to the analysis of composite vertical breakwaters. The companion paper (Bruce et al., 2013) deals with this topic.

- Explanation for the difference of mean overtopping rates between the formulae of Franco et al. (1994) and Allsop et al. (1995) for vertical structures, by physically rational reasoning and reanalysis of a part of the CLASH database. The companion paper (Bruce et al., 2013) deals with this topic.

Sloping structures with low and zero freeboards

Basis of the EurOtop Manual

It is long-established, based on the work of Owen (1980), that the mean wave overtopping discharge, q, on many kinds of coastal structures generally decreases exponentially as the crest freeboard, R_c, increases, with a form:

$$\frac{q}{\sqrt{gH_{m0}^3}} = a\exp\left(-b\frac{R_c}{H_{m0}}\right) \qquad (1)$$

where H_{m0} is the spectral significant wave height, and a and b are fitting coefficients. This form of equation has become popular as it gives a straight line on a log-linear graph, and it has only two coefficients for fitting the data.

For sloping structures like dikes or levees EurOtop (2007) gives the following design formulae:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.067}{\sqrt{\tan\alpha}}\gamma_b \cdot \xi_{m-1,0} \cdot \exp\left(-4.75\frac{R_C}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right) \qquad (2)$$

with a maximum of: $$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.6\frac{R_C}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right) \qquad (3)$$

where α = slope angle; $\xi_{m-1,0}$ = breaker parameter based on the spectral period $T_{m-1,0}$; $\xi_{m-1,0} = \tan\alpha/(2\pi H_{m0}/(gT_{m-1,0}^2))^{0.5}$; γ_x = influence factor, see EurOtop (2007) for more information. Equation 2 generally describes gentle slopes with plunging or breaking waves. In contrast, Equation 3 - the maximum overtopping - describes surging or non-breaking waves on fairly steep slopes. The reliability of Equation 2 is described by a standard deviation (σ) in the exponent σ(4.75) = 0.5. Similarly, the reliability of Equation 3 is described by σ(2.6) = 0.35.

Most data considered for Equations 2 and 3 (see EurOtop 2007, Figures 5.9 and 5.10; also Figures 2 and 3 in this paper) have relative freeboards R_c/H_{m0} > 0.5. The exponential type equations fit the data nicely, except for the data points at zero freeboard, where the equations would significantly over-predict. Overtopping at low and zero freeboards is the first subject to be described here.

Update on reliability of formulae

The EurOtop Manual describes the reliability of the formula by taking one of the coefficients as a stochastic parameter and giving a standard deviation (assuming a normal distribution). Then deterministic and probabilistic approaches are given. Actually, the “deterministic design or safety assessment” approach in the EurOtop Manual should be termed a semi-probabilistic approach as a partial safety factor of one standard deviation is used. This paper presents the following enhanced approaches:

- Deterministic approach. Use the formula as given with the mean value of the stochastic parameter(s). This should be done to predict or compare with test data. Note that this is not the same as the “for deterministic design” approach of EurOtop (2007) and it should not be used for design;
- Semi-probabilistic approach. This is an easy approach for design or safety assessment; this is the deterministic approach above, but now with the inclusion of the uncertainty of the prediction. The

stochastic parameter(s) become(s) $\mu + \sigma$;

- Probabilistic approach. Consider the stochastic parameter(s) with their mean values μ and given standard deviations σ and assume a normal distribution;
- The 5%-exceedance lines, or 90%-confidence band, can be calculated by using $\mu \pm 1.64\sigma$ for the stochastic parameter(s).

In this paper, the formulae are given as the mean prediction ("deterministic approach" above). The formula(e) and 5%-exceedance curves are given in a graphical way. Key coefficients are taken as stochastic variables, and uncertainty is then described by giving the standard deviation, σ.

Wave overtopping according to Battjes (1974) and Dutch guidelines

Battjes (1974) derived an expression for the overtopping volume in periodic waves on smooth gentle slopes and applied this expression to individual waves in a random wave train. A bivariate Rayleigh distribution was assumed for the wave height and wave length. This resulted in an expression for the mean overtopping discharge, which was still a function of the correlation parameter of the bivariate Rayleigh distribution κ (see also Battjes, 1974, Appendix A). With $\kappa = 0$, a lower bound was found and with $\kappa = 1$ an upper bound. Curved lines on a log-linear graph were the result as in Figure 1 (explained in the next paragraph). The overtopping parts of Battjes (1974) were not subsequently used a lot in the Netherlands, the main reason being that crest height design of dikes was still based on the 2%-run-up level and not on wave overtopping. The apparent complexity of the formulae may have also been a factor in the overtopping parts of Battjes' work not seeing wider adoption and exploitation.

TAW (1985) guidance, however, gave the curves of Battjes (1974) in a graphical form and proposed to use the upper boundary, as one large scale test in the Delta flume of Delft Hydraulics (now Deltares) on a 1:3 slope was close to this boundary. This curve is given in Figure 1, together with the mentioned test. The x-axis was given by $R_c \cot \alpha / (H_m L_0)$ and the y-axis by $q\, T_m (\cot \alpha)^{0.5} / (0.1 H_m L_0)$, where H_m is mean wave height; L_0 is mean wave length = $g/2\pi\, T_m^2$, with T_m the mean wave period. A little later in the TAW (1989) guidance, the significant wave height was introduced by $H_{1/3} = 1.6 H_m$ and the significant wave period $T_{1/3} = 1.15\, T_m$, which led to the parameters along the axes in Figure 1.

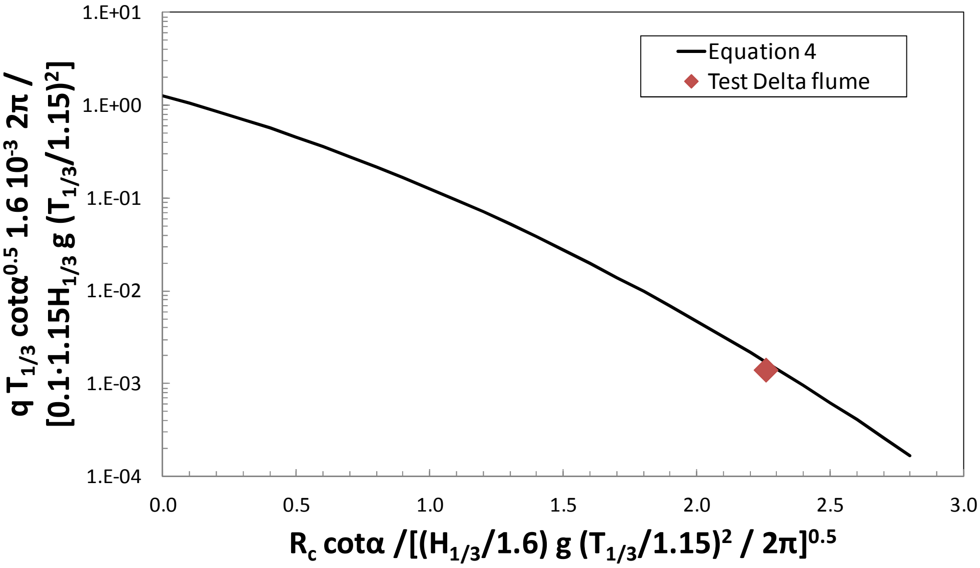

Figure 1. Re-plot of overtopping curve, developed by Battjes (1974) and described in the TAW-guideline (1989).

The curve for wave overtopping was then approximated by:

$$\log(Y) = -0.214X^2 - 0.787X + 0.103 \quad (4)$$

The main difference between the usual exponential function for wave overtopping (Equation 2) and Figure 1 is that Battjes' (1974) curve is not a straight line on a log-linear graph. An exponential fit for larger relative freeboards (a straight line) would be close to the curve in Figure 1, but such a fit would deviate for low freeboards. To better compare Battjes' (1974) approach with the EurOtop methods, the parameters at the horizontal and vertical axes can be rewritten by assuming $H_{1/3} = H_{m0}$ and $T_{1/3} = T_{m-1,0}$. The numeric values can be re-calculated too, giving:

$X = 1.45\ R_c/(H_{m0}\ \xi_{m-1,0})$ and
$Y = 46.1\ q/(gH_{m0}^3)^{0.5}\ (H_{m0}/(L_{m-1,0} \tan\alpha))^{0.5}$

The x- and y-axes are now exactly the same as the EurOtop (2007) formula for breaking waves on a gentle slope, except for the constant multipliers 1.45 and 46.1 (c.f. Equation 2). It means also that the curve in Figure 1 can directly be compared with the data and prediction curve in EurOtop (2007) - Figure 2. The result at first sight is startling, as the curve not only matches the data for positive freeboard and the EurOtop prediction line (Equation 2), but it also fits neatly the zero-freeboard data of Smid et al. (2001) – CLASH data set 102, also referred to as Schüttrumpf and Oumeraci (2005).

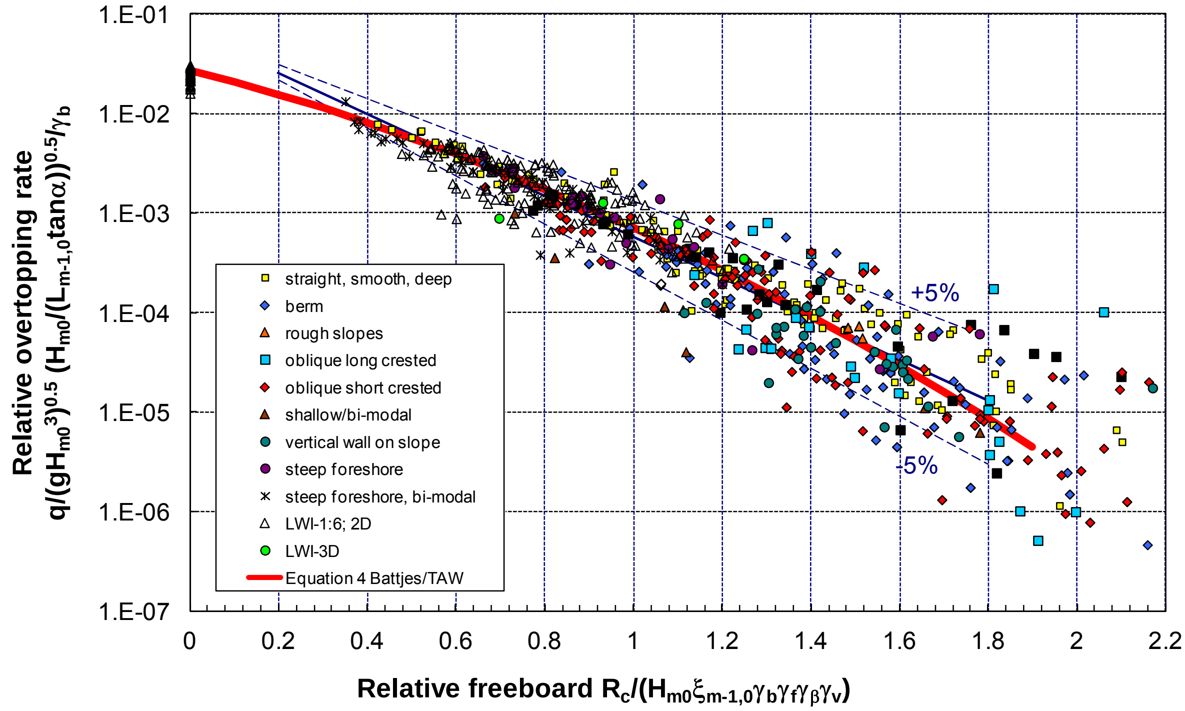

Figure 2. Re-plot of Figure 5.9 in the EurOtop Manual (2007) for breaking waves on gentle slopes, together with Battjes (1974) approximation as used in the TAW guideline(1989).

One should, however, realize that fitting was done on a reliable and large scale test in the Delta flume. From that point of view it is not surprising that the curve would match part of the overtopping data in Figure 2. But it is nevertheless pleasing that it also fits the zero freeboard data so well. It can be asserted therefore that the theory developed by Battjes (1974) gives the correct shape of the curve to describe wave overtopping at gentle slopes for all applications described as $R_c/H_{m0} \geq 0$. It also provides an analytical basis for the EurOtop choices for the parameter groups on horizontal and vertical axes, which were mainly based on analysis of empirical data only and not strongly on analytical reasoning.

Further analysis on sloping structures with low freeboards

Data for zero freeboard are also available for steep slopes and non-breaking waves (Equation 3). Figure 3 gives the re-plot of EurOtop Figure 5.10 for this type of structure, where Smid et al.'s (2001) data give the points for zero freeboard. Schüttrumpf and Oumeraci (2005) is dataset 102 in the CLASH database. Dataset 108 also gives data with zero freeboard and for a slope of 1:1.5. In CLASH this dataset was assigned a reliability factor RF = 4, meaning that the data are deemed unreliable (see Steendam et al., 2004 for a full explanation of "RF"). The reason was that during screening of the dataset in the CLASH work, the different measures of wave period did not seem to be consistent. The wave period is not, however, part of the analysis of overtopping at steep slopes. For this reason the data of dataset 108 for zero freeboard have been restored to Figure 3, although the observation that the data of this dataset 108 for positive freeboards are lower than expected continues to flag a concern over the reliability of the whole dataset.

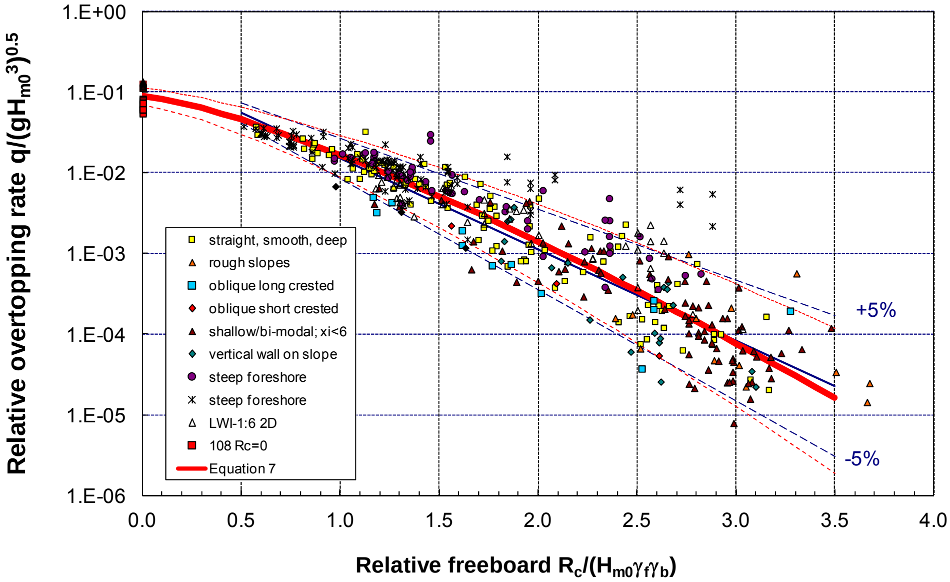

Figure 3. Re-plot of Figure 5.10 in the EurOtop Manual (2007) with dataset 108 added for zero freeboard and with a Weibull-type of fit for the whole range, Eq. 7.

Research in CLASH resulted in a lot of new data and in prediction formulae (Equations 2 and 3) for slopes, for breaking waves as well as non-breaking waves. Both formulae over-predict overtopping for very low and zero freeboard – see Figures 2 and 3. A polynomial fit as in Equation 4 describes the data, but is not easy to use for comparison between different formulae. A new fit for low freeboards only, with an extra set of formulae, would solve the problem. It is more elegant and more physically rational, however, to propose a curved line in an easy way. As the exponential function is a special case of the Weibull distribution, it is possible to go back to a Weibull-type function and use a fitted shape factor. Such a function looks still very much like Equation 1 and is described by:

$$\frac{q}{\sqrt{gH_{m0}^3}} = a \exp\left(-(b\frac{R_c}{H_{m0}})^c \right) \quad (5)$$

Equation 5 needs fitting of the correct shape factor, c, and then a re-fit of coefficient a and exponent b. Analysis gave a shape factor of c = 1.3 for a good fit for both breaking and non-breaking waves. It should be noted that this is not necessarily the best fit, but there is advantage in having the same value for both equations. Figure 3 shows the final curve for non-breaking waves, covering the full range of relative freeboards, Equation 7. The fit for breaking waves, Equation 6, is almost on top of the polynomial fit in Figure 2 and is not shown for that reason.

Overtopping on sloping structures with zero and positive freeboard can then be described by:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.023}{\sqrt{\tan\alpha}} \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left(-(2.7 \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v})^{1.3} \right) \quad (6)$$

with a maximum of: $$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot \exp\left(-(1.5 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta})^{1.3} \right) \quad (7)$$

The reliability of Equation 6 is given by σ(0.023) = 0.003 and σ(2.7) = 0.20, and of Equation 7 by σ(0.09) = 0.013 and σ(1.5) = 0.15. These formulae give almost the same wave overtopping as the original formulae, Equations 2 and 3, but represent nature better for $R_c/H_{m0} < 0.8$. In general, there is no need to replace Equations 2 and 3 by Equations 6 and 7, as they give similar predictions. Only for low and zero freeboards Equations 6 and 7 will be better. But the new equations give better insight in wave overtopping over the full range of zero and positive freeboards and enable also a comparison with very steep and vertical walls, see the next chapter.

Very steep slopes

Figure 4.1 in EurOtop (2007) gives an overall view of overtopping on various types of structures. Figure 4.2 shows that smooth steep sloping structures with non-breaking wave conditions give largest wave overtopping and this should decrease for very steep (battered) and vertical walls. What happens if slopes become steeper than say 1:1.5? The two boundaries can be given: Figure 3 for steep, smooth slopes, and data and formulae for vertical walls at relatively deep water (see also the companion paper Bruce et al. (2013)). This question could be answered most easily if formulae could be based upon similar equations.

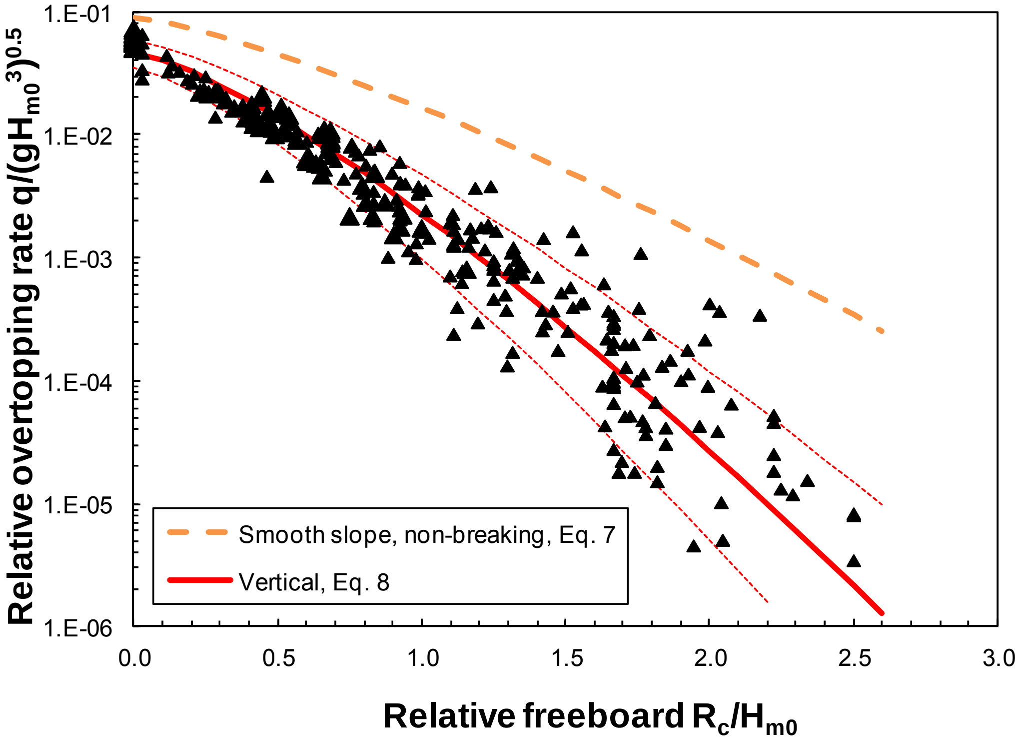

Figure 4. Vertical wall data (deep water and non-impulsive waves with a sloping foreshore) with new fit and curve for slopes under non-breaking wave conditions.

This is achieved by fitting also a Weibull type function through the data in Figure 4, representing overtopping at vertical walls at relatively deep water. That data together with the new fit (Equation 8) and the fit for steep smooth slopes (Equation 7) is shown in Figure 4. The vertical wall data (deep water and non-impulsive with foreshore with $R_c/H_{m0} < 1$, see Bruce et al. (2013)) with new fit gives:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.047 \cdot \exp\left(-(2.35 \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta})^{1.3} \right) \quad (8)$$

The reliability of Equation 8 is given by σ(0.047) = 0.007 and σ(2.35) = 0.2. Note that Equation 8 is not the best fit – that would be an equation with a smaller exponent than 1.3. But there is an advantage in using 1.3 as the equation is then similar to Equation 7, facilitating comparison between, and "joining" of the methods. The resulting curve (Figure 4) is still a good fit, considering the scatter.

Equation 7, for steep slopes and non-breaking waves, and Equation 8, for vertical walls, have the same shape, and only differ in coefficient and exponent. The connecting parameter is the slope angle cot α. Without any data one would probably choose a linear influence to combine Equations 7 and 8 to one general formula. Recently, however, very interesting data by Victor (2012) became available (see also Victor et al., 2012). In total 366 tests were performed on steep and very steep smooth slopes with relatively low freeboards, see Figure 5. Tested slope angles were cot α = 0.36, 0.58, 0.84, 1.0, 1.19, 1.43, 1.73, 2.14 and 2.75. The range of relative freeboards was $0.11 < R_c/H_{m0} < 1.7$. Some of the tests on slope angles of cot α = 2.14 and 2.75 belonged to the breaking wave region (Equation 6), the majority was, however, non-breaking. These data have been given in Figure 5, together with Equations 7. The range of slope angles covers the whole area between the two curves in Figure 4, although vertical walls were not tested.

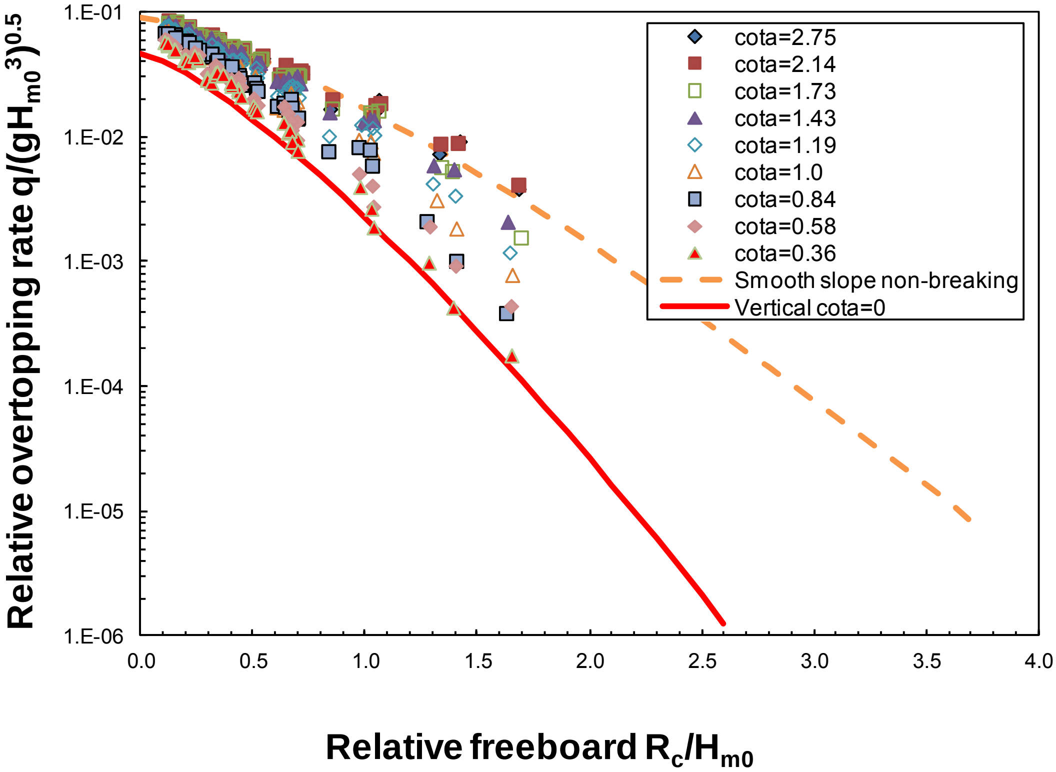

Figure 5. Data of Victor (2012) with very steep slopes from cotα = 0.36 to 2.75 and fairly low relative freeboards (non-breaking data only).

Equation 5 was fitted to the data of each individual slope angle, using c=1.3 and fitting a and b. These values of a and b were then plotted versus slope angle cot α in Figure 6. A rough trend would indeed be a linear expression, but the real trend is a little more curved. The most gentle slopes of cot α = 2.14 and 2.75 were perfectly matched by Equation 6 (see also Figure 5), where a slope angle with cot α = 1.73 showed the first deviation from this equation. One could say that wave overtopping starts to decrease if cot α < 2, although very slowly. Lines were fitted through the data points with a and b and the following equations were found, which should be used in combination with Equation 5 and c = 1.3:

$a = 0.09 - 0.01\,(2 - \cot\alpha)^{2.1}$ and $a = 0.09$ for $\cot\alpha > 2$ (9)

$b = 1.5 + 0.42\,(2 - \cot\alpha)^{1.5}$ with a maximum of $b = 2.35$ and $b = 1.5$ for $\cot\alpha > 2$ (10)

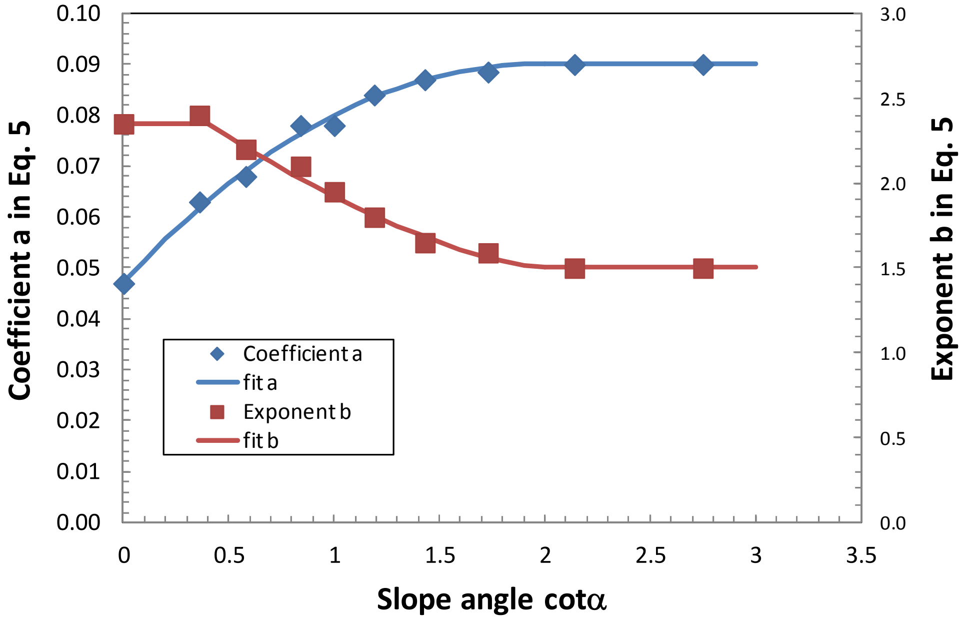

Figure 6. Coefficient a and exponent b in Equation 5 (with c = 1.3), fitted for slope angles with cotα = 0.36 to 2.75 (data of Victor, 2012).

Figure 7 gives the data for slope angles of cot α = 0.36, 0.84, 1.19, 2.14 and 2.75 with Equations 5, 9 and 10. The curves give a good trend of the data and also show that the data of the most gentle slopes of cot α = 2.14 and 2.75 very well match the original Equation 7 for steep slopes. Due to the data of Victor (2012), it was possible to describe wave overtopping for steep slopes and non-breaking waves up to vertical walls with only Equation 5 with a and b in Equations 9 and 10 and c = 1.3.

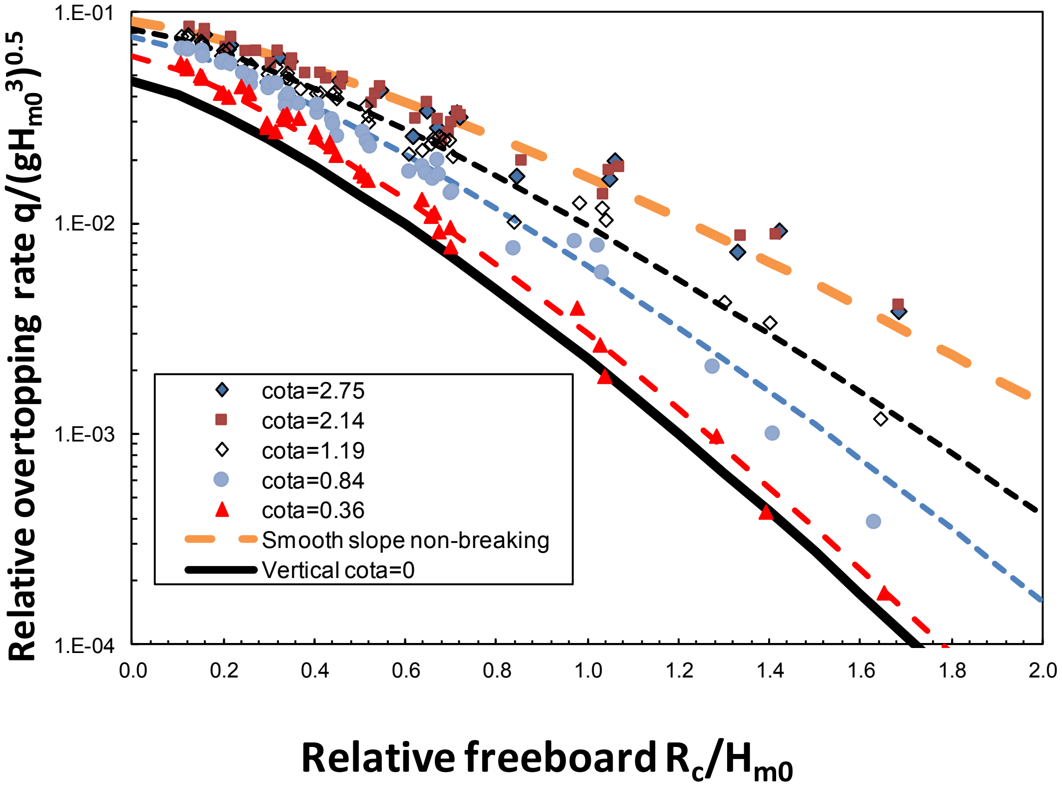

Figure 7. Very steep slopes with cotα = 0.36, 0.84, 1.19, 2.14 and 2.75 and Equations 5, 9 and 10. Data of Victor (2012).

Conclusions

The theoretical analysis of Battjes (1974) demonstrated that wave overtopping at gentle, smooth slopes should be a curved line on a log-linear graph. Such a curve can describe the whole range of overtopping, starting from zero freeboard - something not possible with the conventional exponential-type of overtopping formulae. By using a Weibull-type formula it is possible to describe wave overtopping at slopes for the whole range $R_c/H_{m0} \geq 0$. Equations 6 and 7 describe wave overtopping at slopes and are almost equal to Equation 5.9 and 5.10 in the EurOtop Manual, except that they give a better prediction in the area $0 \leq R_c/H_{m0} \leq \approx 0.8$.

Overtopping at vertical structures in relatively deep water can also be described by one Weibull-type formula, Equation 8, similar to the formulae for slopes, Equations 6 and 7. The only governing parameter between (smooth) steep slopes and vertical walls is the slope angle cot α (Equations 9 and 10).

In fact overtopping at straight slopes (gentle, steep, very steep) and up to vertical structures (in deep water, no sloping foreshore) can be described by the following set of formulae:

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.023}{\sqrt{\tan\alpha}} \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left(-(2.7 \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v})^{1.3}\right) \quad (6)$$

with a maximum of: $$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = a \cdot \exp\left(-(b \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta})^{1.3}\right) \quad (11)$$

and:

$a = 0.09 - 0.01\ (2 - \cot\alpha)^{2.1}$ and $a = 0.09$ for $\cot\alpha > 2$ (9)
$b = 1.5 + 0.42\ (2 - \cot\alpha)^{1.5}$ with a maximum of $b = 2.35$ and $b = 1.5$ for $\cot\alpha > 2$ (10)

Equation 6 gives gentle slopes where equations 9-11 give steep slopes and battered walls up to full vertical walls.

It is recommended that an update of EurOtop (2007) be considered, to include the new insights and design formulae found in this paper for practical use.

Acknowledgments

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