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EXPERIMENTAL STUDY ON THE EFFECT OF THE WAVELENGTH ON WAVE OVERTOPPING RATE OVER RECURVED WALLS

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ABSTRACT

Wave overtopping phenomenon on vertical breakwaters is influenced by various physical parameters, encompassing wave height, period, water depth at the breakwater, breakwater freeboard, and foreshore steepness. Existing equations for estimating overtopping rates predominantly rely on the relative freeboard (R_c/H_{m0}) as the key parameter. This study highlights a significant deviation from this conventional approach when utilizing a recurved wall instead of a plain vertical wall, emphasizing the necessity to consider additional parameters, particularly wave period. In our quest for enhanced accuracy in estimating wave overtopping over recurved breakwaters, we have used $F'=R_c/\ (H_{m0}^2\ L_p)^{1/3}$, as a replacement for the conventional relative freeboard. Comparative analyses reveal that the proposed formulas for both impulsive and non-impulsive waves exhibit superior accuracy compared to existing formulas. Nevertheless, it is noteworthy that, for larger relative freeboards, a robust formula for estimating wave overtopping remains elusive.

KEYWORDS: Wave Overtopping, Relative Freeboard, Wave Period, Non-Dimensional Parameter, Prediction Formula

1 INTRODUCTION

Vertical breakwaters are an important type of coastal structures, to protect infrastructures, harbours, and people from direct exposure to waves. Wave overtopping on the other hand is an unavoidable phenomenon which can endanger what the breakwaters must protect and also the stability of the breakwater itself. Therefore, having a realistic estimation of wave overtopping is essential in the design process, to minimize the risk of damage to infrastructures, harbours and people. Recurved walls are used as an option to reduce wave overtopping over breakwaters and create a safer leeside during the storms. However, the mechanisms determining their effectiveness in terms of reducing the overtopping rate are complex and not yet fully described (EurOtop, 2018).

Wave overtopping over vertical breakwater is a complex phenomenon and depends on different structural and hydrodynamic parameters including wave height and water depth at the toe of the breakwater, wave period, wavelength, and breakwater freeboard. However, most of the available equations to estimate the overtopping rate over vertical breakwaters correlate only to the relative freeboard and neglecting other influencing parameters e.g., Goda (2009) or van der Meer & Bruce (2014). Other approaches like Etemad-Shahidi et al. (2016) and Shaeri & Etemad-Shahidi (2021) on the other hand include several parameters, resulting in very complex equations which are difficult to use during design process. All of the strictly valid only for vertical breakwater without a recurved wall.

Adding a recurved wall to the breakwater increased complexity of the hydrodynamic process resulting in overtopping, adding parameters, such as the size and shape of the recurved wall. It can also increase the influence of other parameters, e.g. the wave period and water depth at the toe of the breakwater, which become more significant when a recurve is added to the top of the breakwater or revetment (Kortenhaus et al. (2002) and Pearson et al. (2005)). However, the same studies prefer to neglect the effect of the wave period on the overtopping rate, probably for simplicity reasons.

In this research, the effect of these parameters (wave period, water depth at the toe of the breakwater) on wave overtopping rates is investigated for vertical walls with a recurved wall on top. The main goal was to investigate all relevant parameter, with effect on the overtopping rate and to increase accuracy of the prediction formula, while keeping its simplicity. For this study, data from the so-called SABAII project (a commercial port study for the Caribbean Island SABA) conducted at Ghent University and a selected part of the EurOtop database are used.

2 EXPERIMENTAL SETUP

A series of wave overtopping tests were conducted at the wave flume at the Department of Civil Engineering at Ghent University during the period of December 2020 to February 2021, to validate the design of main breakwater for SABA island new port breakwaters. The wave flume has a length of 30.00 m, a width of 1.00 m and a height of 1.20 m. A wave paddle equipped with an active wave absorption system generates regular and irregular waves.

The 1:20 model vertical breakwater were constructed on a 1:16 slope foreshore with intermediate water depth. In this situation, the shore has influence on wave condition and therefore water depth at the toe of breakwater becomes important as well. This situation is called influencing foreshore in EurOtop 2018. Figure 1 shows a schematic view of the wave flume and its equipment. Both plain vertical and recurved breakwaters were tested. The recurved wall breakwaters were built by adding a 45° parapet, with height and wide of 2.5 cm on top of the original vertical breakwater (Figure 2). Table 1 provides a summary of the hydrodynamic and structural conditions for the 1:20 scale models of vertical breakwaters, both with and without a parapet. Additionally, it presents the corresponding wave overtopping discharge values for each conducted test.

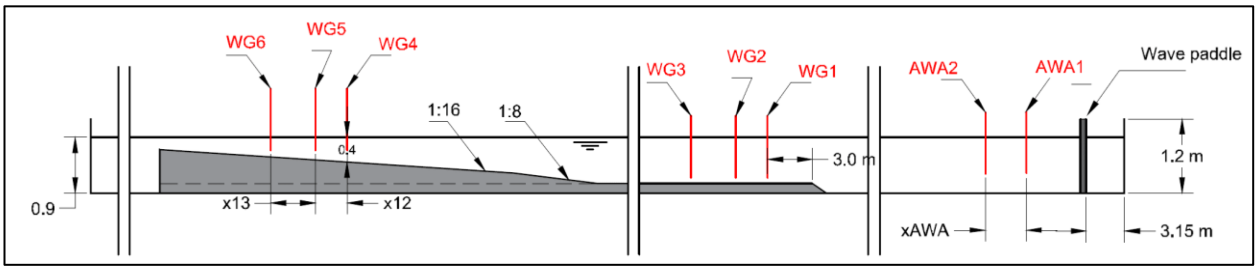

Figure 1 Schematic view of model and measurement set-up in the Ghent University wave flume (all values in model scale)

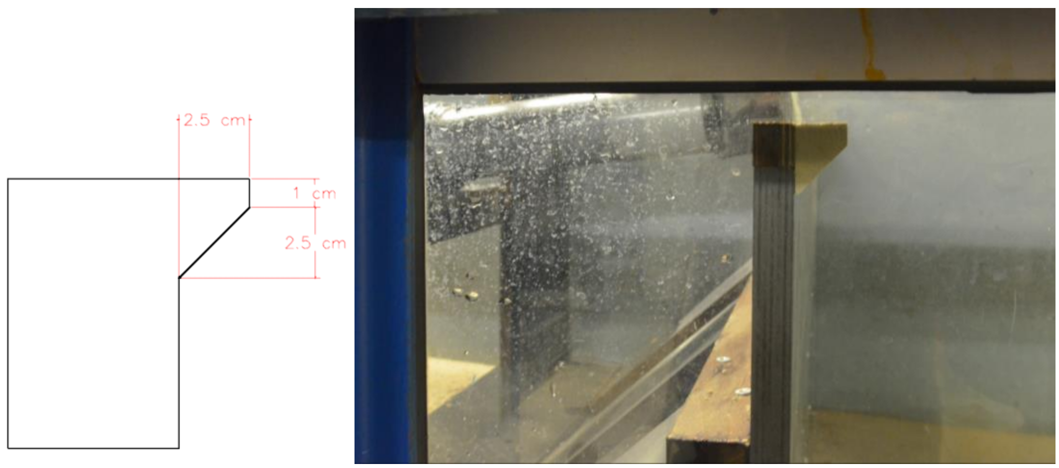

Figure 2 Properties of the parapet installed on the crest of the vertical wall to reduce the overtopping (all values in model scale)

Table 1. Test condition for wave overtopping over model vertical breakwater (all values in model scale)

Test ID	Parapet	H_s (m)	T_p (s)	R_c (m)	Averaged overtopping discharge (l/s/m)
O1	No	0.09	2.24	0.17	0.030
O2	No	0.09	3.2	0.17	0.031
O3	No	0.10	2.24	0.17	0.067
O4	No	0.10	3.01	0.17	0.061

O5	No	0.09	2.24	0.19	0.018
O6	No	0.09	3.2	0.19	0.019
O7	No	0.10	2.24	0.19	0.042
O8	No	0.10	3.01	0.19	0.034
O9	No	0.09	2.24	0.21	0.008
O10	No	0.09	3.2	0.21	0.009
O11	No	0.10	2.24	0.21	0.020
O12	No	0.10	3.01	0.21	0.015
O14	Yes	0.09	2.24	0.19	0.001
O15	Yes	0.09	3.2	0.19	0.009
O16	Yes	0.10	2.24	0.19	0.007
O17	Yes	0.10	3.01	0.19	0.014
O18	Yes	0.09	2.24	0.17	0.013
O19	Yes	0.09	3.2	0.17	0.025
O20	Yes	0.10	2.24	0.17	0.032
O21	Yes	0.10	3.01	0.17	0.047

3 RESULTS AND DISCUSSION

Figure 3 illustrates the non-dimensional overtopping rate q* (=$q/(gH_{m0}{}^{3})^{0.5}$) versus the relative freeboard for tests in Table 1. The blue triangles represent the overtopping results for vertical breakwaters, while the red diamonds depict overtopping on a vertical wall with a parapet. The gray dashed line corresponds to the EurOtop 2018 estimation for wave overtopping rate over vertical breakwaters with influencing foreshore under action of non-impulsive (or deflecting) waves (numbered as Equation 7.5 in EurOtop 2018) mirroring the current modeling conditions for plain vertical breakwaters. Equation 7.5 from EurOtop (20218) is given below:

$$q^{*} = 0.05\exp\left(-2.78\left(\frac{R_c}{H_{m0}}\right)\right) \quad (1)$$

As evident in this figure, this equation underestimates the wave overtopping rate for vertical breakwaters to some extent (dashed line is systematically lower than blue dots). Nevertheless, it is noteworthy that, adding a parapet to the vertical wall could greatly decrease the rate of overtopping (red dots systematically lower than blue dots). However, it is also noted that in case of adding a recurved wall, noticeably different overtopping rates are observed (red dots) even for the same relative freeboard, while it is not the case for the vertical breakwater only (blue dots).

To investigate the reason behind these conspicuous differences, the non-dimensional overtopping rates are plotted versus relative freeboard, distinguishing the wave periods by different colors in Figure 4-A for vertical breakwaters and Figure 4-B for vertical breakwater with parapet. The figures reveal that, in the case of a vertical wall, the influence of wave period on wave overtopping is not prominent. Conversely, for vertical breakwaters with a parapet or recurved wall, larger wave periods result in noticeably higher wave overtopping rates for the same relative freeboard.

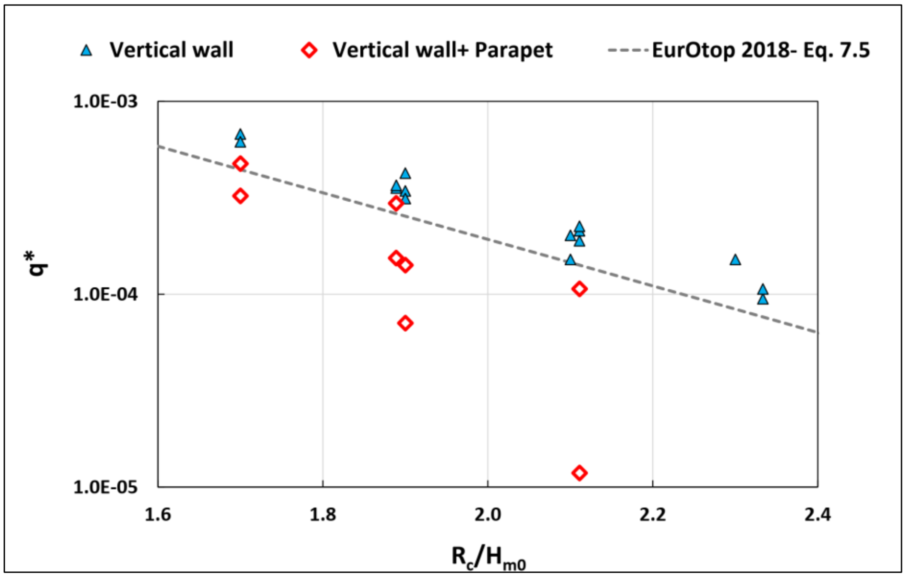

Figure 3 Comparison of non-dimensional wave overtopping rates q* over relative freeboard R_c/H_{m0} for vertical wall (blue dots) and vertical wall with a recurved wall (red dots)

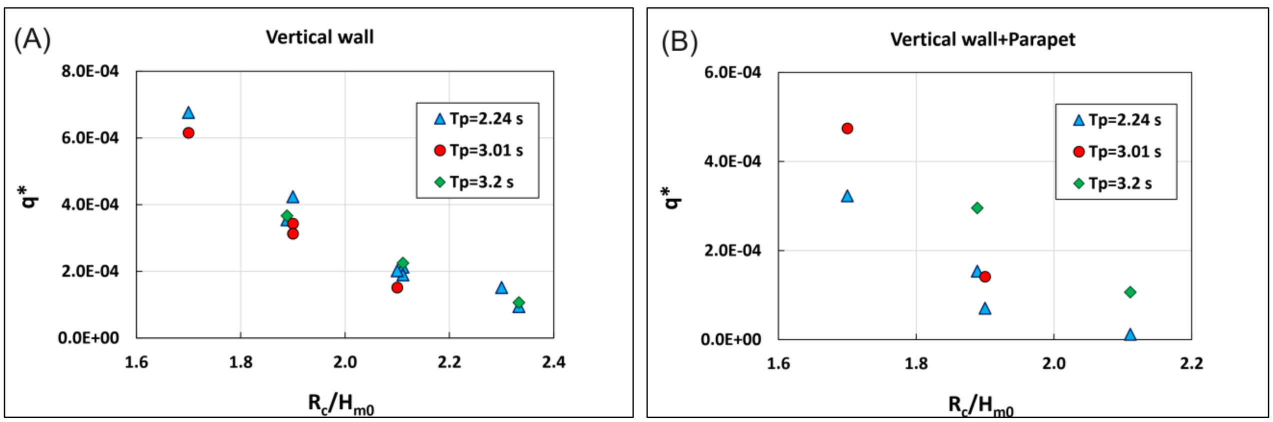

Figure 4 Comparison of non-dimensional wave overtopping rates q* over relative freeboard R_c/H_{m0} for vertical wall (A - left) and vertical wall with recurved wall (B - right)

For a detailed study of the underlying process, videos recorded during tests with similar $R_c/H_{m0,}$ and varying wave period were investigated to discern differences in the overtopping mechanism among waves with different periods. Figure 5 illustrates two series of snapshot from tests O14 and O15 in Table 1, both having similar R_c/H_{m0} but different wave periods. Notably, in the case of smaller wave periods (first snapshot series), the uprushing jet is redirected seaward by the recurve. Conversely, for larger wave periods (second snapshot series), it appears that the gap beneath the recurve becomes filled with water, resulting in less uprush but more overwash. Consequently, the recurve partially loses its effectiveness, leading to a higher overtopping rate.

From the above it can be concluded that incorporating wave period into overtopping equations for recurved wall, may enhance the accuracy of the estimations. With the limited number of overtopping tests involving recurved walls in the SABAII experiments (8 tests), an additional 173 tests from the EurOtop database were included to explore the significance of wave period and other influential parameters on overtopping rates for recurved walls. The selected dataset comprised overtopping tests on vertical walls with a recurve, installed on a sloped shore with intermediate water depth. In this scenario, the interference of the shore with wave conditions makes the water depth at the toe of the breakwater crucial, leading to the classification of this situation as an influencing shore in EurOtop 2018.

The selected tests belong to the experiments performed by Ahrens et al. (1986) and Pearson et al. (2003). To formulate a new adapted equation, a decision on which parameters to include in the adapted prediction was necessary. The influencing parameters consist of wave heigh and period, water depth at the toe of the breakwater, breakwater freeboard, recurve size and shape. In most of the tests in this study, the size and shape of the recurved were kept constant. In addition, when Pearson et al. (2005) studied different size of recurves they observed that in their study, overtopping reduction due to the recurve was more strongly influenced by wave period than by the recurve width. Therefore, in this study, it was decided not to consider the recurve shape and size as effective parameters.

Following a sensitivity study to find a suitable non-dimensional parameter that could encompass most of the influencing parameters, it was decided to employ $F' = R_c / (H_{m0}^2 L_p)^{1/3}$, as proposed by Ahrens et al. (1986), instead of the conventional relative freeboard R_c/H_{m0}. The addition of the L_p parameter allowed for the consideration of both wave period and water depth at the toe of the breakwater in the adapted equation.

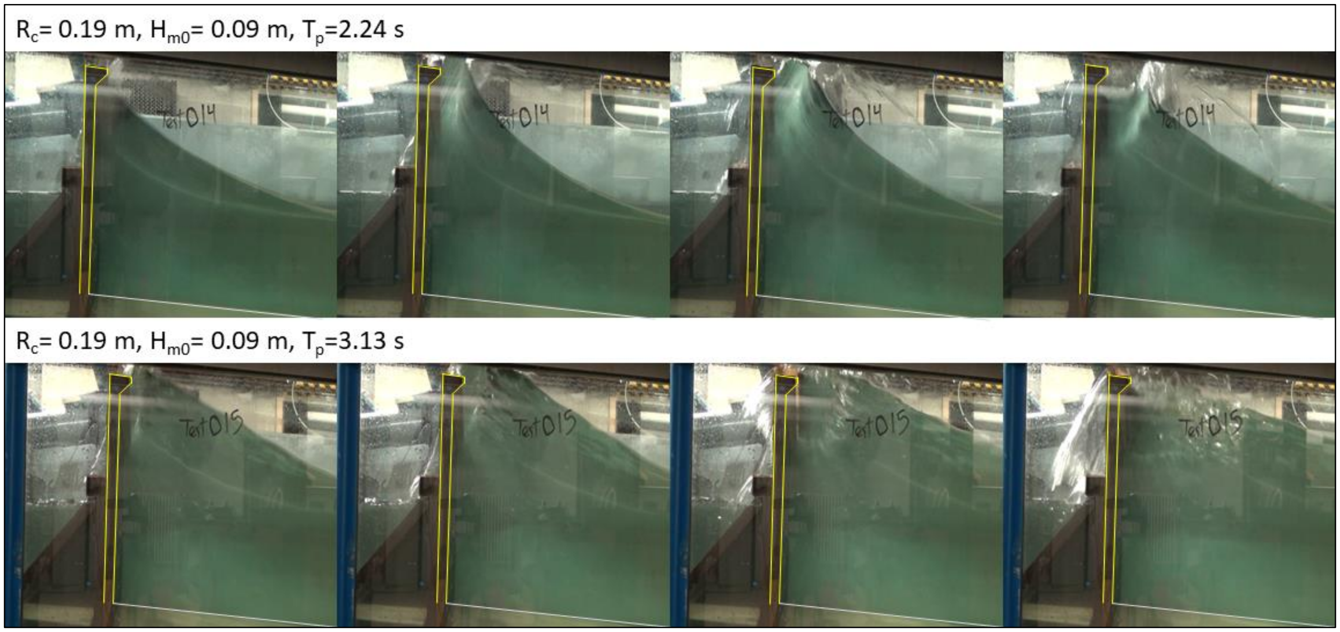

Figure 5 Comparison between overtopping waves with equal wave height and different wave period (upper snapshot sequence T = 2.24 s and lower snapshot sequence T = 3.13 s) for a vertical wall breakwater with recurve in SABAII tests

Figure 6 (A) and (B) present the comparison between wave overtopping rates of the selected tests in the EurOtop data base and SABAII experiments against R_c/H_{m0} and F', respectively. The comparison reveals that the wave overtopping data exhibits less dispersion for F', particularly when the relative freeboard is minimal. Consequently, F' appears to be a more suitable parameter than R_c/H_{m0} for formulating equations to predict wave overtopping rates. The dataset was segregated based on impulsive (or breaking or impacting) and non-impulsive waves, utilizing $h^2/(H_{m0}L_{m-1,0}) = 0.23$ as a discriminator, as suggested by J. van der Meer & Bruce (2014).

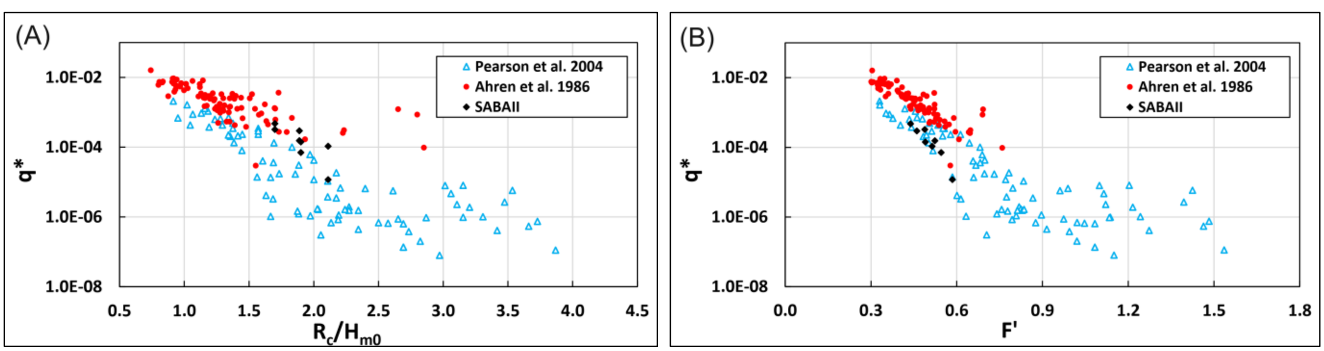

Figure 6 Non-dimensional wave overtopping rate q* versus relative freeboard R_c/H_{m0} (A -left) and F' (B – right)

3.1 Non-impulsive waves overtopping

Test data with $h^2/(H_{m0}L_{m-1,0})>0.23$ is plotted in Figure 7, representing non-impulsive wave conditions. In Figure 7-A q* is plotted versus R_c/H_{m0}m, while in Figure 7-B, it is plotted against F'. A comparison between these two figures demonstrates that F' serves as a significantly superior parameter for estimating wave overtopping compared to R_c/H_{m0}. Using the least square method, the following exponential equation is suggested for wave overtopping over a recurved wall under non-impulsive wave conditions:

$$q^* = 0.1\exp(-11.5\acute{F}) \qquad (2)$$

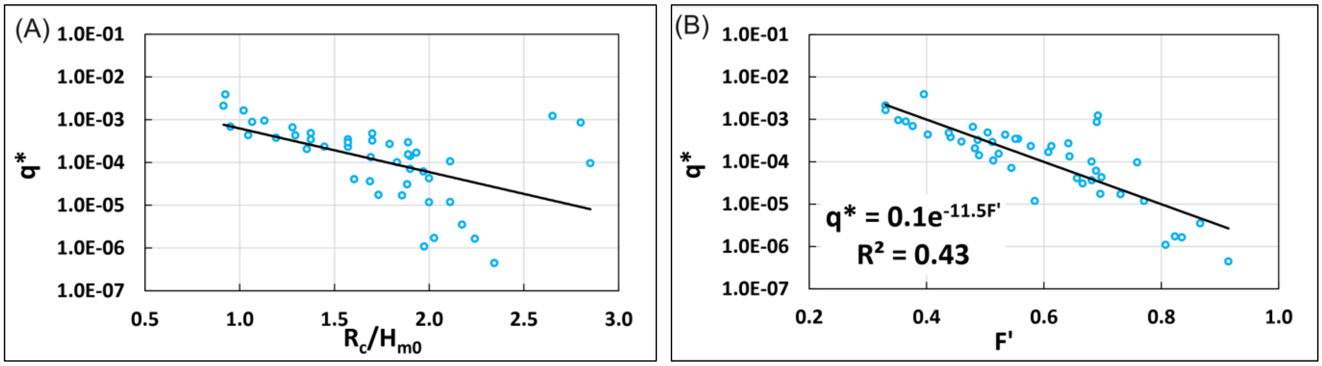

Figure 7 Non-impulsive wave overtopping data versus relative freeboard R_c/H_{m0} (A - left) and F' (B – right)

Equation (2) was assessed for accuracy by comparing it with the established EurOtop 2018 formula for non-impulsive waves. This comparison utilized non-impulsive SABAII data and non-impulsive data from Ahrens et al. (1986), as illustrated in Figure 8. The EurOtop 2018 formula incorporates an effectiveness parameter, k_{bn}, introduced to estimate wave overtopping over recurved walls, referencing overtopping over plain vertical breakwaters in the same condition (numbered as Equation 7.23 in EurOtop 2018):

$$k_{bn} = \frac{q_{with\ bullnose}}{q_{without\ bullnose}} \qquad (3)$$

The estimation of k_{bn} involves referring to a decision chart, detailed in EurOtop 2018, section 7.3.4, for additional information. To calculate $q_{without\ bullnose}$, the most suitable method for a plain vertical wall in the same conditions should be employed. In this case, as all the tests are conducted on an influencing shore, therefore, the calculation for wave overtopping over a plain breakwater should be carried out using following Equation (numbered as Equation 7.5 in EurOtop 2018):

$$q^* = 0.05\exp\left(-2.78\frac{R_c}{H_{m0}}\right) \qquad (4)$$

Multiplying the overtopping rate calculated by Equation (4) with the k_{bn} determined by Equation (3) allows for the calculation of wave overtopping over the recurved wall, as depicted by the red crosses in Figure 8. A comparison with the overtopping rates estimated by Equation (2) (illustrated as blue circles in Figure 8) demonstrates that Equation (2) yields a more successful and realistic estimation.

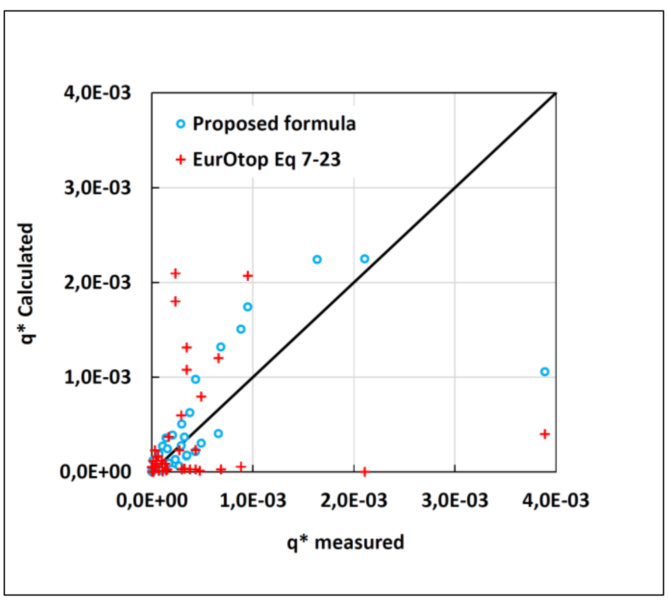

Figure 8 Comparison between the proposed formula for non-impulsive waves overtopping (blue dots) and EurOtop 2018 (red dots)

3.2 Impulsive waves overtopping

Test data with $h^2/(H_{m0}L_{m-1,0}) \leq 0.23$ are plotted in Figure 9, illustrating impulsive wave conditions. In Figure 9 (A) q* is plotted versus R_c/H_{m0} in Figure 9 (A) while it is plotted versus F' in Figure 9 (B). A comparative analysis of these figures highlights that, similar to non-impulsive conditions, F' proves to be a notably superior parameter for estimating wave overtopping than R_c/H_{m0} for impulsive wave conditions as well. Notably, the dataset exhibits a bimodal distribution in both plots, with one region more concentrated at F'≤0.5 (or $R_c/H_{m0} \leq 1.6$), better represented by an exponential distribution, and a more scattered region at F>0.5 (or $R_c/H_{m0} > 1.6$), better represented by a power distribution.

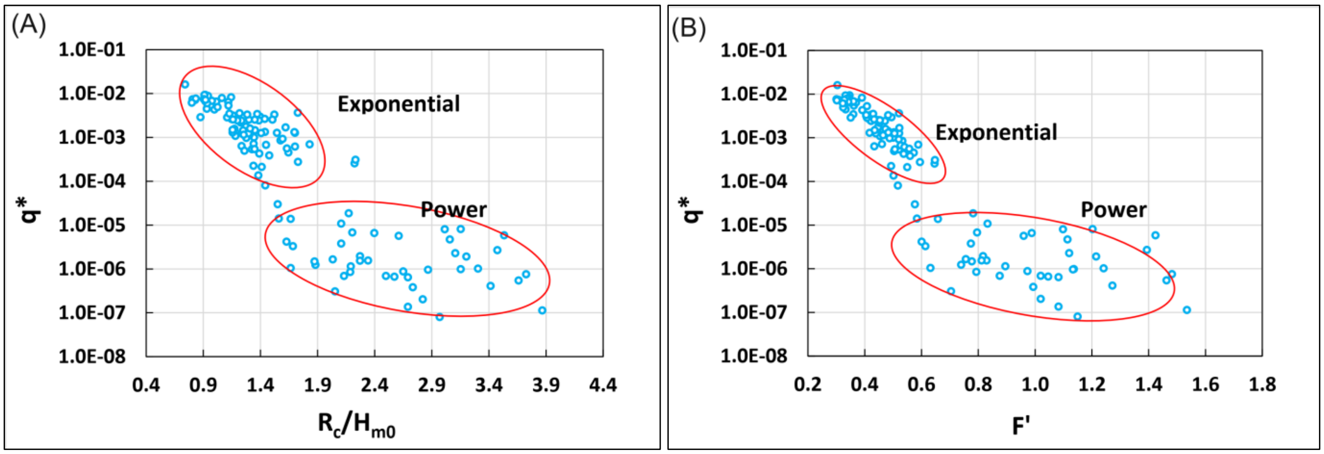

Figure 9 Impulsive wave overtopping data versus relative freeboard R_c/H_{m0} (A) and F' (B)

The exponential region of the impulsive dataset is illustrated again in Figure 10. Based on Figure 10 (B), which shows q* versus F', an exponential formula is introduced using the least square method for the impulsive waves for F'<0.5 as follow:

$$q^* = 0.4\exp\left(-12.13\acute{F}\right) \qquad F'<0.5 \qquad (5)$$

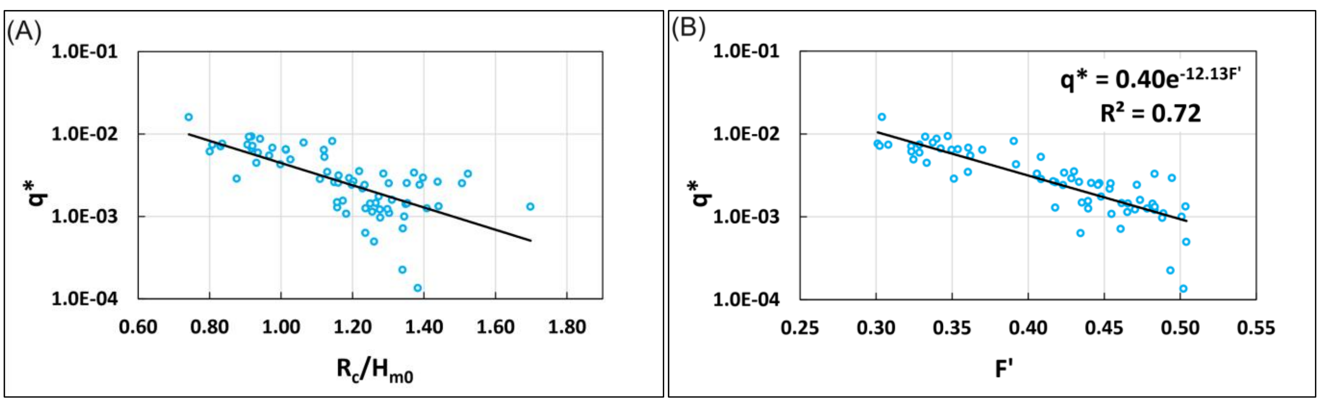

Figure 10 Exponential part of the impulsive wave overtopping dataset versus relative freeboard R_c/H_{m0} (A) and F' (B)

The second region of the impulsive wave condition dataset, characterized by F'≥0.5, is depicted in Figure 11 A and B. Notably, this dataset exhibits substantial scatter in both F' and R_c/H_{m0} correlations, indicating a challenging scenario for deriving an accurate prediction formula. In this situation, when the freeboard is relatively high the wave overtopping rate is too small. The stochastic variability of very small overtopping volumes is connected to small changes in the realization of the wave trains reaching the structure and in small alterations of the overtopping process itself, as well as larger relative measurement errors lead, which all lead to a larger scatter in the results. Hence, any prediction formula should be applied with consideration in this region. The following formula has been derived using least square method:

$$q^* = 0.000019\acute{F}^{-5.02} \qquad F'\geq 0.5 \qquad (6)$$

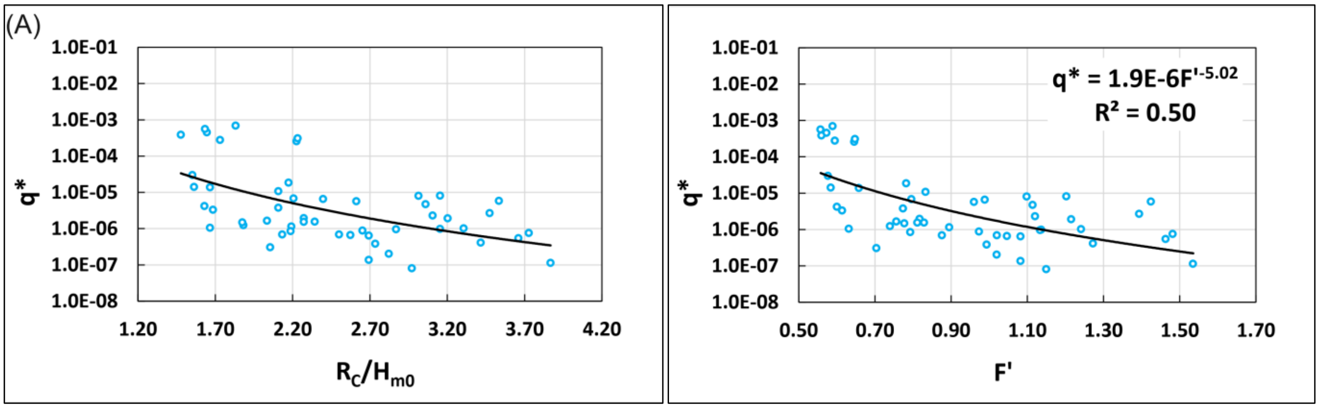

Figure 11 Power part of impulsive wave overtopping data versus relative freeboard R_c/H_{m0} (A) and F' (B)

The accuracy of Equation (5) and (6) were compared with the results of multiplying the related k_{bn} with the overtopping rates calculated using existing EurOtop 2018 formula for wave overtopping on plain vertical breakwater under impulsive waves (numbered as equation 7.7 and 7.8 in EurOtop 2018 manual), given as follow:

$$q^* = 0.011\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5} exp\left(-2.2\frac{R_c}{H_{m0}}\right) \qquad \text{for } 0< R_c/H_{m0}<1.35 \qquad (7)$$

$$q^* = 0.014\left(\frac{H_{m0}}{hs_{m-1,0}}\right)^{0.5}\left(\frac{R_c}{H_{m0}}\right)^{-3} \qquad \text{for } R_c/H_{m0}\geq 1.35 \qquad (8)$$

where $s_{m-1,0}$, is the (fictitious) wave steepness with wavelength based on $T_{m-1,0}$. Using the impulsive data from Ahrens et al. (1986) the proposed formulas for impulsive waves, i.e., equation (5) and (6) are compared with EurOtop 2018 in (Figure 12). The proposed formula for the exponential part of impulsive waves condition, i.e., Equation (5) could estimate the overtopping rate with more accuracy than EurOtop 2018 Formula which seems to slightly under-estimate the overtopping rates (Figure 12 (A)). Regarding the formula for relatively large freeboards ($R_c/H_{m0}\geq 1.35$), not the proposed formula nor the EurOtop 2018 formula were successful in estimating the overtopping rate (Figure 12 (B)). This result was expected, given the above explanation for the larger scatter of overtopping data in regions with relatively large freeboards.

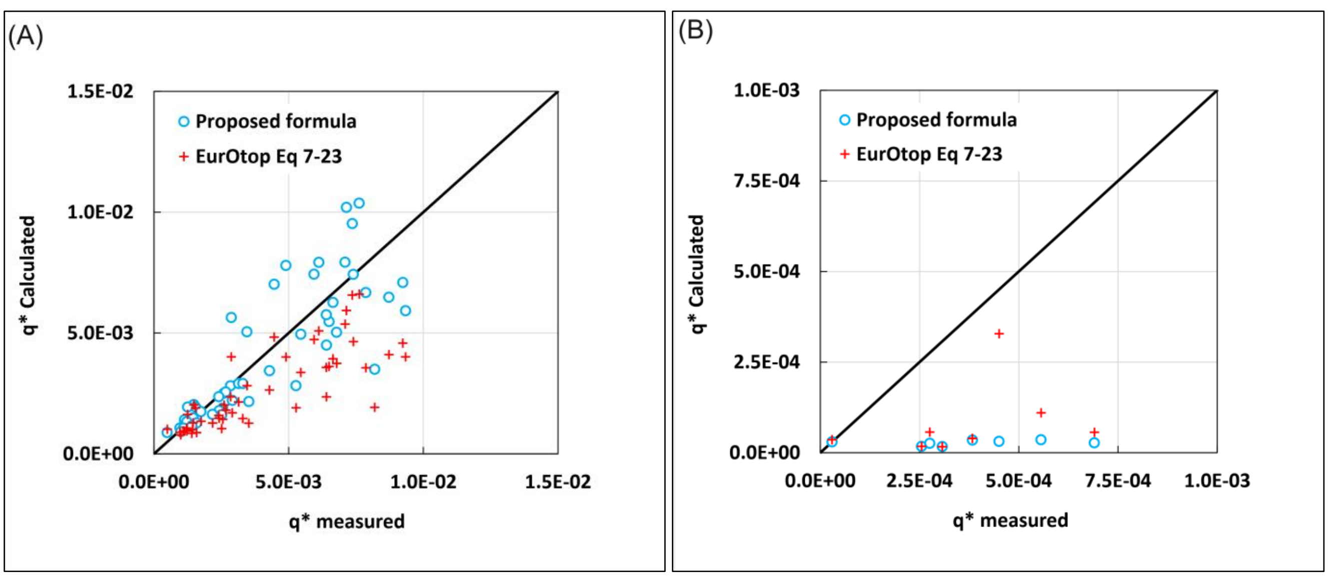

Figure 12 Comparison between the proposed equation for non-impulsive waves overtopping and EurOtop 2018, for the exponential region (A) and the power region (B)

4 CONCLUSION

In validating the design of the new main breakwater for the Caribbean Island SABA, an extensive test campaign was conducted in the 2D wave flume of the Department of Civil Engineering at Ghent University. The experiments focused on wave overtopping over both a plain vertical breakwater and a vertical breakwater featuring a recurved wall, with measurements taken under various wave and structural conditions. Notably, the presence of a recurved wall amplified the influence of the wave period on wave overtopping. To further explore the impact of wave period on overtopping rates with a recurved wall setup, additional data from the EurOtop database, specifically tests by Ahrens et al. (1986) and Pearson et al. (2003), were incorporated into the SABAII project dataset. All tests within this combined dataset involved a recurved wall installed on an influencing foreshore.

Initially, the dataset was categorized into non-impulsive and impulsive wave conditions using $h^2/(H_{m0}L_{m-1,0}) = 0.23$ as a discriminator, following the approach proposed by J. van der Meer & Bruce (2014). To derive accurate prediction formulas for estimating wave overtopping rates over a recurved breakwater, the non-dimensional parameter $F'=R_c/\ (H_{m0}^2\ L_p)^{1/3}$, suggested by Ahrens et al. (1986), was utilized instead of the commonly employed relative freeboard. The results indicated a superior correlation for F' compared to relative freeboard approaches. For non-impulsive waves, a modified formula was proposed, showcasing a notable enhancement in accuracy when contrasted with the formula in EurOtop 2018, which employs relative freeboard as the nondimensional parameter.

For the impulsive waves, the data included a wide range of F', from 0.3 to 1.5. For $F'<0.5$, which is roughly equal to the situations that $R_c/H_{m0}<1.35$, an exponential formula was proposed which could improve the accuracy of the wave overtopping estimation in comparison with EurOtop 2018 formula. For $F'\geq0.5$, which is roughly equal to the situations of large relative freeboards $R_c/H_{m0}\geq1.35$, the data is too scattered due to physical reasons related to small overtopping volumes and proposing an accurate formula is almost impossible. For these conditions, detailed physical model study should be considered as mentioned in EurOtop 2018.

In the case of impulsive waves, the dataset covered a broad range of F', from 0.3 to 1.5. For $F' < 0.5$ (equivalent to $R_c/H_{m0}<1.35$), an exponential formula was introduced, improving the accuracy of wave overtopping estimation compared to the EurOtop 2018 formula. However, for $F' \geq 0.5$ (roughly corresponding to situations with large relative freeboards, $R_c/H_{m0}\geq1.35$), the data exhibited considerable scatter due to physical factors related to small overtopping volumes. Formulating an accurate formula under these conditions proved challenging. For these conditions, detailed physical model study should be considered as mentioned in EurOtop 2018.

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