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The Influence of a Berm and a Wave Wall at Dikes on Overtopping by Oblique and Breaking Waves

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Abstract: This paper describes the fitness for wave overtopping in a situation with a 1:3 lower slope, a berm followed by a vertical wave wall in combination with oblique and breaking waves. 3D model tests were carried out in a project called ‘Vlieland’. A literature study and combined analysis of the new Vlieland data with existing data from Harlingen (van der Meer (1997)) and Van Doorslaer (2018) took place, where the influence of the different influence factors on wave overtopping was studied: wave obliquity, a berm and a wave wall. The measured overtopping rates can be well predicted by the existing methods or by a newly developed method, which are both presented in this paper.

Keywords: overtopping, oblique, wave wall, berm, breaking waves, EurOtop

1 Introduction

In EurOtop (2018), several different methods are proposed to estimate the amount of wave overtopping for configurations/situations when a vertical wave wall is used at the end of a berm. This design was considered for the reinforcement of the dike at the Frisian island of Vlieland, which is part of the Wadden Sea in the Netherlands.

However, none of these methods from EurOtop (2018), which are elaborated in section 3.2, seem to accurately describe the Vlieland situation. On top of that, the dike is facing oblique breaking short-crested waves. There is no literature on the combination of a wave wall and oblique wave attack and this specific combination has never been tested in scale models before. This led to many uncertainties in the design. Therefore, 3D physical model tests were carried out in May 2018 to obtain more certainty. The tests were conducted in the Deltabasin at Deltares in order to be able to reproduce oblique incoming waves (50º). The tested cross-section is described in Fig. 1. The dike design consists of a 1:3 slope followed by a short berm (3m prototype) and a wave-wall (1m high in prototype). The dike crest equals NAP+5.5m and is 1.1 meter above the design water level (prototype) with wave heights of approx. 1.5m. Thus, the freeboard equals 1.1m, which is almost the same as the tested wall height of 1.0m, meaning that the toe of the wall is only barely emerged.

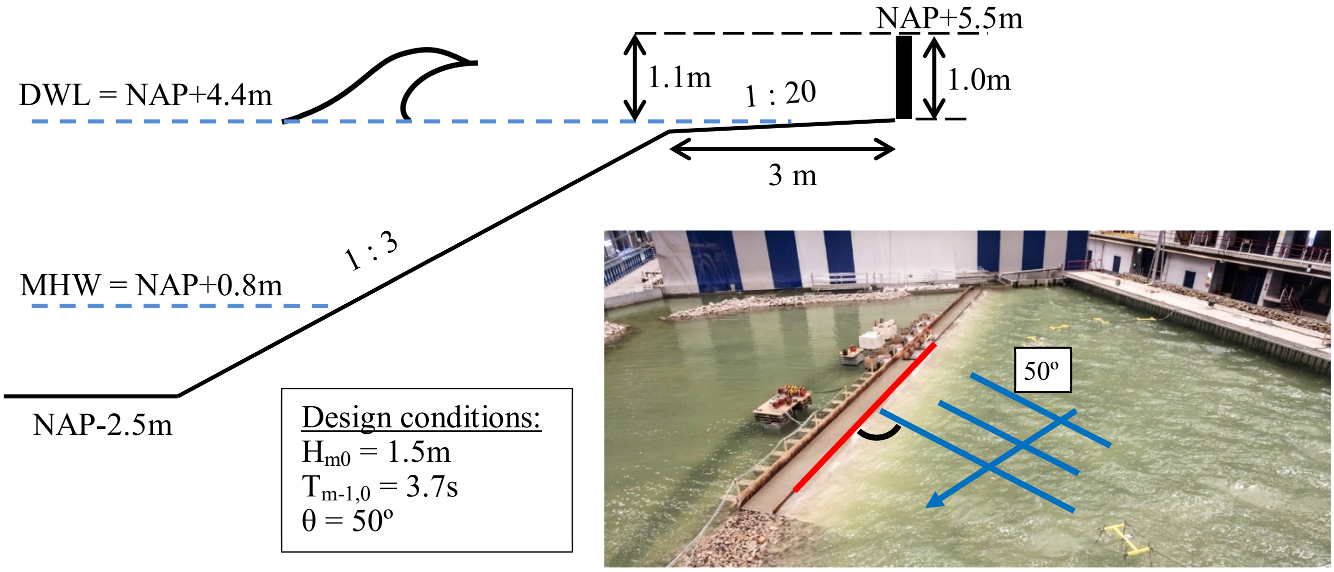

Fig. 1. Cross section (prototype dimensions) of the test set-up

2 Vlieland test program and other existing data for overtopping of wave walls

2.1 Vlieland test program

In total 25 tests were carried out using a scale of 1 in 10 and were analyzed by Schoemaker (2019). 11 tests have been carried out with a plain vertical wall and another 14 with different kinds of bullnoses added to the wave wall. In this paper, the focus is on the tests without bullnoses. The Vlieland tests are characterized by short wave periods of $T_{m-1,0}$ = 3.7 to 4.3s prototype with a few exceptions of 5 to 5.3s, leading to wave steepness $s_{m-1,0}$ between 5 and 6%. The wave breaker parameters are below 1.5 indicating that these short waves are breaking. The wave spectrum varied between Bretschneider with a decay factor of 2.5 (as this resembles the Wadden Sea the best) and Jonswap (γ = 3.3).

2.2 Other data of wave overtopping with wave walls

More tests have been executed with wave overtopping and wave walls, such as the Harlingen (1997) data set. In this data set, 38 tests have been carried out on dike slopes (tan α = 1:2.5 and 1:3) with a wave wall. 20 tests have been carried out on a dike with the wave wall directly at the end of the dike slope, in 18 other tests a small berm was present in front of the wave wall. The tested design water level in these 38 tests was both above and below the berm level. This means the toe of the wave wall was emerged in some tests, submerged in others. The analysis of these tests by van der Meer (1997) have led to the methodology that was first included in EurOtop (2007).

More recently, Van Doorslaer (2018) has set up a large data set for slopes 1:2 and 1:3 (with rather large wave periods, leading to non-breaking waves) and a small data set for slopes 1:6 (also with rather large wave periods, however leading to breaking waves due to the mild slope). A wave wall and/or berm was present in his database, and also a bullnose was included in some of the tests. The tested design water level in his database was (except for 2/255 datapoints) always below the top of the dike slope or berm level. This means the toe of the wave wall was always emerged. Based on the analysis by Van Doorslaer (2018), the advice in EurOtop (2007) on the influence of wave walls was extended. See section 5.4.7 of the EurOtop manual (2018).

Fig. 2 shows the different data sets of tests with a wave wall. This plot has the breaker parameter on the horizontal axis (breaking vs non-breaking), and h_{wall}/R_c on the vertical axis (water level below the toe of the wall vs water level above the toe of the wall). The Vlieland tests have been included in the plot (black circles) to show were the tests contribute to. As can be seen, the tests are in the breaking domain with a slightly emerged wall, the same domain as the breaking tests from Harlingen and Van Doorslaer breaking. However, in this quadrant Van Doorslaer tested a 1:6 profile without a berm. In the analyses for Vlieland only the data for 1:3 slopes with a berm were considered due to similar geometry.

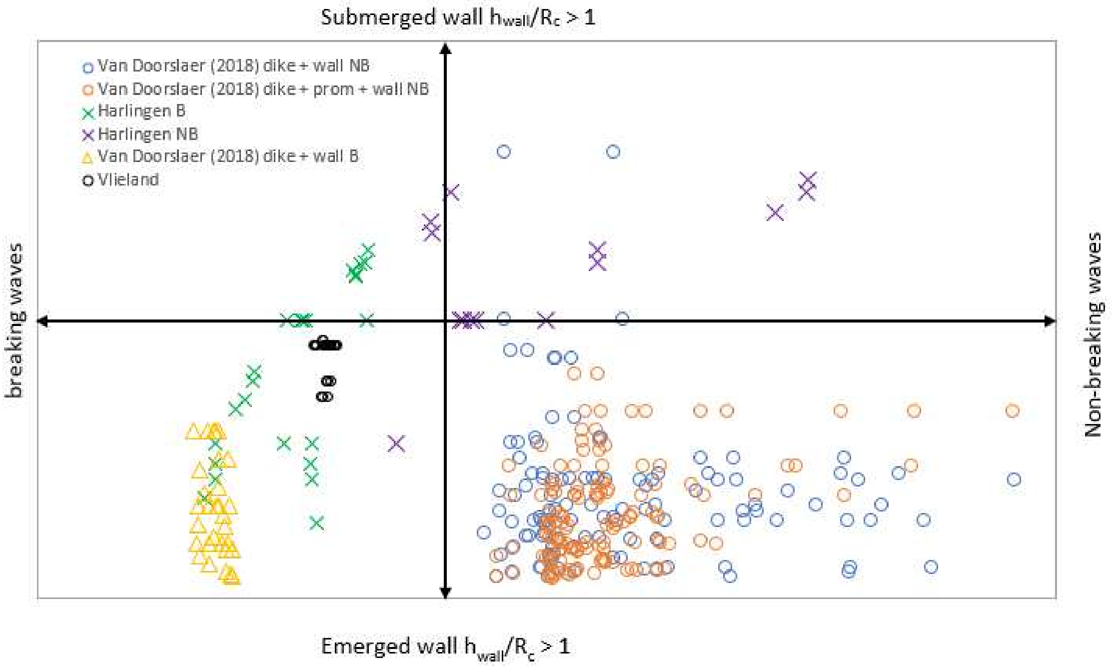

Fig. 2. Available data from physical model tests with wave overtopping and a wave wall; data divided by breaking vs non-breaking conditions on the horizontal axis and submerged vs emerged wave wall on the vertical axis

In addition to the 11 relevant tests for Vlieland, 10 other tests from the Harlingen data set were included in the analysis presented in this paper. These 10 tests have comparable geometry: a 1 in 3 lower slope, followed by a berm with a fixed width of 40 cm, ending with a vertical wall varying in height at the end of the berm. Water levels, wave heights and wave periods have been varied. The wave steepness was between 0.023 and 0.051 based on the spectral period $T_{m-1,0}$, leading to wave breaker parameters between 1.5 and 2.0, and thus also breaking wave conditions.

3 Analysis and Results

3.1 Influence of wave obliquity, spectrum and bullnoses

As mentioned earlier, the combination of a berm, a wave wall and oblique waves has not been tested before. EurOtop suggests (without making a hard statement about it) to simply multiply the individual influences. Van Doorslaer (2018) has shown that this is not always the case, e.g. the individual influences of a promenade and a wave wall cannot be simply multiplied when both reducing influences are combined. The geometrical differences may cause changes in the physical response of the waves to the structure and may lead to different results for wave overtopping. Without proper testing, influence factors cannot simply be multiplied. The present work thus presents a unique data set from which the influence factor for wave obliquity in combination with a berm and a wave wall can be derived.

In the Vlieland test program, 3 tests have been carried out with waves perpendicular to the dike, the same 3 tests have been repeated with an obliquity of 50° and 1 test has been carried out with an intermediate 30° wave angle. Fig. 3 shows the results of these tests. The black line indicates the influence factor as advised by EurOtop (2018), which is depicted by Eq. [1].

$$\gamma_\beta = 1 - 0.0033|\gamma| \text{ for } 0° \leq |\beta| \leq 80°$$
$$\gamma_\beta = 0.736 \text{ for } |\beta| > 80° \quad [1]$$

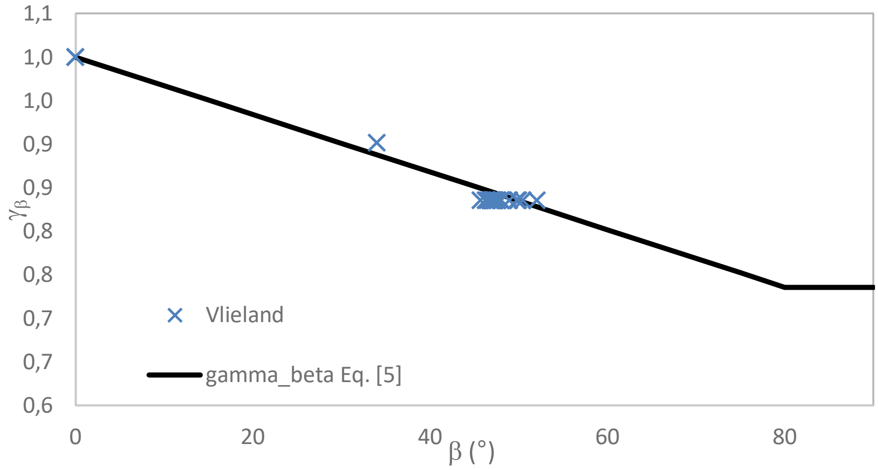

Fig. 3. Influence factor γ_β as a function of β related to the EurOtop trendline

As can be seen, the influence of the oblique wave attack in the tests is as predicted. This means that in combination with a berm and a wave wall, the influence of oblique waves can be predicted by Eq. [1].

Two further aspects were tested during the Vlieland testing series: the influence of spectrum and bullnose. Both will not be further discussed in the paper, but a conclusion is given here:

- No big difference between both was found between the tested Jonswap (γ = 3.3) and Bretschneider 2.5 tests.
- For the bullnoses an average extra influence of γ_{bn} = 0.86 was found on top of the other influence factors, like wave wall $\gamma_{v,}$ regardless of its shape.

3.2 Influence of a berm and wave wall

In this section the performance of several methods from the EurOtop (2018) and a newly proposed method are compared to predict/calculate wave overtopping rates for a 1:3 dike slope with a berm and a wave wall. Eq. [2] and [3] are the basis for this analysis. The data set from the Vlieland tests and the selected data from the Harlingen tests (see section 2.2) have been applied.

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.023}{\sqrt{tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot exp\left(-2.7 \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\xi_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right) \quad [2]$$

$$\text{with a maximum } \frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot exp\left(-1.5 \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta \cdot \gamma^*}\right) \quad [3]$$

3.2.1 Harlingen approach

The method proposed by van der Meer (1997) on the Harlingen data set, is summarized below.

- Calculate the average slope by Eq. [4] and influence of the berm by Eq [5] (also apply correction from EurOtop manual if water level is different than the berm level), where the wave wall is represented as a 1:1 slope. This is graphically represented in Fig. 4.
- Calculate the wave breaker parameter with the average slope from Eq. [4]
- If $\gamma_b \cdot \xi_{0p} < 3$, the waves are classified as breaking. Eq. [2] has to be used with a reduction factor for the wave wall $\gamma_v = 0.65$.
- If $\gamma_b \cdot \xi_{0p} \geq 3$, the waves are classified as non-breaking. Eq. [3] has to be used where no extra reduction factor for the wave wall has to be included, $\gamma_v = 1$.
- Note that the transition between breaking and non-breaking has moved from 2 to 3 for these geometries.

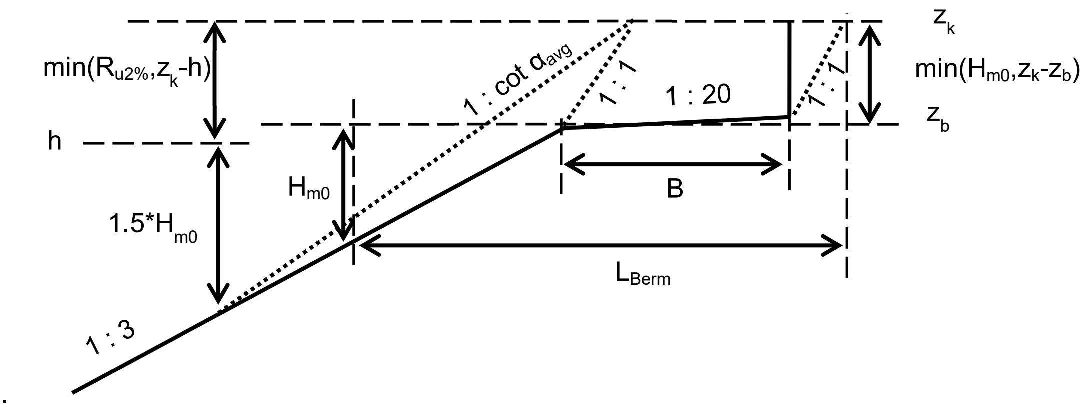

Fig. 4. Harlingen approach for Vlieland geometry

With the water level the same as the berm level and if the crest is not exceeded by one significant wave height above the berm or by the 2% wave run-up $R_{u2\%}$, the following parameters are valid:

$$\xi_{0,m-1,0} = \frac{\tan \alpha_{avg}}{\sqrt{s_{0,m-1,0}}} \text{ with } \tan \alpha_{avg} = \frac{z_k - h + 1.5 \cdot H_{m0}}{(z_k - z_b) \cdot 1 + (z_b - h + 1.5 \cdot H_{m0}) \cdot 3} \quad [4]$$

$$\gamma_b = 1 - \frac{B}{L_{Berm}} \quad [5]$$

$$\gamma_v = 0.65 \quad [6]$$

The method is applied to the regarded tests (Vlieland and Harlingen with slope 1:3). Results are displayed in Fig. 5.

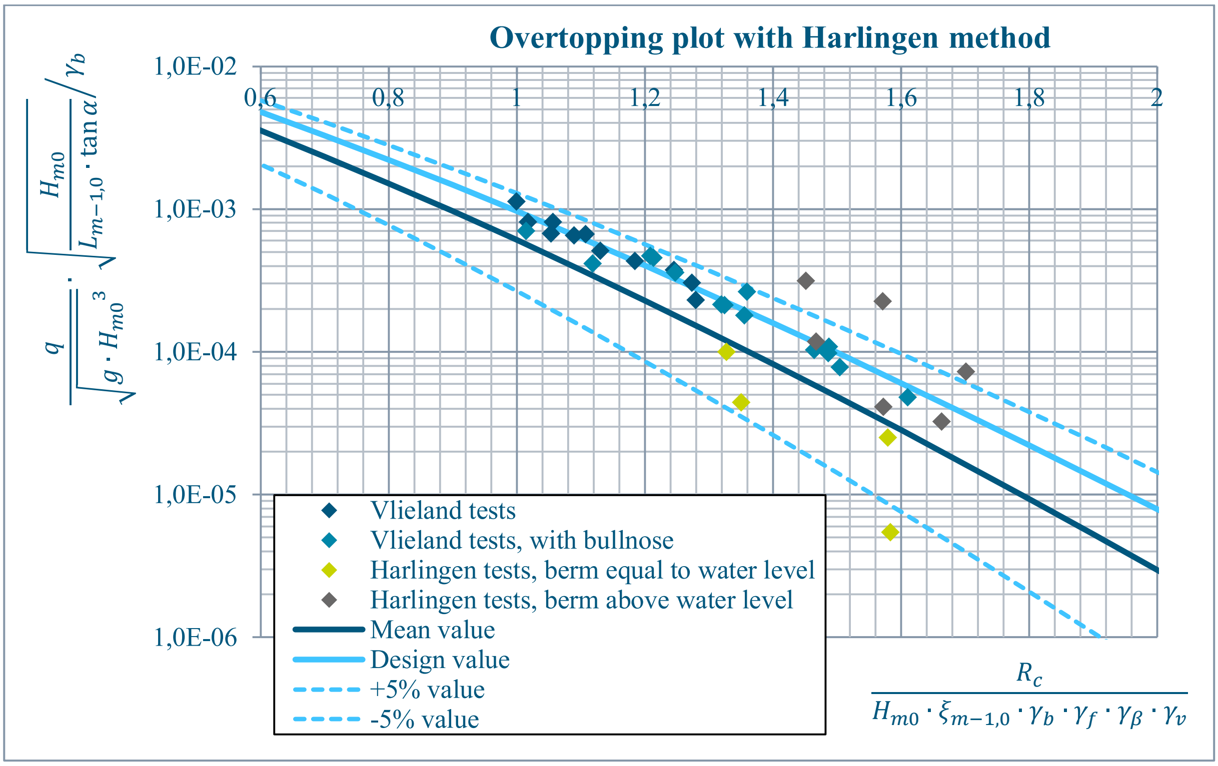

Fig. 5. Results of the Vlieland and selected Harlingen data with the Harlingen methodology

It can be seen from the figure that the fit is relatively good. However, the Vlieland data are more or less mainly about one standard deviation above the average trend line from Eq. [3]. Most measurements fall within the 90% confidence interval, except for a few Harlingen measurements.

3.2.2 Van Doorslaer approach

Van Doorslaer (2018) has tested a similar geometry as for the Vlieland tests, a dike slope 1:3 with berm/promenade and wave wall. Van Doorslaer used larger wave periods, leading to non-breaking waves, where Vlieland has short wave periods leading to breaking waves.

Van Doorslaer (2018) has also tested breaking waves, but the breaking is caused by a much more gentle dike slope of 1:6 in combination with periods that are larger than the Vlieland tests.

Both methods by Van Doorslaer (2018) will be used to plot the Vlieland and selected Harlingen dataset.

3.2.2.1 Van Doorslaer for non-breaking waves

The following equations are defined for non-breaking waves on a 1:3 slope with promenade and wave wall:

$$\gamma_v = exp\left(-0.56 \cdot \frac{R_c}{H_{m0}}\right) \quad [7]$$

$$\gamma_{prom} = 1 - 0.47 \cdot \frac{G_c}{L_{m-1,0}} \quad [8]$$

$$\gamma_{prom\_v} = 0.87 \cdot \gamma_{prom} \cdot \gamma_v \quad [9]$$

In this method by Van Doorslaer (2018) G_c represents the promenade. We use the berm width B for G_c. Eq. [7] to [9] are applied using the breaking waves overtopping Eq. [2] on the data of Vlieland and the selected Harlingen tests (even though Eq. [7] to [9] were defined for non-breaking waves). This leads to Fig. 5. The result is that quite some data now falls outside the confidence interval, meaning that the influence factor for non-breaking waves cannot be used for breaking waves.

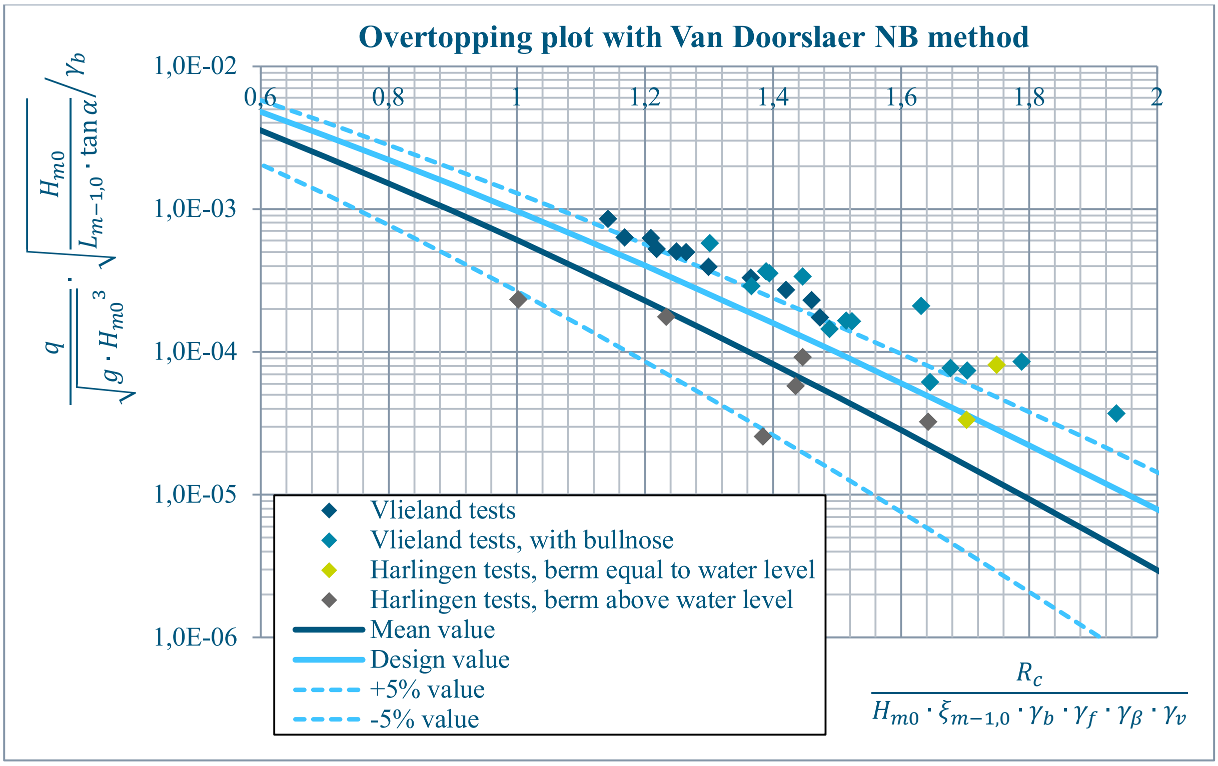

Fig. 5. Results of the Vlieland and selected Harlingen data with the Van Doorslaer (2018) non-breaking reduction factors used in Eq. [2] for breaking waves

3.2.2.2 Van Doorslaer for breaking waves

For breaking wave conditions Van Doorslaer only tested a 1:6 dike slope, both with and without wave wall. From this a reduction coefficient for the wave wall of $\gamma_v = 0.92$ was deducted. No tests with a berm/promenade were tested on this geometry, so no γ_b or γ_{prom} was analyzed in his research for breaking waves. Van Doorslaer advises not to combine this reduction factor for a wave wall (γ_v=0.92) with the ones for a berm/promenade (γ_b or γ_{prom}) derived for non-breaking conditions. Nevertheless, here this combination is tested on the selected data. As no method for the determination of the influence of the berm is provided, the method described by Van der Meer (1997) (see section 2.1) is tested. Results are displayed in Fig. 6.

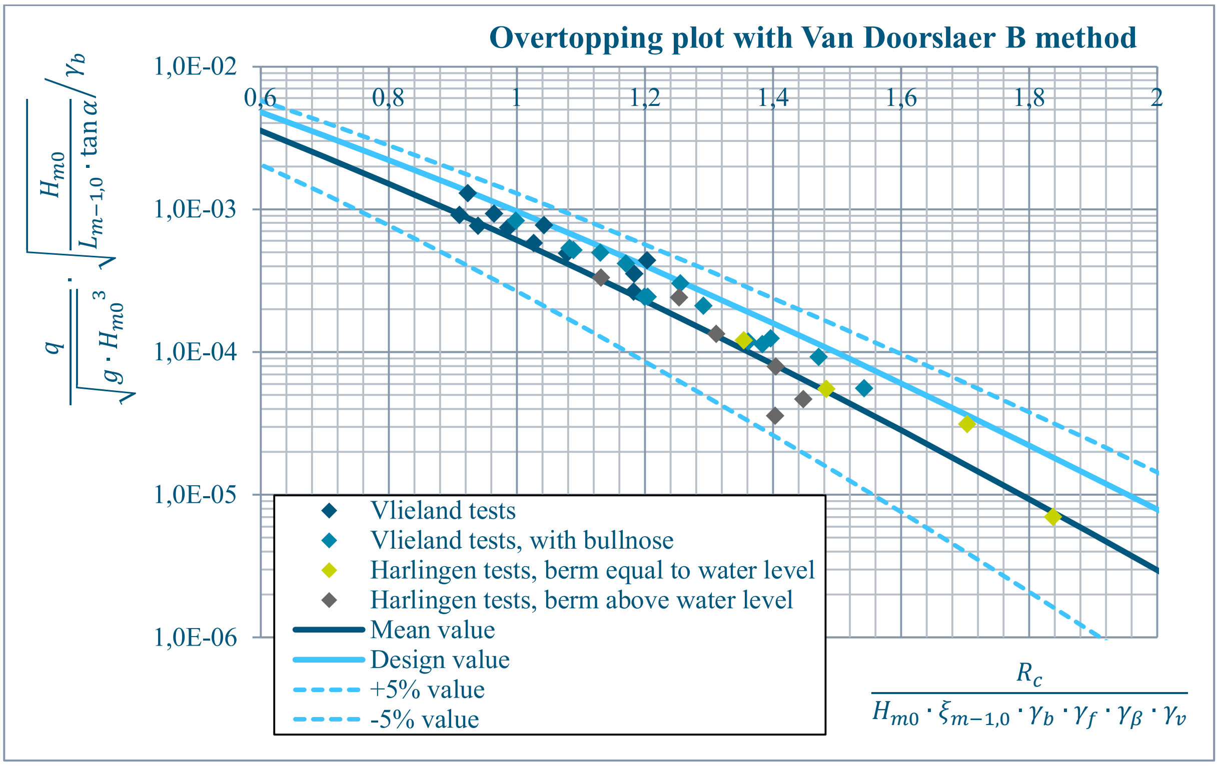

Fig. 6. Results of the Vlieland and selected Harlingen data with the Van Doorslaer (2018) breaking approach using the Van der Meer (1997) for the influence of the berm

As can be seen, the overtopping prediction is rather good. The spread of the data seems to be reduced in comparison to the other methods that have been tested. However, measured overtopping is on average somewhat higher than predicted by the method.

3.2.3 A newly proposed method

The previous sections have provided a fair, a bad and a rather good description of the data. In the next section, a new method is proposed to optimize the prediction for the presented data.

3.2.3.1 Description and analysis

The Harlingen method uses a fictive 1:1 slope where the wall is located. This makes the average slope milder compared to using the vertical wall. This average slope is particularly important for the breaker parameter: it is the slope that the wave "feels" when it breaks and rolls onto the dike. If the dike has different sections with different slopes, and the wave breaks on this slope, this is a logical approach. If however a wall is present at the top of the dike, above the design water level, this does most often not influence the breaking process on the dike slope, especially with the presence of a berm. The wave mainly breaks on the lower slope before it reaches the wall, as shown in Fig. 7. Off course, this also depends strongly on the water level. For the breaker parameter it would be more logical to only include the lower slope of such geometries. Using the actual (lower) slope instead of the average slope is for the same reason also done in Van Doorslaer (2018). In this newly proposed Vlieland method we also calculate the breaker parameter with the actual lower slope.

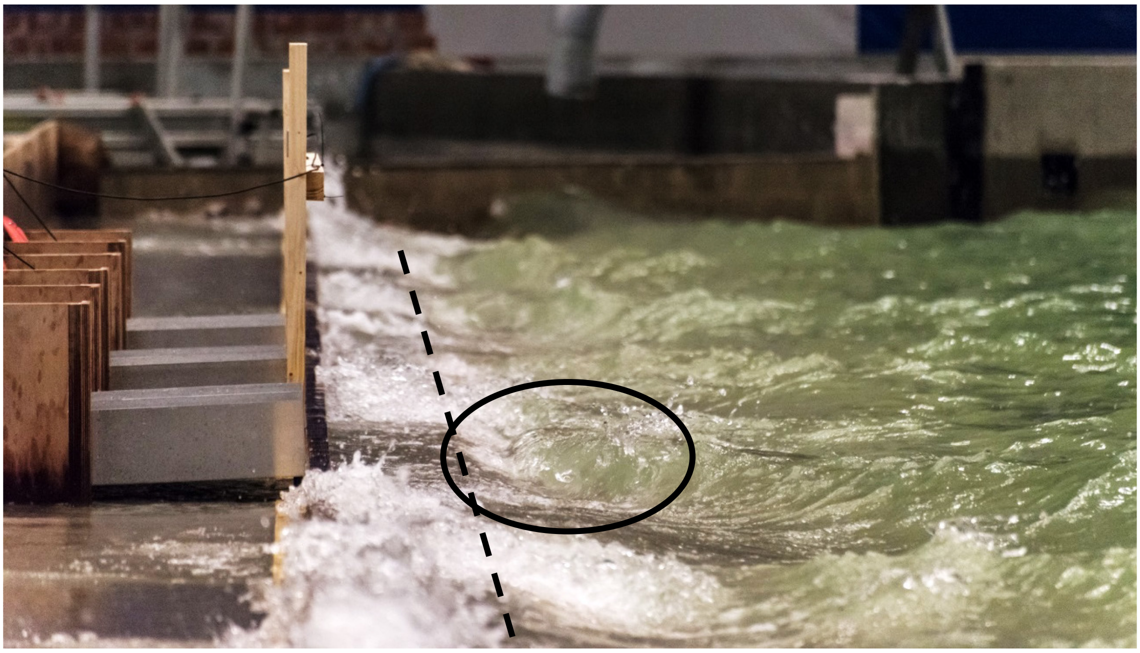

Fig. 7. Wave breaking on the lower slope

Since the lower slope is used for the breaker parameter, replacing the wall by the same slope is tested rather than replacing it with a 1:1 slope. Graphically this can be interpreted as displayed in Fig. 8. This serves as input for Eq. [5] to determine the influence of the berm.

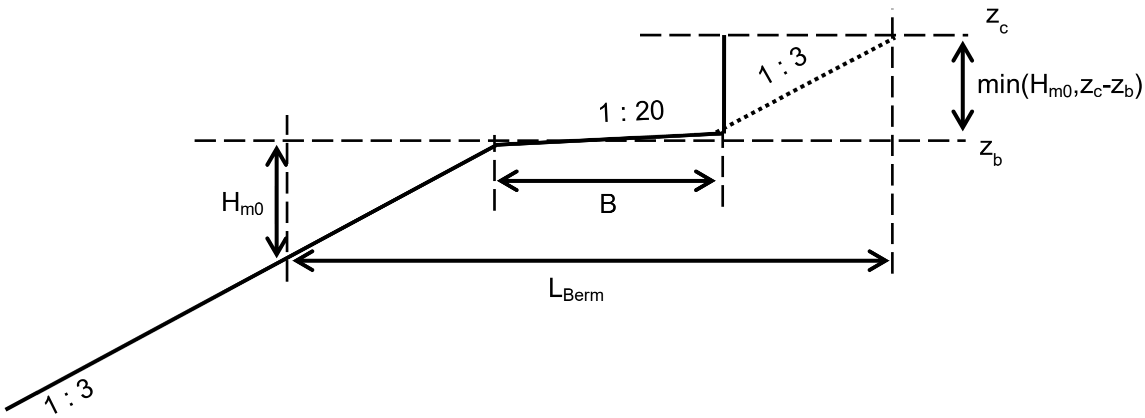

Fig. 8. Proposed interpretation of berm influence factor

Comparable to the Van Doorslaer (2018) method for breaking waves, a γ_v is deducted. For a 1:6 slope – without a berm – a value of γ_v = 0.92 was found. By means of a RMSE approach, using the data from both the Vlieland and Harlingen test for breaking wave conditions, a new value of γ_v = 0.84 is found for the 1:3 slope in these tests. The resulting overtopping plot is displayed in Fig. 9.

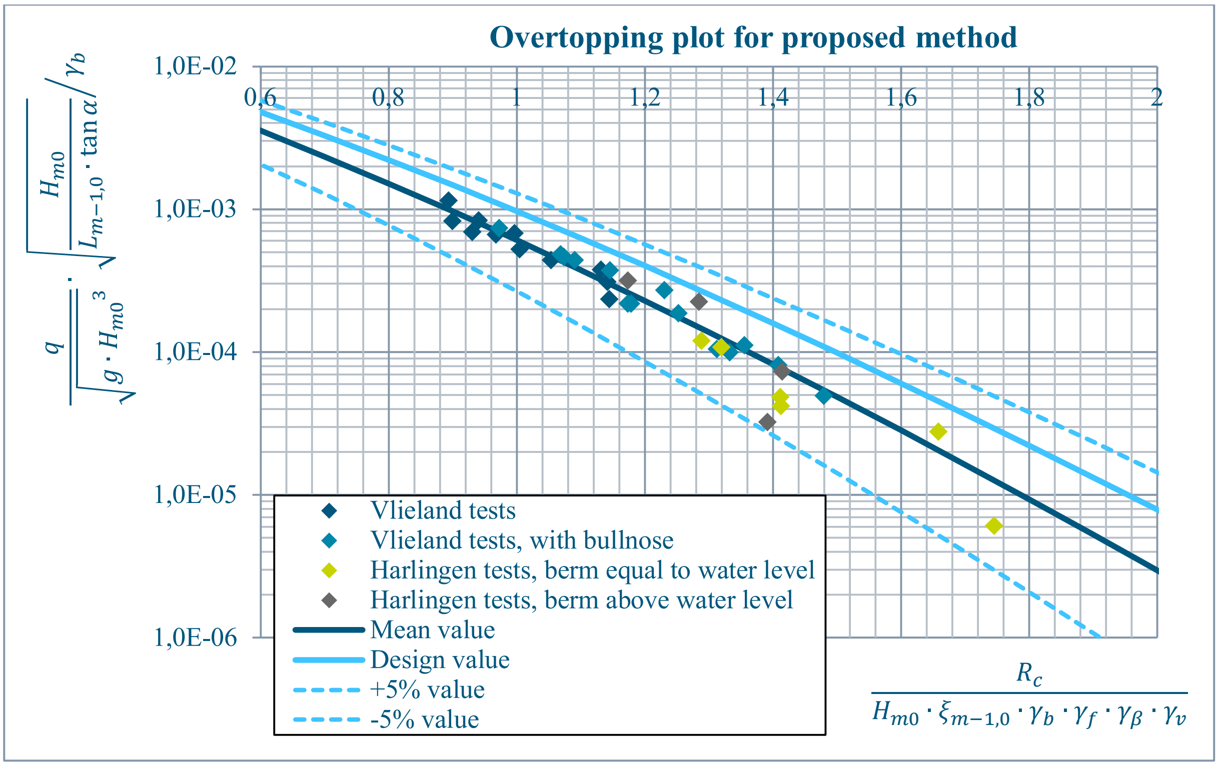

Fig. 9. Results of the Vlieland and selected Harlingen data with the new approach for breaking waves on a 1:3 slope

The method does not differ too much from the method described in section 3.2.2.2 in which Van Doorslaer (2018) on breaking waves is combined with Van der Meer (1997). Both use the lower slope for the breaker parameter and a replacement slope for the wave wall combined with a fixed influence factor γ_v for the wall. The only actual difference is the replacement slope for the wave wall, leading to a different γ_b and γ_v. The results hence also do not differ too much. Spreading of the data is about equal, but the average prediction error is less, which is because the data is fitted.

3.2.3.2 Applicability of the proposed method

The proposed method is tested on a limited set of test data. Within the limits of these test conditions, the new method holds. These limits have been summarized in the following table. It may well be that the actual limits are more flexible, however this requires additional tests.

Tab. 1. Limits of the applicability of the proposed method

Parameter	**Value**
Lower slope	1 in 3
Water level	Berm level or lower
Berm design	Such that $\gamma_b > 0.65$ (according to van der Meer (1997)) in which the wall is replaced by a fictive 1:3 slope
Wave height / wall height	$H_{m0} < 1.5$ * wall height, if water level is equal to berm level. Possibly higher if water level is lower, no exact limit known
Breaker parameter	$\xi_{m-1,0} < 2.0$
Wave steepness	Short-crested, $s_{m-1,0} > 5\%$
Angle of attack	≤ 50° with γ_β according to EurOtop (2018)

4 Conclusions and recommendations

Wave overtopping tests on a 1:3 dike slope, with a berm and wave wall were conducted in a wave basin. This paper has shown the validity of the influence factor for oblique waves to be used on the proposed geometry. For schematization of the berm and wave wall, also tests performed in Harlingen were included in our analysis. It was found that two methods seem to be valid to describe the overtopping discharges over these geometries well:

- Van Doorslaer (2018) for breaking waves with $\gamma_v = 0.91$ in combination with schematization of the berm by Van der Meer (1997) in which the wall is represented by a 1:1 slope.
- A newly proposed method in which the wall is represented by the same slope as a lower slope with $\gamma_v = 0.84$ for a 1:3 slope.

In both methods the value of the lower slope is used for the breaker parameter and the influence of the berm is determined by replacing the wall with a slope. This significantly reduces the spreading of the data.

It's not possible to promote one method over the other, since testing and the analysis has been done on a limited number of geometries, all of which the lower slope is 1:3. Van Doorslaer (2018) tested a 1:6 slope, but without the presence of a berm. Yet, the analysis has shown that results for both methods are promising. Therefore, to find out whether either of these methods is applicable for a wider range of geometries, further testing is recommended for the following situations:

- More accurate determination of the limits and applicability of the method, among such are:
    - Wider range of water levels;
    - Wider range of wave heights and wave steepness;
- Wider range of dike slopes to determine possible relationships between influence factors for the wall and slopes
- Wider range of berm width and wave wall height.

This may lead to more comprehensive understanding of the behavior of wave walls behind berms for design purposes. This can then be used for wider variety of types of coastal defense structures in which other functions such as a promenade function can be integrated with revetment design.

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