THE INFLUENCE OF A BERM AND A VERTICAL WALL ABOVE SWL ON THE REDUCTION OF WAVE OVERTOPPING

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The Eurotop Manual, based on the TAW guidelines, recognizes the reducing effect of a vertical wall or a berm on wave overtopping over an impermeable slope. Nevertheless, these reduction factors are only introduced in the formula for breaking waves. Furthermore, the berms for which reduction factors are proposed are mainly located below the SWL. In this paper, the reducing effect of a berm above SWL, a vertical wall and the combination of both are investigated. Reduction factors have been deducted, and are introduced in the existing overtopping formulae for an impermeable slope.

Keywords: wave overtopping, reduction factors, vertical wall, berm

1. Introduction

Belgium has a short shoreline (67km), but is densely populated and of high economic importance. Mostly dunes, beaches and dikes protect this shoreline. The typical geometry of such dikes is presented in Figure 1, with the beach reaching the dike, and a tourist promenade on top of the sloping dike. However, at certain locations the beach is eroded or absent and the still water level (SWL) and therefore the waves can reach the dikes, thereby threatening the safety of pedestrians and apartment buildings along the shoreline (see Figure 1).

Figure 1. Typical dike geometry along the Belgian coast (left), causing dangerous situations during a storm (right)

With a dike-slope of 1/2, the waves reaching this structure are classified as non-breaking waves (classification as described in the TAW guidelines (TAW, 2002) or the overtopping manual (EurOtop, 2007)). Overtopping will be calculated using formula [1][1].

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.6 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta}\right) \qquad [1]$$

In this formula, q stands for average overtopping discharge per m; g = acceleration due to gravity; H_{m0} = incident spectral wave height; R_c = freeboard; γ = reduction factor due to the slope roughness (γ_f) or the angle of incident waves (γ_β).

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[1] The coefficient 2.6 is the mean value in the probabilistic formulae and is used to compare with our laboratory results. For design purposes, the deterministic formula should be used: Coefficient 2.6 then changes in 2.3.

Note that for non-breaking waves only the wave angle (γ_β) and the structure's roughness (γ_f) will reduce the wave overtopping, while there is no influence of a vertical (crown)wall at top of the dike (γ_v), a stormwall (γ_v), or the tourist promenade above SWL (γ_b) according to formula [1]. Nevertheless, it is clear that those elements will positively influence the result. Therefore, wave overtopping tests have been carried out in the 2D wave flume at Ghent University. Results are presented in this paper.

Secondly, according to the existing formulae, all acting reduction factors are being multiplied up to a lower limit of 0.4. (TAW, 2002). In this paper, the combination of both a berm and a vertical wall has been investigated. Results are slightly different than the multiplication of both reduction-factors, and are presented here.

2. Reference case: overtopping over an impermeable smooth dike

Instead of using existing formulae available in the EurOtop Manual, 51 tests have been carried out on a smooth impermeable dike with slope 1/2 and perpendicular wave impact, for a range of sea states with varying H_S and T_P, to deduct our own reference formula and compare it to the existing formula [1]. Tests have been carried out in the wave flume (L = 30.0m x W = 1.0m x H = 1.20m) of Ghent University. A Jonswap spectrum with peak enhancement factor 3.3 has been used, and all laboratory results can be scaled up to the desired prototype values using the Froude scaling laws.
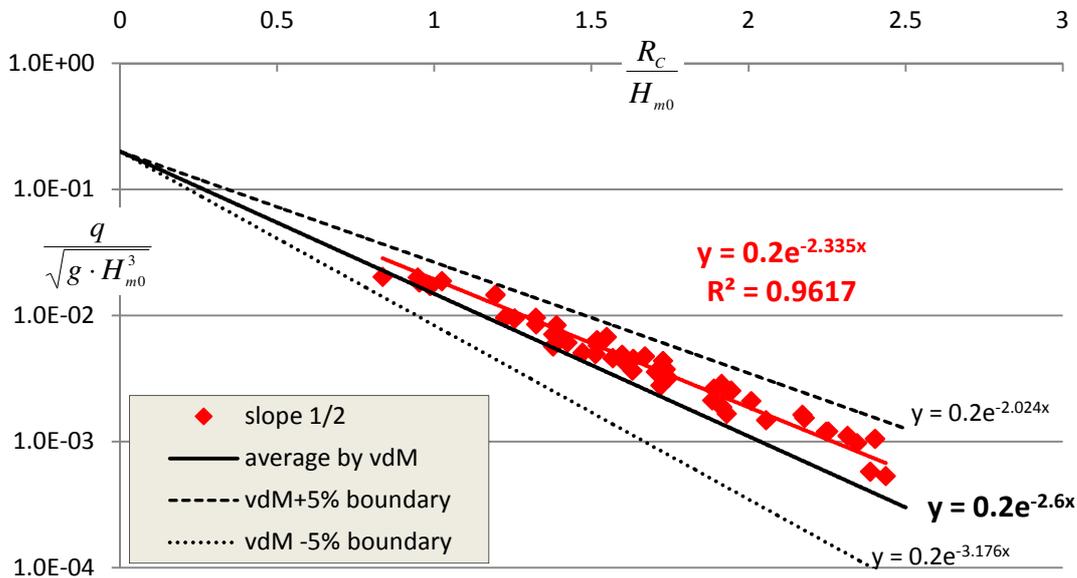
Figure 2. Reference data set: overtopping over a smooth impermeable dike.

If all data are plotted in the semi-logarithmic diagram, with dimensionless freeboard on the X-axis and dimensionless overtopping discharge on the Y-axis, they are all located in between the dotted lines who indicate the 90% confidence interval of formula [1]. The best fitting curve is

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.335 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta}\right) \qquad [2]$$

On behalf of the evaluation of all geometrical modifications (berm, vertical wall, …), this formula [2] will be used as reference formula. In further graphs, also the +5% and -5% boundaries are related to this reference formula.

3. Reduction by means of a vertical wall

A small vertical wall has been built into the dike, as shown on Figure 3. Hereby the crest level remains the same, which causes no visual implications for tourists or people living behind the dike. The zone behind the vertical wall can be filled up, creating a wider tourist promenade. If there are no visual restrictions, the wall can also be built on top of the dike, increasing the crest height.

88 tests have been carried out, with vertical walls of 2, 4, 5, 6 and 8cm in height. The resulting overtopping data have been plotted in Figure 4, using different symbols and colours.
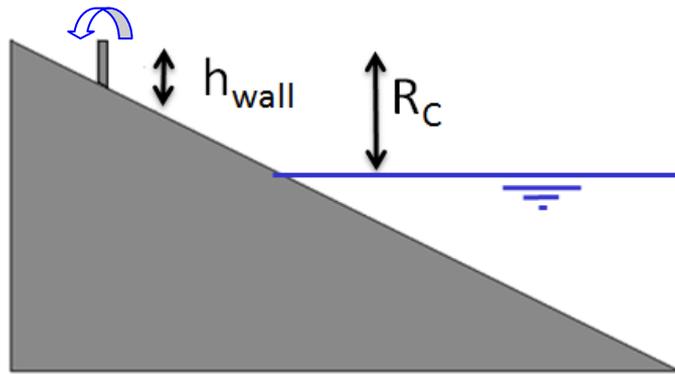
Figure 3. Principle of the vertical wall built in the dike.
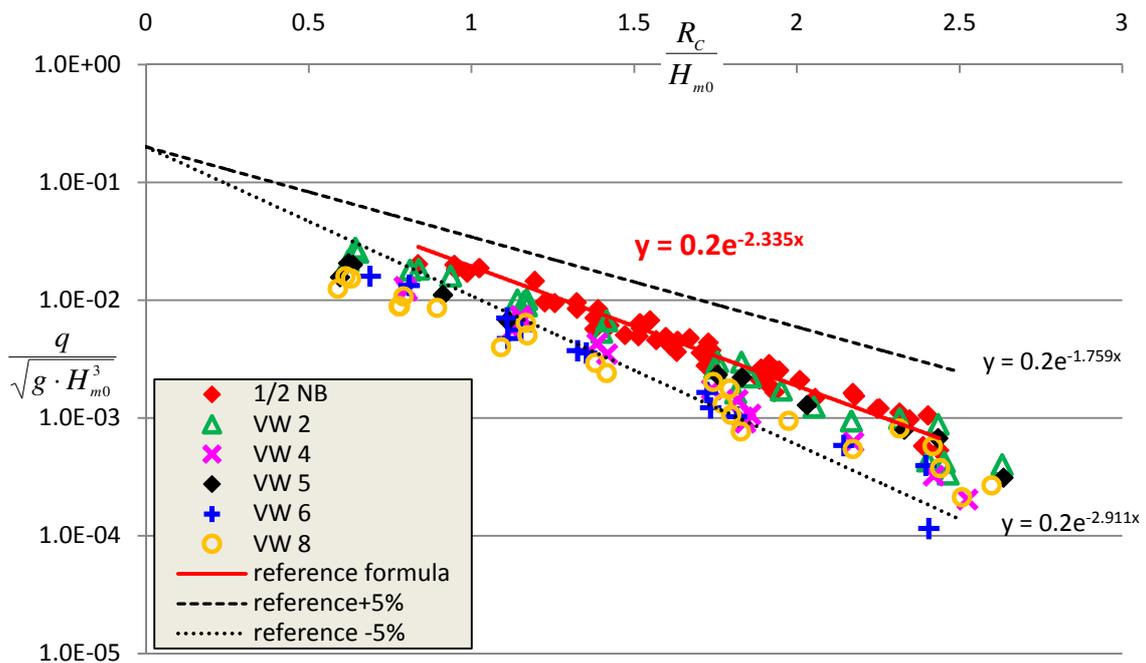
Figure 4. Reduction after use of a vertical wall

The reference data are indicated in Figure 4 as "1/2 NB" and are plotted in red diamonds. The data coming from the tests with vertical wall are grouped by the height of the wall, each in a different colour. They are indicated as VW and a number, which indicates the height in cm of the wall in model dimensions. The reference formula with its 90% confidence interval are also plotted.

Figure 4 shows that there is a clear reduction in overtopping due to the vertical wall. Quite a lot of data are located outside the 90% confidence bound of the red reference line. A reduction factor γ_v should be introduced in formula [2]. A similar γ_v as for the breaking waves is not useful, since the one stated in the overtopping manual is independent of the height of the wall (formula [3] with α_{wall} the angle of the wall: 90° for vertical walls):

$$\gamma_{v,breaking,EurOtop} = 1.35 - 0.0078 \cdot \alpha_{wall} = 0.648 \qquad [3]$$

Figure 4 however shows a clear dependency of the wall height. For every data point with a vertical wall, it can be calculated how much the data point needs to be shifted to end up on the red reference line. This is plotted versus the dimensionless wall height h_{wall}/R_C in Figure 5.
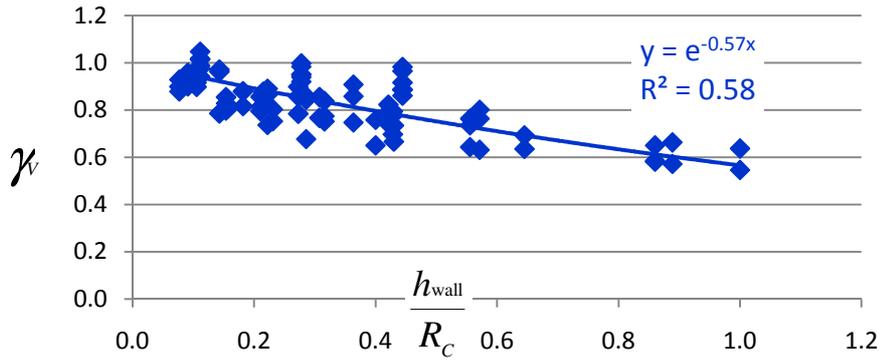
Figure 5. Reduction factor γ_v as a function of the dimensionless wall height

Figure 5 leads to an exponential relation, which can be used as reduction factor γ_v to calculate the overtopping rate of non-breaking waves overtopping a smooth dike with vertical wall.

$$\gamma_{V,non-breaking} = \exp\left(-0.57 \cdot \frac{h_{wall}}{R_C}\right) \qquad [4]$$

If this reduction factor is introduced in formula [2], formula [5] is obtained. All data are now plotted using $R_C/H_{m0}/\gamma_v$ on the X-axis (Figure 6). Compared to Figure 4, all datapoints are now located in the 90% confidence interval, closer by the reference line. Formula [5] gives a much better prediction of overtopping over a smooth dike with vertical wall, than formula [2]

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \exp\left(-2.335 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_v}\right) \qquad [5]$$

In this formula [5], only the effect of the vertical wall is considered.
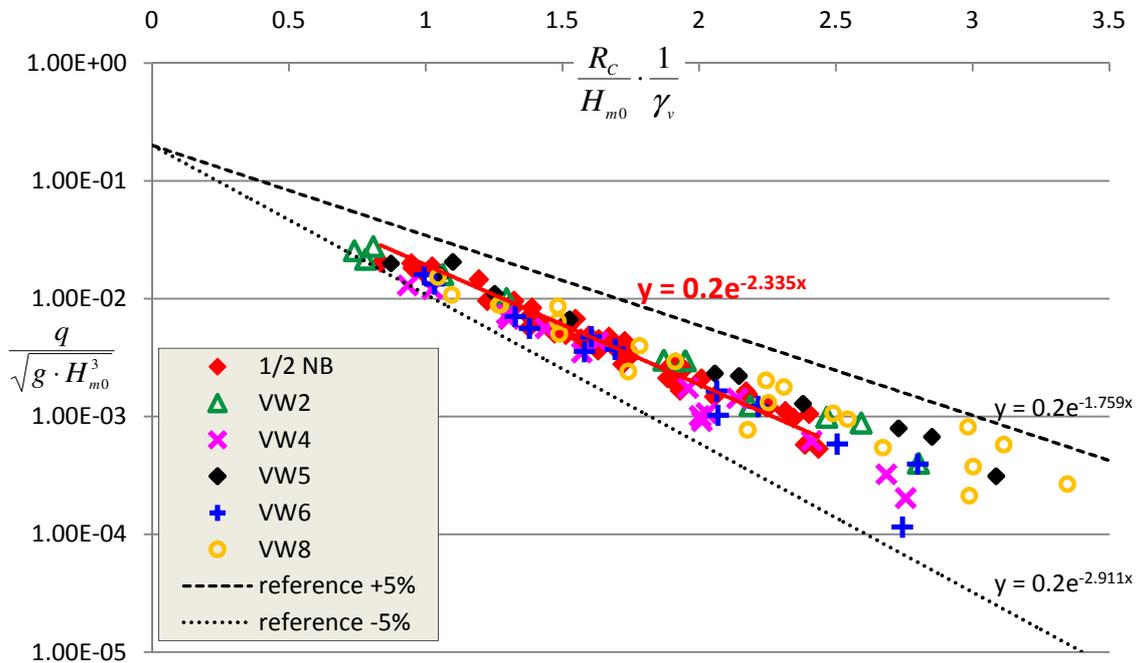
Figure 6. Better prediction by formula [5] of data points with a vertical wall on top of the smooth dike

4. Reduction by means of a berm above SWL
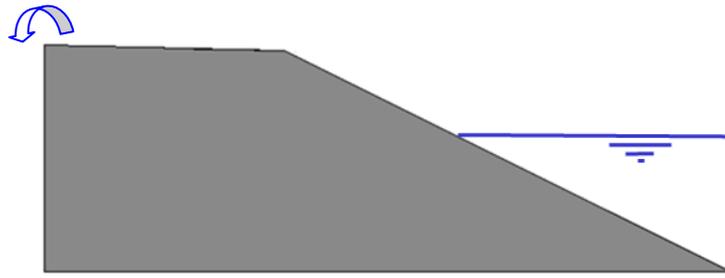
Figure 7. Tourist promenade, a berm above SWL

40 tests have been carried out on 3 different berm lengths: 33.3cm, 66.6cm and 100cm. This relates to the Belgian promenades with a Froude scale of $\alpha_L = 30$, so full scale promenades of 10m, 20m and 30m are considered. All berms have a 2% slope, to stimulate drainage. Obtainted results are only valid for these geometrical boundary conditions.

The longer the berm length, the less overtopping occurs at the end of the berm. This can be seen from Figure 8, where the data points of the berm 100cm (yellow) are located clearly below the ones from 33.3cm (blue).
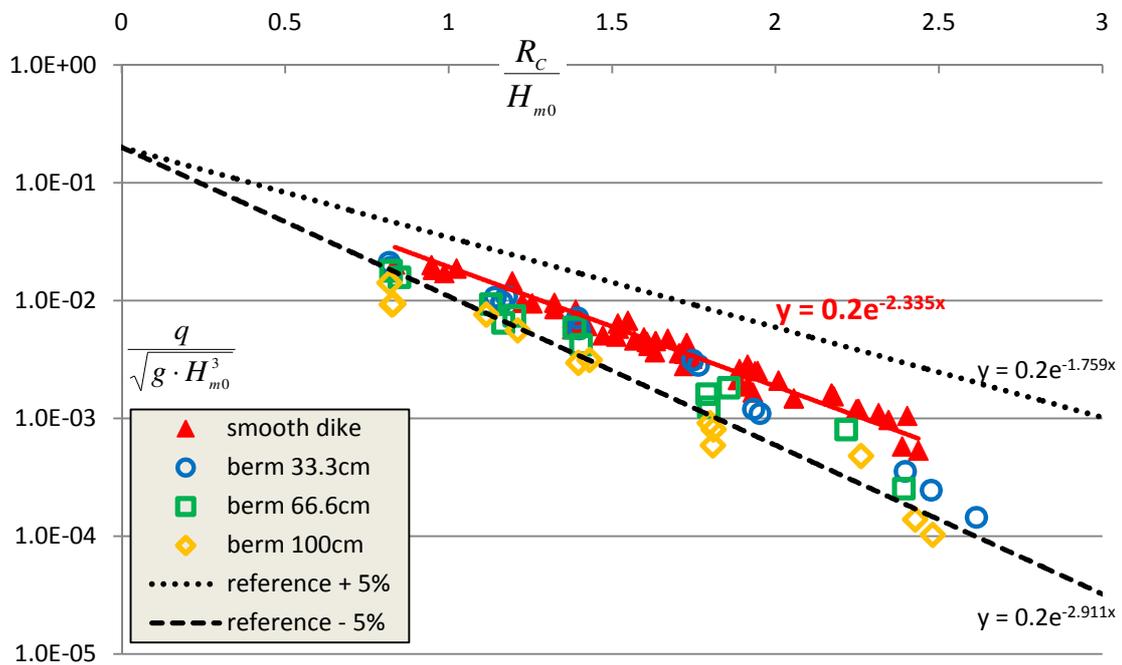
Figure 8. Reduction after use of a berm above SWL.

Analysis has been carried out, and a dimensionless reduction factor γ_b has been deducted from the data. Best results were obtained with R_C defined as the difference between the SWL and the start of the promenade. It is no longer the difference between the SWL and the highest point of the construction, since this long berm changes the non-breaking waves into breaking. Therefore, R_C is defined towards the front of the berm, as shown on Figure 9.

B_h is the horizontal berm width, while B is the berm width along the slope of the berm. By this definition, B_h implicitly contains the slope 2%. Results of this research must be used within the same geometrical boundary conditions.
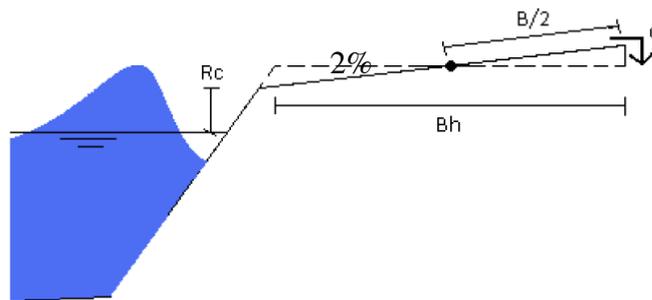
Figure 9. Definition of B_h and R_C

The most accurate description of γ_b is when it is related to the dimensionless berm length $B_h{}^2/L_0/R_C$.
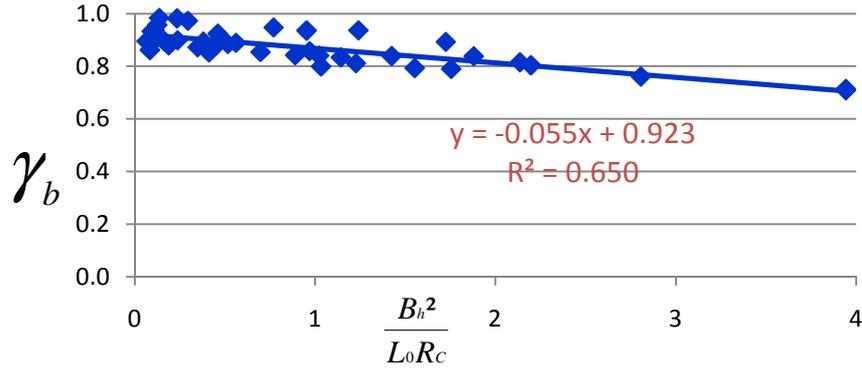
Figure 10. Reduction factor γ_b as a function of the dimensionless berm length

$$\gamma_{b,non-breaking} = 0.923 - 0.055 \cdot \frac{B_h^2}{L_0 \cdot R_C} \qquad [6]$$

Note that this relationship is not equal to 1 when the berm length is zero. A more usable trend could be worked out, but the scatter of the formula then increases. More data of shorter berm lenghts (5m prototype) are needed to finetune the formula [6], which is now only valid for $B_h^2/L_0/R_C \in [0.05 ; 4.0]$. When there is no berm (B = B_h = 0m), γ_b is equal to one by definition.

Implementation of reduction factor [6] in formula [2] leads to Figure 11 and formula [7]. The highest correlation could be obtained when γ_b is introduced both inside and outside the exponential part of the formula. The same structure as the overtopping formula for breaking waves is now obtained. As can be seen from Figure 11, formula [7] gives a good description to calculate overtopping over a dike with berm above SWL.
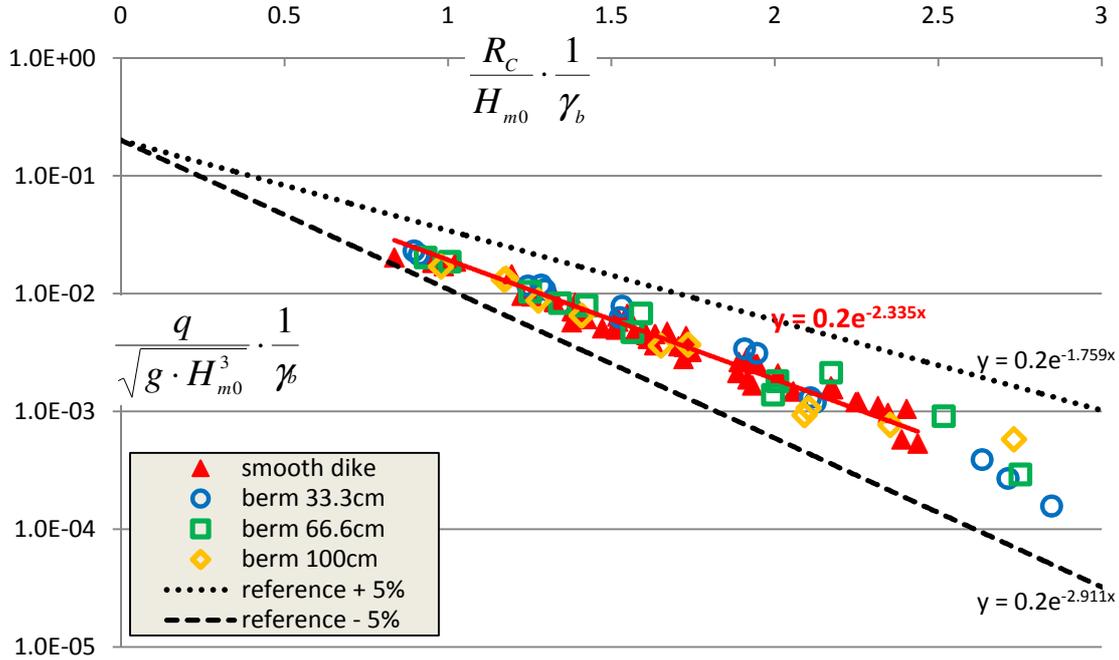
Figure 11. Better prediction by formula [7] of data points with a berm above SWL

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \gamma_b \cdot \exp\left(-2.335 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_b}\right) \qquad [7]$$

In this formula, only the effect of the berm is considered. The use of γ_b is only valid for the described boundary conditions (R_C defined towards the front of the promanade; B_h is the horizontal berm which contains the 2% slope).

5. Combination of reduction factors

Eventhough all reduction factors in the breaking and non-breaking overtopping formulae have been defined separately, they are being multiplied in the existing formulae without experimental research has been executed on this matter. The physical process of a wave hitting a wall is different when the same wave first passes by a rough structure

or a berm. Layer thickness and layer speed differ, leading to differences in overtopping discharges.

Therefore 130 tests were carried out with 10 different combinations of a berm above SWL (33.3cm to 100cm) and a vertical wall (2cm to 8cm) at the end of this promenade, to investigate if their reduction factors [4] and [6] can just be multiplied to predict the overtopping discharge.
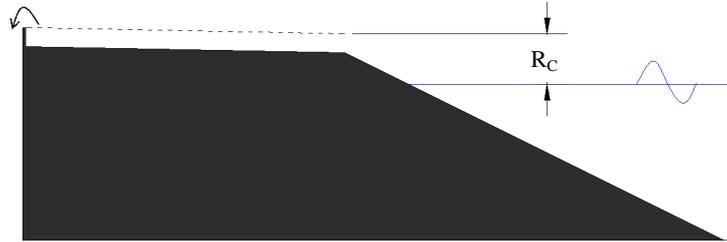
Figure 12. Tourist promenade, a berm above SWL

The crest freeboard now is defined as the difference between the SWL and the front of the promenade (as in paragraph 4), augmented by the height of the wall (Figure 12). The 2% slope is again implicitly processed in B_h in γ_b.

Along the Belgian coastline, no permanent wall will be built but a removable storm wall may be used when necessary (Figure 13). The anchoring will be built, the stakes and partitions will be stored and installed at storm alert. This creates no visual implications for the tourists or people living at the coastline, but guarantees the safety of the hinterland against flooding.

Figure 13. Removable storm wall
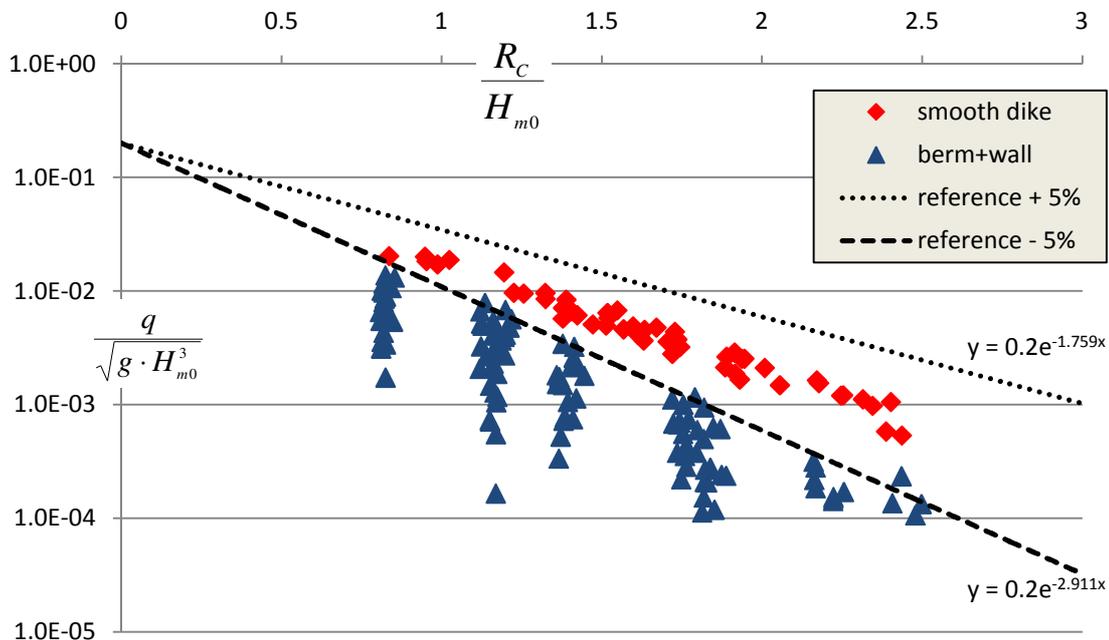
Figure 14. Combination of berm and storm wall as in Figure 12

All blue triangular data points are located below the red diamond reference data which means the berm and wall are clearly reducing the overtopping discharge. The data points are also located outside the 90% confidence interval of the reference formula, which means they are not predicted well by this formula. Both remarks lead to the conclusion that a reduction factor is needed for this situation. We can calculate how much is needed for every blue data point to shift to the red reference line (formula [2]). This reduction factor is now defined as γ_{bv}, and compare it to the multiplication of γ_v (formula [4]) and γ_b (formula [6]).

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \gamma_b \cdot \exp\left(-2.335 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_{bv}}\right) \qquad [8]$$

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.2 \cdot \gamma_b \cdot \exp\left(-2.335 \cdot \frac{R_C}{H_{m0}} \cdot \frac{1}{\gamma_b \cdot \gamma_v}\right) \qquad [9]$$
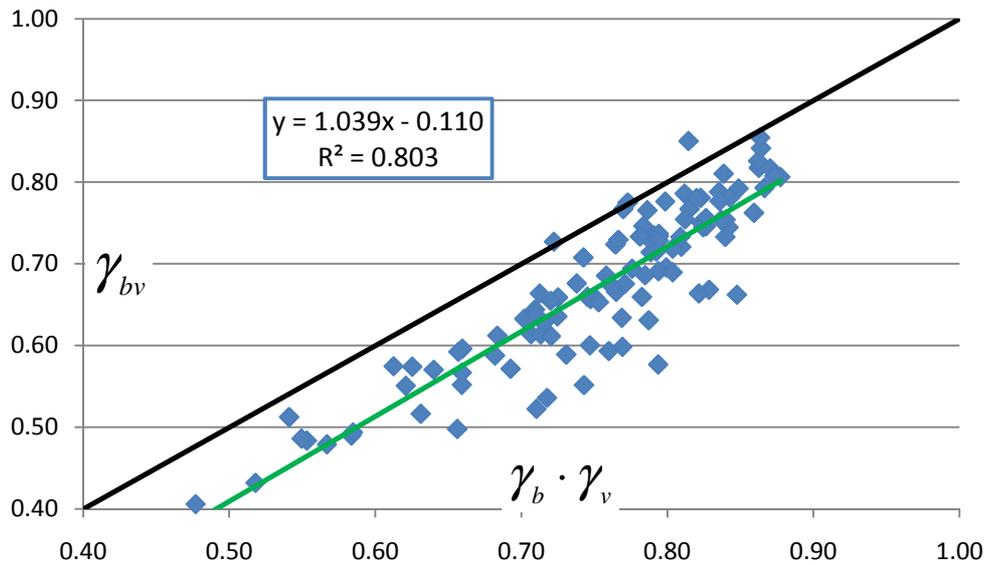
Figure 15. Comparison of γ_{bv} and $\gamma_b \cdot \gamma_v$

Figure 15 clearly shows that the actual reduction factor γ_{bv} is lower than the product of γ_b and γ_v, meaning there is a higher reduction with this combined geometry than predicted by multiplying the seperately deducted reduction factors γ_b and γ_v.

The same can also be seen from Figure 16: the prediction of the overtopping discharge by formula [9], with multiplication of reduction factors γ_v and γ_b, is not sufficiently accurate. The original data from Figure 14 are shifted towards the red reference line, but not enough: the blue triangles end up below the red diamonds.
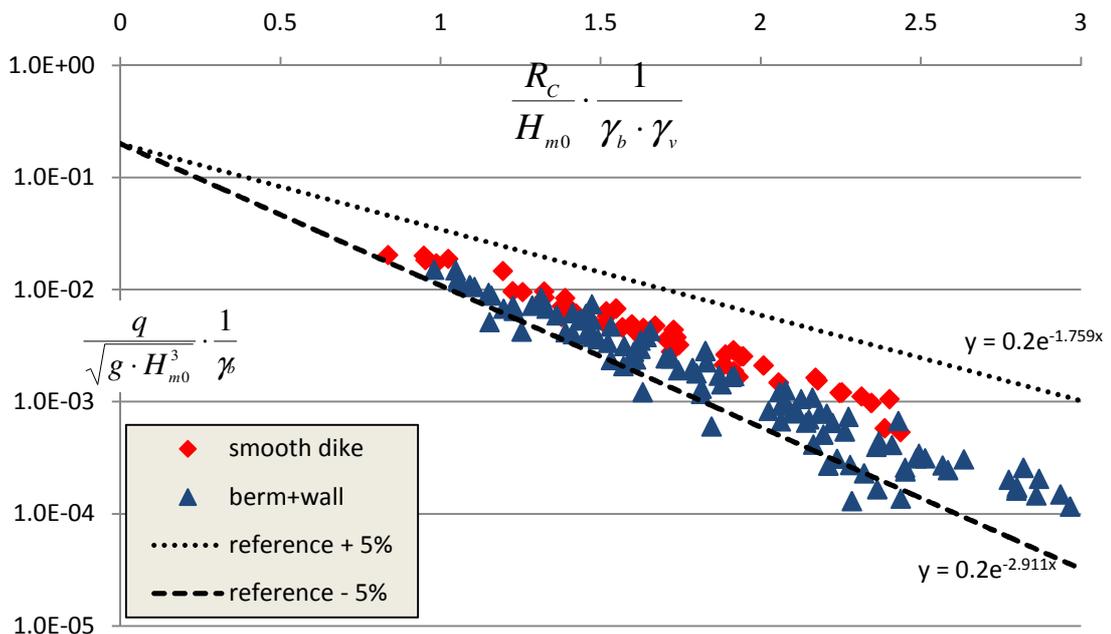
Figure 16. No accurate description by multiplying 2 independent reduction factors γ_b and γ_v

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A much better prediction can be achieved when applying the linear relationship from Figure 15.

$$\gamma_{bv} = 1.039 \cdot \gamma_b \cdot \gamma_v - 0.11 \qquad [10]$$

The exact same data are now plotted using the above relationship [10] in formula [8]. The blue data are now shifted towards the red reference line. Formula 8 is a good description to calculate overtopping over a smooth dike with both berm and vertical wall as reducing elements.
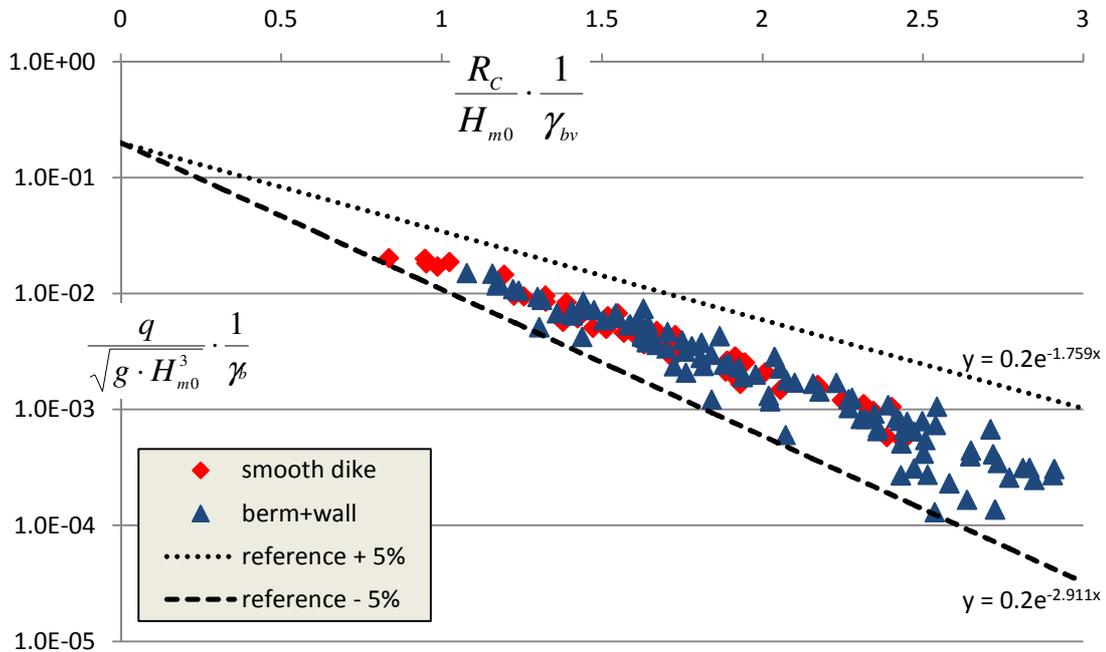
Figure 17. Good description of the situation berm+wall when reduction factor γ_{bv} is implemented in the reference formula

6. Example

If an incoming wave of $H_{m0} = 2$m, $T_P = 9$s reaches a smooth impermeable dike with crest freeboard $R_C = 2.0$m, the predicted average overtopping discharge would be calculated with formula [2]: q = 171.5 l/s/m.
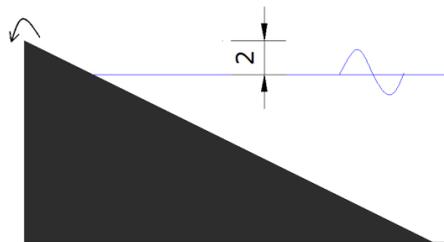
Figure 18. q = 171.5l/s/m over a smooth impermeable dike

If a berm above SWL of 20m wide and a 2% slope would be introduced, the original formula from the overtopping manual doesn't count on it. This paper however has shown that a reduction γ_b of 0.839 can be applied, reducing the overtopping to q = 109.7 l/s/m.
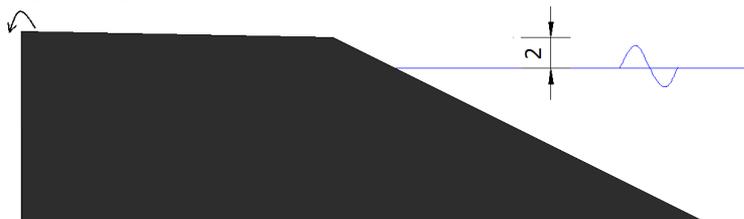
Figure 19. q reduces to 109.7l/s/m according to the formulae of this paper

If a vertical stormwall of 1.2m high is built on top of the dike, the freeboard increases to 3.2m reducing q to 42.3 l/s/m (formula [2]). By introducing the reduction factor $\gamma_v = 0.808$ the overtopping discharge decreases to 17.3 l/s/m (formula [5]).

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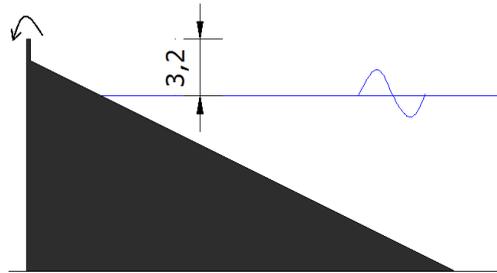
Figure 20. Due to γ_v the overtopping is 17.3l/s/m in stead of 42.3l/s/m

When using formula [2] to calculate the overtopping over the dike in Figure 21, with R_C = 3.6m (2m + 2% * 20m of the berm + 1.2m of the wall), the overtopping discharge would be 26.5l/m/s. If formula [9], with $\gamma_b \cdot \gamma_v$ = 0.703, would be used with R_C = 3.20m (2m + 1.2m wall; the 40cm due to the berm is implicitly incorporated in γ_b), the overtopping discharge would be 8.7l/m/s.

In paragraph 5 however is shown that the correct prediction of the overtopping discharge is made by using formula [8] with R_C = 3.20m (2m + 1.2m wall; the 40cm due to the berm is implicitly incorporated in γ_b) and an actual reduction factor γ_{bv} = 0.62. The overtopping discharge is 4.3l/s/m.
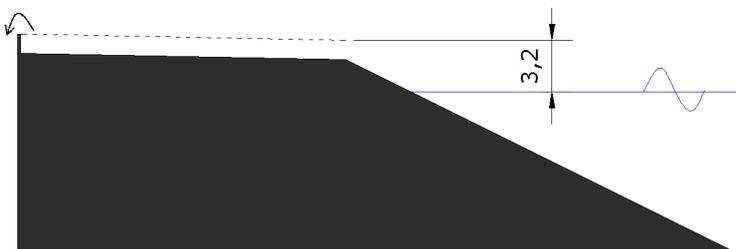
Figure 21. Dike with berm and storm wall. q = 4.3l/m/s

7. Conclusions and future research

In this paper a modified overtopping formula for non-breaking waves has been proposed. It has been shown that next to roughness and wave obliqueness also a berm and/or a vertical wall can reduce overtopping of non-breaking waves. Reduction factors for vertical wall and berm above SWL have been deducted from scale model tests and are proposed in formula [4] and [6]. Note that R_C is always defined towards the end of the ½ slope (included the vertical wall, excluded the promenade). The promenade changes the non-breaking waves into different wave conditions. Therefore, R_C is always defined without the increased height due to the small promenade inclination (2%). This effect is captured in the definition of the horizontal berm width B_h and thus in the factor γ_b.

Next, we investigated whether both reduction factors may be multiplied when both geometries (berm and vertical wall) are combined on top of the impermeable slope. Multiplying both gamma factors leads to an overestimation of the overtopping discharge as can be seen from the example in paragraph 6. Formula [10] and [8] should be used to calculate overtopping over this geometry.

It is recommended to always carry out physical testing when the geometry of the dike is not standard, and more reduction factors should be combined. Multiplying the existing reduction factors without any further notice may over- or underestimate the overtopping discharges.

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