

SPATIAL DISTRIBUTION OF OVERTOPPING

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The scope of this research is to find an empirical formula to describe the distribution of wave overtopping in the region behind the crest. A physical model was set up in which irregular waves were generated. In order to find a formula which adequately describes the test observations, the influence of several parameters has been analysed. The proper determination of the crest freeboard, which is a dominant factor, has been investigated. Finally, the test results have been used to assess and compare the existing relevant computational methods.

Keywords: overtopping; rubble-mound breakwater; physical modelling; spatial distribution; crest freeboard

INTRODUCTION

The initial goal of this study was to develop a computational tool to calculate the wave overtopping discharge at certain point behind the crest of a simple rubble mound breakwater without any crest element (Figure 1). The computational methods of wave overtopping which are included in the coastal guidelines and manuals have been developed to calculate the discharge at top of the crest. However, for the design of some coastal protection structures the maximum tolerable discharge is specified at a certain point behind the crest. Therefore, the spatial distribution of overtopping can become an issue with significant impact on the design of the structure.

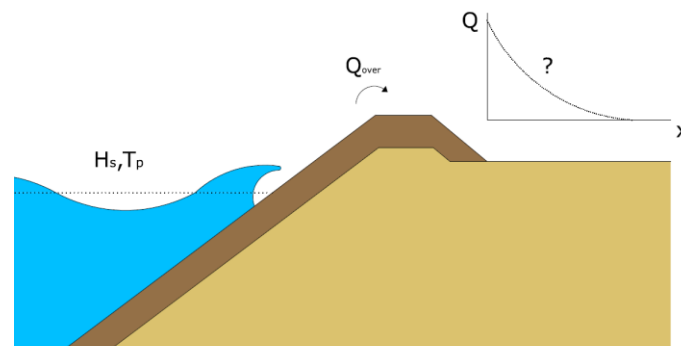


Figure 1. Research objectives.

This topic has been studied by Juul Jensen (1984), Besley (1999) and Lykke Andersen (2006) for different structural configurations. Juul Jensen's research was based on physical model tests of several rubble mound breakwater types. Lykke Andersen (2006), also based on a large physical modelling dataset, investigated the landward distribution of breakwaters with a crest element. Besley (1999) described the influence of a wide crest on the overtopping discharge by introducing a reduction factor. The last two methods are included in the EurOtop Manual (2007).

All the existing computational methods for overtopping are purely empirical. Thus, a similar approach to the previous studies has been used in this research, by means of experimental 2D testing. A physical model of a typical rock breakwater or revetment was set up in the wave flume of the Fluid Mechanics Laboratory of the TU Delft.

PHYSICAL MODEL

Wave flume

The experiments have been performed in the at the wave flume "Lange Spuurwerk Goot" at the Fluid Mechanics Laboratory of the TU Delft. It has a length of 40m and a cross-section of 0.80m x 0.80m (width x height). The wave generator in this flume operates with mechanical pressure. It is a second order wave generator which means that the second-order effects of the first higher and first lower harmonics of the wave field are taken into account in the wave generator motion. It is also

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equipped with Active Reflection Compensator (ACR) which reduces the wave reflection. The wave generator is controlled with the use of DASYLab, software developed by National Instruments®. The function of the generator is determined by a steering file which contains all the wave information: the requested wave height and period, the type of the spectrum (JONSWAP, Pierson/Moscowitz, simple sinusoidal etc.), its characteristics (peak-enhancement factor, peak-width factor) and the duration. In this research only JONSWAP spectra have been generated changing only the peak-enhancement factor from 3.3 to 9 for wind and swell waves accordingly.

Prototype and scale model

The prototype structure was a conventional rubble mound breakwater with a double rock layer on a permeable core. Since the scope of this study was the basic understanding of the overtopping processes, no further configurations (crest elements, toe or berm) have been considered. The hydraulic stability of the structure was determined with the use of the method proposed in the Rock Manual.

To fit properly in the wave flume the prototype structure was scaled with a factor 1:20. The rock properties were $D_{n50}=60\text{mm}$ and 25mm for armour layer and core respectively. The slope of the structure varied from 1:1.5 to 1:3. The armour layer thickness and the crest width were determined according to the Rock Manual; ie. $2*D_{n50}$ and $3*D_{n50}$, respectively. The crest level of the model was held constant and the freeboard was varied by adjusting the water level. The dimensions of the model are presented in the next figure (Figure 2).

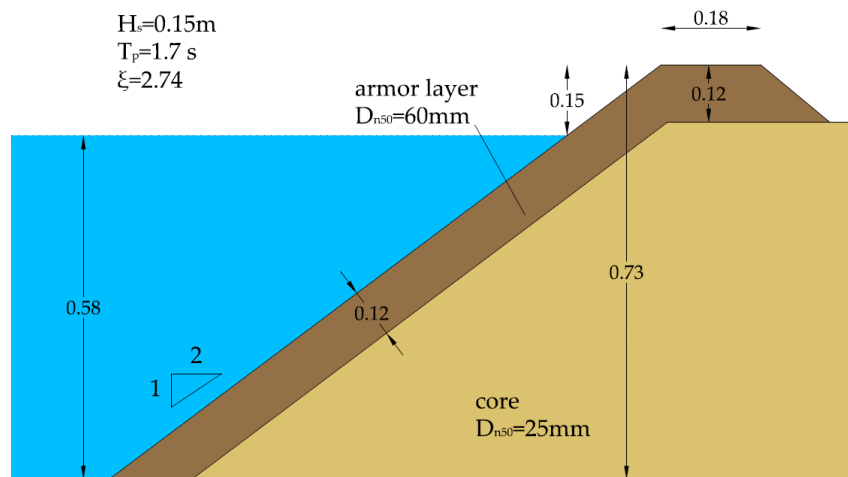


Figure 2. Physical model properties



Figure 3. Pictures of the scale model

Measuring system

A number of important issues had to be tackled in this model set-up. The first was that the measurement of the water in several locations behind the crest should be done within the same experiment in order to keep the test conditions constant for each experiment. To measure the overtopping discharge at several points simultaneously a series of splitting bins were installed in the backfill (the area behind the crest), separating the area into 6 sectors (see Figure 4). Since from the

related literature it was known that the decay of the overtopping is exponential, the width of these bins was not constant. The first two bins were 0.05m wide, the next two 0.10m and the last two 0.20m.

The next and more important issue which had to be solved was the water loss during the experiment. To measure the overtopping water it is extracted from the flume leading to (significant in this case) water loss. This loss results in reduction of the water level in the flume which means that the crest freeboard, which is one of the most influential factors, would not remain constant during the experiment.

This problem has been solved by storing the collected overtopping water into floating tanks behind the structure (collecting tanks – see Figure 4). In that way, the water which is initially collected into the splitting bins (sectors) is pumped into the floating tanks (one for each bin/sector). The free water flow through the core and below the bins ensured the equalisation of the water level in front and behind the model. In fact, the overtopping water stays inside the flume; it is only separated from the rest of the water. In this way the total amount of water in the flume was maintained during the experiment and the water level at the sea side of the model did not reduce because of the collection of overtopping water. Thus, the crest freeboard remained constant during the whole procedure.

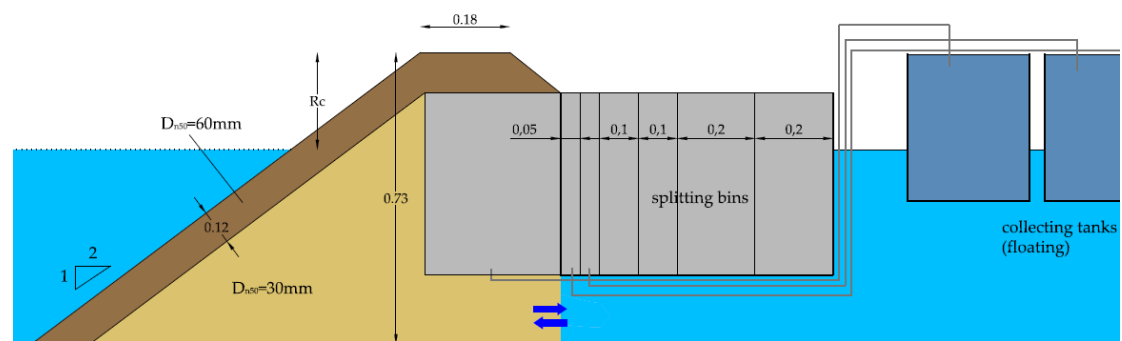


Figure 4. Measuring system

Test set-up and programme

Four parameters were varied in this research: the wave height, the wave steepness (period), the crest freeboard and the slope of the structure. The tested range of each parameter is listed below.

- Wave height: 0.08-0.10m (swells), 0.12m, 0.14m, 0.16m and 0.18m.
- Wave steepness: $1/20$ (≈ 0.05), $1/35$ (≈ 0.03), $1/50$ (≈ 0.02) and $1/200$ (≈ 0.005 – swells).
- Crest freeboard: $1 \cdot H_s$ and $1.5 \cdot H_s$. For the swells: $2 \cdot H_s$.
- Slope $\tan \alpha$: 1:1.5, 1:2 and 1:3

Each test consisted of a wave train of 1000 waves approximately. The generated spectrum was JONSWAP with peak enhancement factor equal to $\gamma = 3.3$ for all the experiments except from those with swell. In that case $\gamma = 9$.

During the literature study some ambiguities were found in the definition of the crest freeboard between different guidelines. To investigate this issue the entire test programme was later repeated (by Z. Afridi) with a “closed” (impermeable) crest as shown in the next figure.



Figure 5. “Closed” – impermeable crest.

RESULTS ANALYSIS

According to the existing relevant literature, the main input for the computation of the spatial distribution is the total overtopping. Although this process has been thoroughly studied by many researchers it is important to investigate the most suitable way to introduce it in this study and to use it in order to develop a computational formula for the spatial distribution. For this reason, even though the main topic of this research is the overtopping behind the crest, a large part of the analysis has been dedicated to the total overtopping.

Crest freeboard definition

According to the relevant literature two different definitions of the crest freeboard exist. The standard definition is described in the most of the guidelines as the vertical distance between the top horizontal part of the crest and the still water level. In Figure 6 it is defined as A_c . It must be noted that since the armour has a relatively rough surface, the determination of “the top horizontal part of the crest” can vary depending on the measuring method and equipment (e.g. semi-spherical or point staff). To avoid any confusion on this issue, in this research this level has been determined as the level of a thin plate placed on top of the crest and it coincides basically with the top part of the stones. This is commonly used as the “design crest level”. The other methods result in slightly lower levels.

In the EurOtop Manual it is suggested that for rubble mound structures without a crest element, the upper limit is the top level of the (impermeable) backfill or underlayer and not the top level of the rubble mound armouring. (The latter distance is called *armour* freeboard A_c). Thus the crest freeboard in this case is defined as the distance from still water level to the upper non (or only slightly) water-permeable layer (R_c in Figure 6).

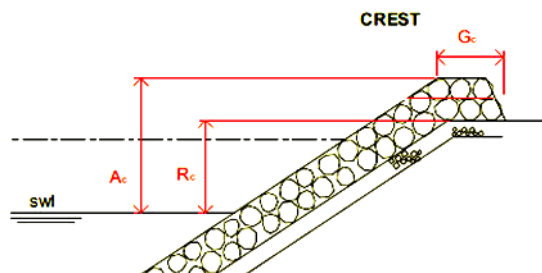


Figure 6: Crest freeboard definition according to EurOtop Manual

According to these definitions for the original scale model (see Figure 2) the freeboard is:

- 0,15m (standard definition, the permeable crest is taken into account)
- 0,03m (EurOtop suggestion, the permeable crest is not considered).

Figure 7 presents the data collected for the 1:2 slope using both definitions. In this graph, the data from tests with impermeable crest are also shown. (In this case there is no doubt about the freeboard: the full crest level should be applied). The line shown in the figure is the theoretical overtopping prediction using the EurOtop formula. All the data are plotted using the dimensionless parameters proposed by EurOtop: Q^* , dimensionless overtopping discharge and R_c^* , dimensionless freeboard.

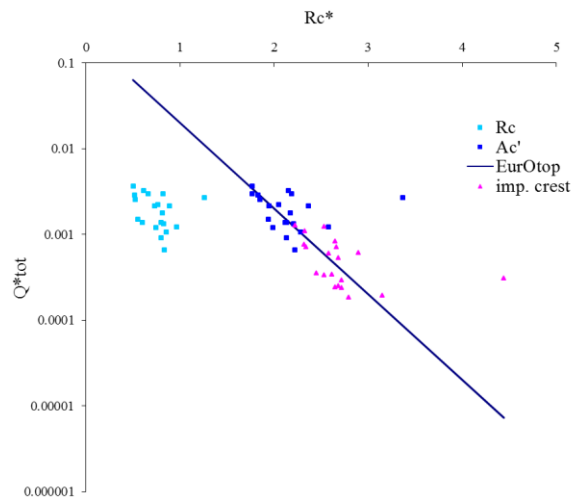


Figure 7: Total overtopping (in 1:2 slope) - Impact of the crest freeboard definition

The impact of the freeboard definition in this plot is apparent: depending on the definition the observations are shifted parallel to the X-axis (R_c^*).

When the EurOtop definition is applied, a considerable difference has been observed between the experimental data and the theoretical prediction. The prediction formula leads to significant overestimation, which can be explained by the fact that the entire crest has not been taken into account.

The use of the standard definition presented a better correlation with the theoretical line, but a general underestimation trend of the prediction formula has been observed. However, this is expected since the top layer of the crest is more permeable and allows more overtopping water to flow through it.

A better fit of the data with the theoretical line is achieved when the standard-defined freeboard has been reduced by $0.9 \cdot D_{n50}$ (denoted as $A_c' = A_c - 0.9 \cdot D_{n50}$ in Figure 7). Note that this reduction applies when the top level is measured in the previously described way.

In Figure 6, the results of the test with the “closed” or impermeable crest have also been plotted. They follow the same trend as the data with A_c' and they present an equally good fit with the EurOtop formula. This correlation enhances the idea that the standard definition (A_c') better describes the conditions of this model. For this reason, the analysis of the test results has been performed using the adjusted standard definition (A_c'). Since freeboard is always denoted as “ R_c ” in the entire relevant literature, to avoid confusion, this notation will be kept in this research also (instead of A_c').

Total overtopping

For the computation of the total overtopping, the EurOtop method has been used. This method makes a distinction between breaking and non-breaking wave conditions. The parameters that determine the whole process according to the method are:

- wave height
- wave period /steepness
- crest freeboard
- slope angle
- roughness
- angle of incident wave

The main difference between the two formulas is that the breaking-wave formula takes into account the wave steepness and the slope of the structure (with the introduction of the breaker number $\xi_{m-1,0}$ – computed with $T_{m-1,0}$) contrary to the non-breaking-wave formula, which implies that these two factors do not have any influence on the total overtopping.

The wave conditions applied in the entire experimental process have been chosen to be non-breaking (the breaker number $\xi_{m-1,0} > 2$ in all the tests) and thus according to the relevant formula of EurOtop the wave steepness and the slope of the structure shall not be taken into account. To obtain a better insight into the prediction method the influence of these parameters is shown separately.

Impact of the wave steepness

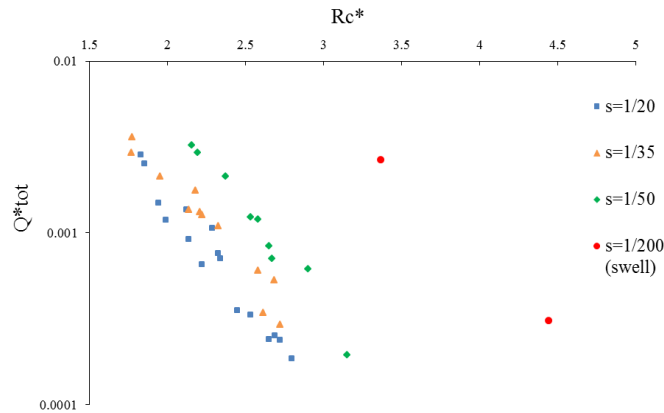


Figure 8: Total overtopping (in 1:2 slope) - Impact of the wave steepness

The test results for the total overtopping on 1:2 slope are presented in Figure 8. In order to check influence of the wave steepness (and period) on the prediction formula the observations are plotted against the dimensionless parameters proposed by EurOtop.

The main observation on this graph is that the measured overtopping discharges are clearly grouped according to wave steepness: longer waves produce larger overtopping and vice versa. Furthermore these groups follow the same trend. This implies that the wave period has some influence on the total overtopping.

Impact of the slope

Figure 9 presents the total overtopping measured for three different slopes: 1:1.5, 1:2 and 1:3. In the graph, the EurOtop formula is also denoted.

From this graph, it can be observed the data are grouped according to slope. Generally, a vertical shift of the data (parallel to y-axis) can be observed implying a relation between total overtopping and slope: steeper slopes result in higher overtopping rates.

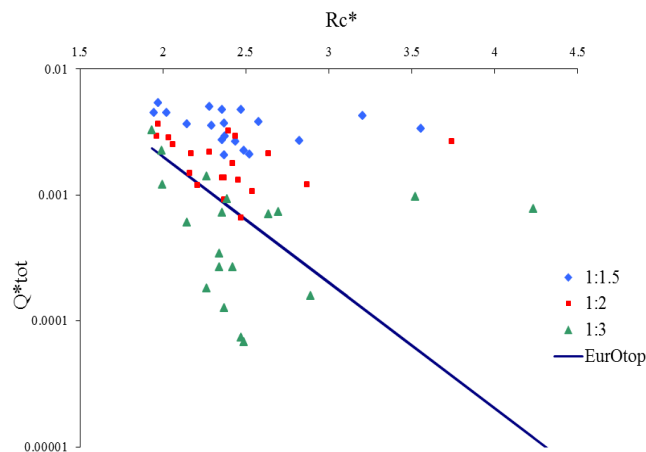


Figure 9: Total overtopping (all slopes) - Impact of the wave steepness

Compared to the EurOtop method, it seems that the prediction formula has a tendency to overestimate the overtopping discharge for mild slopes (1:3 and milder) and to underestimate it for steeper slopes (1:1.5).

EurOtop method - adjustment

The investigation of the impact of the wave steepness and slope showed that these two parameters were not irrelevant with the total overtopping. The existence of a scatter (caused by the wave steepness and slope) in the graphs presented above means that the dimensionless parameters (Q^* and R_c^*) do not properly describe this influence of the wave period.

Since these two parameters are already introduced in the EurOtop formula for breaking waves (with the use of the breaker number ζ), the first and more logical attempt to solve this issue is to use this formula instead of the non-breaking which is suggested in the manual. The graph in Figure 8 present the entire dataset plotted according to the breaking-wave formula. Note that the axes are adjusted accordingly.

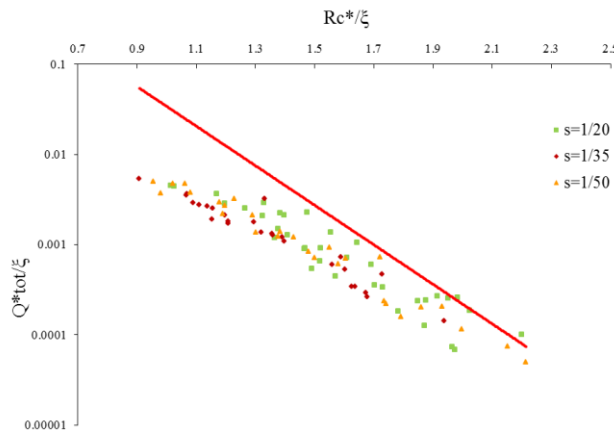


Figure 10: Total overtopping – Breaking-wave formula

This graph shows a better correlation between the measurements and the prediction, compared with the graph plotted with the non-breaking-wave formula (Figure 8). The scatter is smaller and the measurements lay closer to the EurOtop line. Even the data from tests with very long waves (swells) stay closer to the other experiments and to the theoretical prediction line. This implies that wave period/steepness is well introduced with the parameter R_c^*/ξ_0 ($R_c^*/\xi_{m-1,0}$).

The second observation when comparing the these two graphs (Figure 8 and 10) is that while in Figure 8 the non-breaking-wave formula was underestimating the results (especially for longer waves), in the later it happens exactly the opposite: breaking-wave formula overestimates all the data, notably those with small steepness (large period). This means that in the first case the breaker number is “under-represented” and in the second “over-represented”.

The latest remark leads to the conclusion that an intermediate solution would solve this issue. Since the only change between the two formulas is the breaker number ζ_0 , it is suggested to be raised in a power k (with $0 < k < 1$). The constant values of the formulas are also linearly interpolated based on the value of power k . The resulting formula is the following:

$$\frac{Q}{\sqrt{gH_{m0}^3}} = (0.2 - 0.133 \cdot k) \cdot \left(\frac{\gamma_b \cdot \xi_0}{\sqrt{\tan a}} \right)^k \exp \left[- (2.6 + 2.15 \cdot k) \frac{R_c}{H_{m0} \gamma_f \cdot \gamma_\beta \cdot (\gamma_b \cdot \gamma_v \cdot \xi_0)^k} \right] \quad (1)$$

This formula is in fact a generic form of the standard EurOtop method which combines both formulas: if power k is 1 the breaking-wave formula is formed and when $k=0$ the non-breaking-wave.

For the test results of this experimental research the k -value which presented the best fit was $k=0.60$. According to EurOtop for this case the roughness factor γ_f should be 0.4 (for two layers of armour stone over permeable core). A better fit has been achieved with $\gamma_f = 0.45$ which is reasonable since the permeability of the core in this model has been affected from the wall of the splitting bin

installed under the crest (see Figure 4). The reduction factors for berm and vertical walls are 1 in this case and thus it cannot be concluded from this study if they should be raised to the power k . For mathematical consistency reasons they are presented in this form; however further investigation is strongly recommended in case of structures with berm or vertical wall.

Figure 11 presents all the results plotted against the adjusted EurOtop formula (1). Note that both axes have changed accordingly: the x-axis is R_c^*/ξ^k (instead of R_c^* or R_c^*/ξ_0) and the y-axis has changed to $Q^*/(\gamma_b \cdot \xi_0 / \sqrt{\tan \alpha})^k$. For practical reason the later will be denoted as Q^*/ξ^* in the graphs.

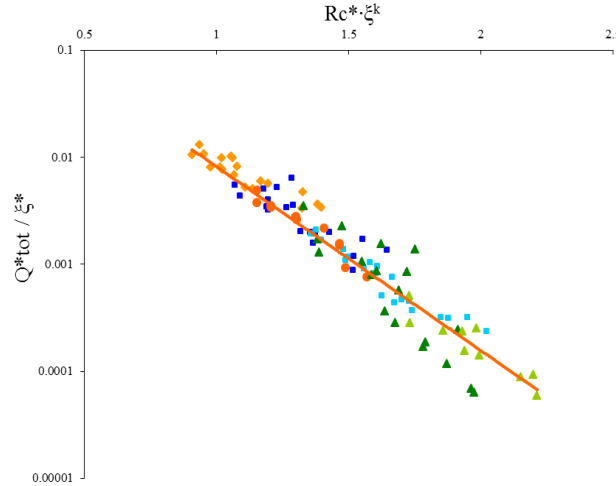


Figure 11: Total overtopping – Adjusted EurOtop formula (with $k=0.6$)

The graph in Figure 11 shows an improved fit of the results. No obvious grouping can be observed: all the results (both for “open”/permeable and “closed” crest) follow the same trend which coincides with the adjusted theoretical line. This leads to the conclusion that the breaker number (and thus the wave steepness and slope) is properly introduced in the prediction formula.

Since with the adjusted formula a better correlation is achieved which means that the process is better described, for the next steps of this research (determination of the spatial distribution) the total overtopping will be computed using this method.

Spatial distribution

The landward region of coastal protection structures consists of two areas: the crest and the backfill. These two surfaces have different physical characteristics (geometry, roughness and permeability) and as consequence the flow of overtopping water on/through them may deviate. For this reason, in order to define the spatial distribution in the backfill it is suggested to estimate first the overtopping directly behind the crest and use it as an input for the landward distribution.

Overtopping directly behind the crest

Initially the test results directly behind the crest are plotted with the adjusted EurOtop formula (Figure 12a) in order to compare them with the total overtopping and have a first idea of the reduction. The main observation on this graph is first that the reduction in the water quantities is uniform and secondly that the results follow a common trend which is similar to the total overtopping prediction. The later leads to the conclusion that the same parameters are dominant in this case also and that the prediction formula could be used as a basis to describe the overtopping at this point.

Similarly to the other reduction factors of the method (for berm, oblique waves, roughness and vertical walls) a new reduction factor γ_c is proposed to be introduced in the adjusted EurOtop formula (1):

$$\frac{Q}{\sqrt{gH_{m0}^3}} = (0.2 - 0.133 \cdot k) \cdot \left(\frac{\gamma_b \cdot \xi}{\sqrt{\tan \alpha}} \right)^k \exp \left[-(2.6 + 2.15 \cdot k) \frac{R_c}{H_{m0}} \frac{1}{\gamma_f \cdot \gamma_\beta \cdot (\gamma_b \cdot \gamma_v \cdot \xi_0)^k \cdot \gamma_c} \right] \quad (2)$$

In Figure 12b the test results are plotted relatively to the formula (2). The best fit has been achieved for a $\gamma_c=0.6$.

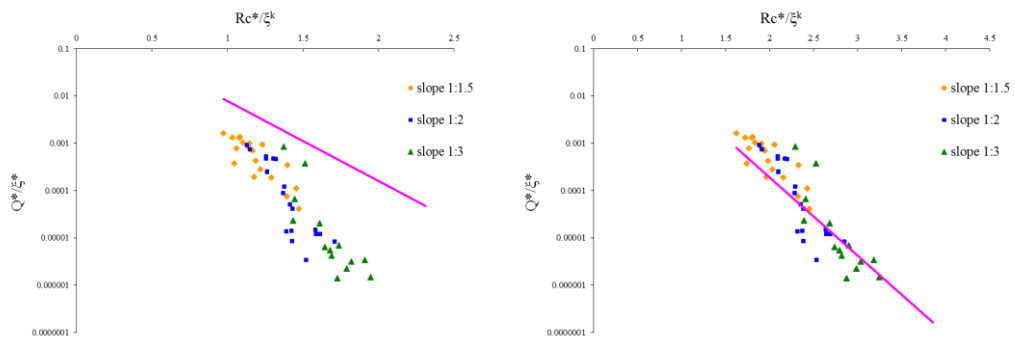


Figure 12: Overtopping directly behind the crest – Adjusted EurOtop formula for a) $\gamma_c=1$ and b) $\gamma_c=0.6$

Spatial distribution

Since a correlation between the adjusted EurOtop formula (2) and the test findings was found (with the introduction of reduction factor γ_c), the data collected for certain distances behind the crest will be presented again in the same way.

For each point a range of values of γ_c have been tested in order to achieve the best fit. For locations further from the crest, the spread of the results is larger. This is expected because at this points the measured water quantities were very small and thus the relative error was large.

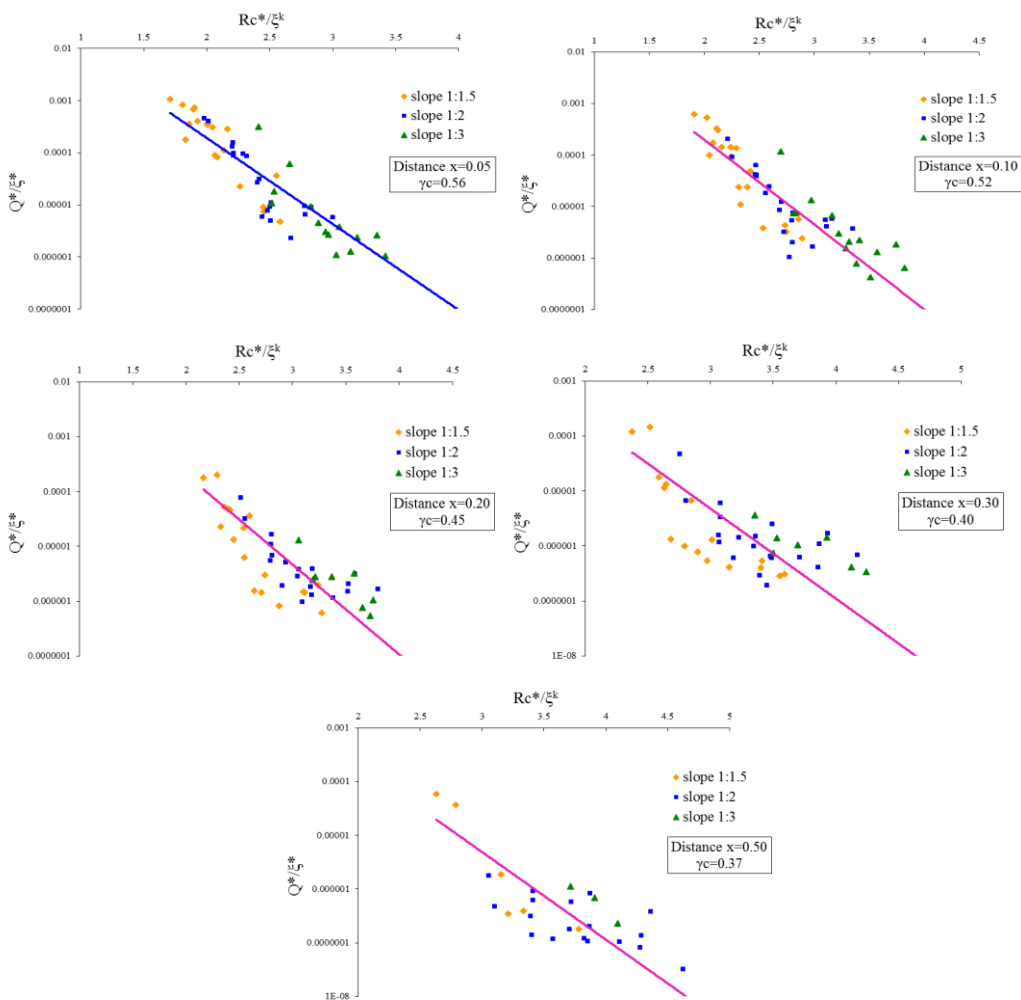


Figure 13: Overtopping at certain points behind the crest

In general it can be concluded that the test results follow the same trend as the prediction line and they present a good correlation with the adjusted EurOtop formula.

It must be noted that the analysed dataset contains a large range of wave and structural conditions: the breaker number ξ varies between 2 to more than 9, the slope varies from 1:1.5 to 1:3, different freeboards and crest configurations (“open”/ “closed”) have been tested. However it is validated only for this type of structure; even though this is a typical and representative structure, for different configurations the use of this prediction formula shall be further studied.

Since according to the literature (Juul Jensen (1984)) one of the dominant parameters in the spatial distribution is the crest width B (also denoted as G_c in literature e.g. EurOtop – Figure 6), the change of new reduction factor γ_c is suggested to be plotted as a function of it (Figure 14). In this way γ_c is expressed in a dimensionless form which makes it easier to be applied.

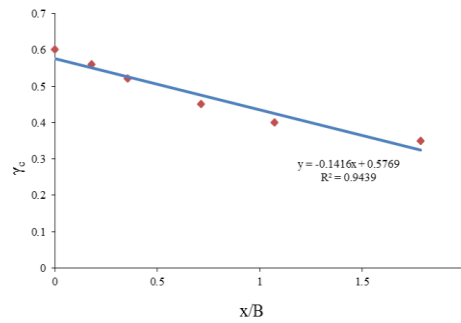


Figure 14: Distribution of the new reduction factor γ_c

From Figure 13 it is observed that the various γ_c values can be connected linearly with the following simplified formula:

$$\gamma_c = -0.142 \cdot \frac{x}{B} + 0.577 \quad (3)$$

Remark: The distance starts measuring from the point where the crest ends. This means that for $x=0$, the reduction factor for the overtopping directly behind the crest is calculated.

COMPARISON WITH EXISTING METHODS

The findings of this research has been analysed and compared with the most relevant methods on this issue which are that of Juul Jensen (1984) and Besley (1999).

Juul Jensen

Juul Jensen’s method uses two main input parameters to predict the spatial distribution: the overtopping intensity directly behind the crest and a β factor which is a function of crest width B . Concerning the first parameter, it is derived from the total overtopping (not computed in the same way as the EurOtop method). According to the result analysis presented previously this may lead to a (considerable) overestimation. Thus to do a proper assessment of the method it is proposed to use the overtopping-directly-behind-the-crest instead.

Since the number of tests was significant only the results of two representative tests are presented: one with relatively steep waves ($s=1/20$) on 1:2 slopes (Figure 15a) and another with longer waves ($s=1/35$) on slope 1:1.5 (Figure 15b).

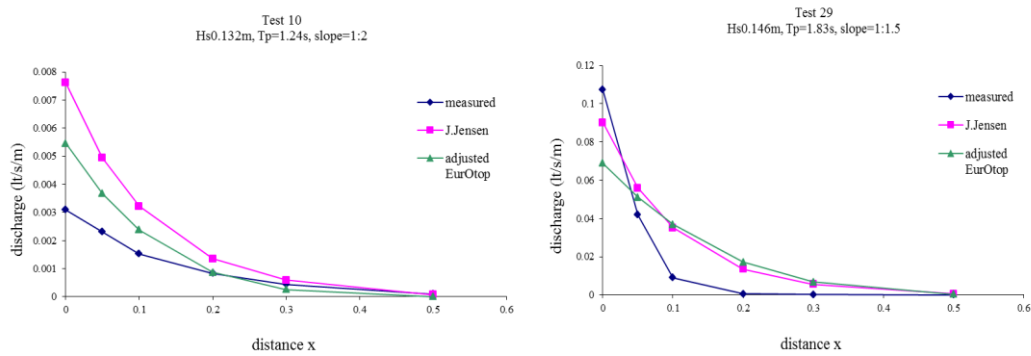


Figure 15: Distribution of overtopping (comparison with Juul Jansen method)

Most of the comparison graphs presented the same pattern as Figure 15a. From these graphs it can be seen that the Juul Jensen method (with the proposed adjustment) describes reasonably well the distribution of overtopping. The shape of the decay coincides with both measured and predicted with adjusted EurOtop formula. Some tendency for overestimation has been observed when compared with the results of this research but generally the deviation was not considerable in most of the cases.

Figure 16 presents an overall comparison between the measured and the computed with Juul Jensen method results.

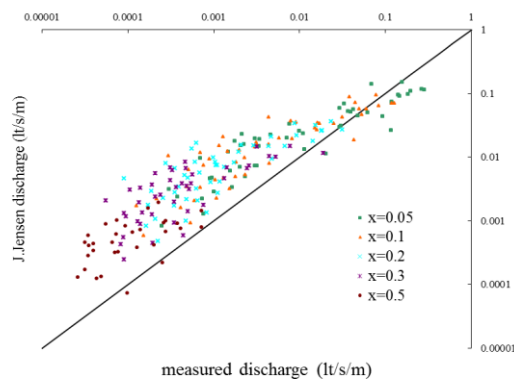


Figure 16: Comparison between Juul Jensen and measured overtopping

The largest spread is observed for smaller overtopping discharges. In reality though this difference is trivial (in the order to magnitude of 10^{-4} - 10^{-5} l/s/m) and it can be explained by the fact that these test results concerned very small water quantities where the accuracy in the measurement has been dominated by model effects.

Besley

Besley’s method is included in the EurOtop Manual as a simple way to describe the effect of a wide crest. The idea is to use a factor C_r to express the reduction of total overtopping at certain distance.

Figure 17 presents the test results with the use of the Besley method.

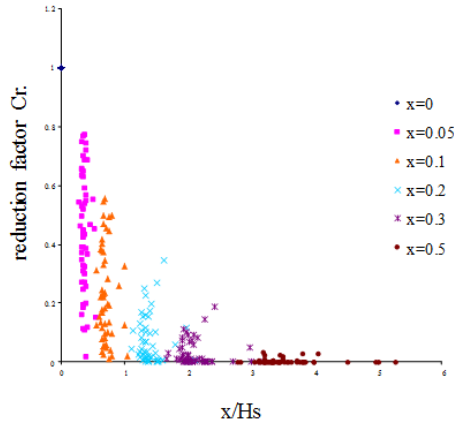


Figure 17: Overtopping distribution (Besley method)

This graph shows that no correlation between the predicted and measured data exists. The shape of the decay (exponential) is well predicted but the spread of the result is significant. This can be explained by the fact that this method takes into account only the wave height. Furthermore it was not originally developed to predict the distribution of overtopping but the effect of a wide crest.

CONCLUSIONS AND RECOMMENDATIONS

The main goal of this research has been to study, by means of physical modelling, the spatial distribution of overtopping in the area behind the crest. The main input of this process is the total overtopping and thus it has been further investigated. From the study the following can be concluded:

- The standard crest freeboard definition reduced by $0.9 \cdot D_{n50}$ presented better results compared with the EurOtop definition.
- The total overtopping has been better described with an adjusted version of EurOtop formula:

$$\frac{Q}{\sqrt{gH_{m0}^3}} = (0.2 - 0.133 \cdot k) \cdot \left(\frac{\gamma_b \cdot \xi_0}{\sqrt{\tan a}} \right)^k \exp \left[-(2.6 + 2.15 \cdot k) \frac{R_c}{H_{m0}} \frac{1}{\gamma_f \cdot \gamma_\beta \cdot (\gamma_b \cdot \gamma_v \cdot \xi_0)^k} \right] \quad (1)$$

For the test results of this study the best fit has been achieved for $k=0.6$.

- For the spatial distribution a new reduction factor γ_c is introduced in the adjusted EurOtop formula:

$$\frac{Q}{\sqrt{gH_{m0}^3}} = (0.2 - 0.133 \cdot k) \cdot \left(\frac{\gamma_b \cdot \xi_0}{\sqrt{\tan a}} \right)^k \exp \left[-(2.6 + 2.15 \cdot k) \frac{R_c}{H_{m0}} \frac{1}{\gamma_f \cdot \gamma_\beta \cdot (\gamma_b \cdot \gamma_v \cdot \xi_0)^k \cdot \gamma_c} \right] \quad (2)$$

This factor is expressed as a function of crest width B and can be determined by the following formula:

$$\gamma_c = -0.142 \cdot \frac{x}{B} + 0.577 \quad (3)$$

- The Juul Jensen (1984) method presents good correlation compared with the test results when the overtopping-directly-behind-the-crest is used as an input instead of the total overtopping.
- No correlation between the Besley (1999) method and the adjusted EurOtop could be found.

Based on the findings of this study the following recommendations are given:

- The analysed dataset contains a large range of wave and structural conditions: the breaker number ξ varies between 2 to more than 9, the slope varies from 1:1.5 to 1:3, different freeboards and crest configurations (“open”/ “closed”) have been tested. However it is validated only for this type of structure; even though this is a typical and representative structure, for different configurations the use of this prediction formula shall be further studied.

- The effect of other parameters such as berm, oblique waves, crest width etc. are not taken into account; for such cases the presented theory shall be further studied.

ACKNOWLEDGMENTS

The contribution of Zirgham Afridi (exchange MSc student from Imperial College, UK at the time that the physical modelling had been performed) who conducted part of the experimental procedure ("closed"/impermeable crest tests) is greatly acknowledged. The comments and corrections made by Jan Kees Krom, MSc student at TU Delft and intern in Van Oord, are highly appreciated.

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