OVERTOPPING REDUCTION FOR HARBOR QUAYS UNDER VERY OBLIQUE WAVES ATTACK

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Abstract

The overtopping discharge is one of the most important issues when the safety of a coast is considered. Usually the waves approach the structures at angles between 0° and 45° and for this directions there are well documented formulae to estimate the overtopping discharge (i.e. EurOtop Manual, 2007). However, in some particular situations, such as inside of two Belgian harbors, the waves can approach the quay at a very oblique angle. This situation was not investigated comprehensively in the previous studies. The main objective of the present research is to study the overtopping reduction at very oblique wave angles, while additional objectives regard the influence of storm return walls and slopes for the overtopping discharge.

To test the hypothesis that the overtopping largely decreases for very oblique waves a 3D physical experiment was designed in the wave tank of Flanders Hydraulics Research, Antwerp. The scale of the experiment was decided to be 1:50 and the structure mimicking a harbor quay has 8 m length, 0.2 m height and 1 m width, in model scale. On top of the structure a storm return wall (0.02/0.04 m) is placed at different positions with respect to the front edge of the quay. On the back of the structure 16 boxes were placed to collect the overtopping volumes. The water level is ranging between -0.015 and +0.020 m with respect to the quay level, while the waves have H_s=0.03-0.06 m and T_p=1.1-1.7 s. The wave angle used for simulations is 80° with respect to the structure normal. The wave characteristics are measured using 17 wave gauges placed in arrays in such way to characterize the total wave height pattern at the toe of the structure. The mentioned analysis was performed using WaveLab v3.54 (© Aalborg University). As the wave paddle has no active absorption system a generous amount of passive absorption mattresses was placed around the basin to minimize the wave reflection.

After finalisation of 71 tests the results show a clear decrease in the measured overtopping volumes with respect to those calculated. Moreover there is high variability of the overtopping volumes along the structure. The experiment result in new overtopping reduction factors for very oblique waves at the vertical quays and advise for the height and position of the storm return wall.

Keywords: Very oblique waves; overtopping reduction; WaveLab; vertical quay; sloping dyke.

1. Introduction

A master plan to strengthen the weak links along the Belgian coast was established based on coastal flooding risk calculations (Coastal Safety Master Plan, 2011). Most vulnerable to extreme storms are the harbors such as Blankenberge and Oostende. Waves can penetrate into these harbors and attack the quay at an angle of approximately 80° with respect to the normal. Storm return walls are present in some parts and planned to be built in other parts.

To assess the vulnerability of these harbors to the 1000 year return storm (H_s=4.75 m, T_p=12 s, water level +8 m TAW) the overtopping discharge has to be estimated. The EurOtop Manual provides validated formulae to calculate the overtopping discharge for classical configurations. In the case of perpendicular wave attack on a storm return wall the overtopping is maximum, but for larger wave angles a reduction factor (γ_β) is applied to account for the overtopping discharge decrease. This factor for vertical quay decreases gradually for wave angles between 0° and 45° and it keeps a constant value for wave angles larger than 45°. However, our hypothesis is that the overtopping discharge will keep the decreasing trend for larger wave angles (very oblique waves). A proper assessment of this reduction is outstanding, since the height of storm return walls will be designed based on this information.

The mean wave overtopping is mainly function of the relative freeboard and the relationship between the overtopping discharge and the freeboard is expressed through an exponential formula. Several reduction coefficients are introduced, maintaining the exponential structure, to take into account the effects of: presence of a berm (γ_b), presence of a crown wall (γ_w), surface roughness (γ_f) and wave obliqueness (γ_β).

In particular incoming waves with wave fronts almost parallel to the coastal structure (perpendicular wave attacks) lead to higher overtopping rates than oblique wave fronts. Based on previous experimental results, especially those gathered in the CLASH database (Steendam *et al.*, 2004; De Rouck *et al.*, 2005), expressions for γ_β are proposed in the EurOtop Manual (2007).

For vertical dikes, the reduction factor for obliqueness is (non-impulsive waves):

- γ_β = 1- 0.0062β, for 0° < β < 45°

- γ_β = 0.72, for β ≥ 45°

where β is the angle of attack relative to the normal, in degrees.

Only for some specific impulsive conditions is specified that the formula can be applied in case of oblique waves. Otherwise no correction factor is suggested in the EurOtop Manual. For sloping dikes, the reduction factor for obliqueness is:

- γ_β = 1- 0.0033 β for 0° < β < 80°

- γ_β = 0.736 for β ≥ 80°

Nørgaard *et al.* (2013) propose for non-breaking short crested waves γ_β = 0.95-0.0035·β.

It can be noticed that there is no difference between 45° and 80° for the vertical dikes, so very oblique waves should lead to overtopping rates comparable with 45°. Differently, the formulation for the sloping dikes describes the variation of the reduction coefficient with the wave angle even for very oblique waves such as 80°. Theoretically, it is expected, under certain conditions, a smaller overtopping discharge for very oblique waves on vertical dikes than that predicted using the EurOtop formulae.

2

The CLASH database has been investigated, finding that there are no data with wave angle larger than 45° for vertical quays with no or gentle foreshore like the present case. Moreover, from the CLASH database analysis, it has been verified that there also overtopping data for sloping dikes (1:2.5) under oblique wave attack. Thereby the present analysis aims to overcome the aforementioned limitations, investigating in detail the influence of very large obliqueness on the wave overtopping on vertical quays without foreshore and 1:2.5 sloping sea dikes.

The main objective of this study is to investigate the overtopping discharge reduction for waves approaching a structure at very oblique angles. The existing formulae indicate a reliable reduction factor for the wave angles ranging between 0 and 45°, but for larger wave angles it is suggested to keep the same reduction factor as for 45°. Additional objectives are related to the influence on overtopping discharge of the positions and size of storm return wall and the presence of a slope in front of the quay.

2.   Methods

To investigate the overtopping reduction with the wave angle increase a physical model was designed and built at Flanders Hydraulics Research (FHR), Antwerp.

2.1   Experiment setup

Simple numerical modelling shows that is very likely to have wave height variation along the structure, so it is important that the model will have similar extension as general prototype conditions. The easier way to accommodate in the wave tank a large structure is to choose a smaller scale. However the scale cannot be smaller than 1:50 because some wave height scenarios would be smaller than 0.03 m in the model. Below this threshold the surface tension of the water starts to play an important role in the propagation and breaking of the waves, thus altering the reproduction of the prototype conditions (Hughes, 1993).

Another issue was the distance between the wave maker and the structure. Ideally, this distance should be rather large, but in practice it is always limited to few wavelengths due to the limited size of the wave tank. However a minimum distance between the wave maker and the structure equal to two wavelengths is required all the time. Considering the limitations detailed above we decided to build a laminated wooden structure of 8.0 m long and 1.0 m wide. Attached to this structure, at its backside, there are 16 boxes, built from the same material, designed to collect the overtopping water during the experiment. Each box is 1.5 m long, 0.48 m wide and 0.18 m deep (Figure 1). The structure was positioned in the basin in such a way that the wave angle with respect to the structure normal is 80° and the wave paddle is at the maximum distance.

2.2   Wave tank

The experiments are carried out in the wave tank at FHR (dimensions 17.50 x 12.20 x 0.45 m). The wave tank is equipped with a piston - type wave generator. The wave generator has a width of 12.0 m and generates long-crested waves, but with no wave active absorption. Both regular and irregular wave patterns can be generated. Since the wave generator is displaceable, there are different angles of potential wave incidence (between -22.5 ° and +22.5 ° with respect to the wave normal incidence).

2.3   Instrumentation

Seventeen wave gauges were used to measure the wave characteristics (height, period and direction). One wave gauge is permanently situated in front of the wave maker to check the generated waves. Two arrays have been built, each comprised of five wave gauges (**Erro! A**

the wave gauges were located in such way that a directional spectral analysis is easy to be made when the data were processed. The last 6 wave gauges were mounted equidistantly, just close to the structure to provide information about the variation of the total wave height along the structure. Wave analysis was done using the WaveLab 3.39 software (Aalborg University, 2011). Every overtopping box comprises a mechanism to read the water level using a needle touching the water surface and a metallic ruler. The water level is determined before and after the experiment, the difference is the overtopped volume. Additionally, three of the boxes have other instruments (Balluff), which record automatically and in real time the water level.
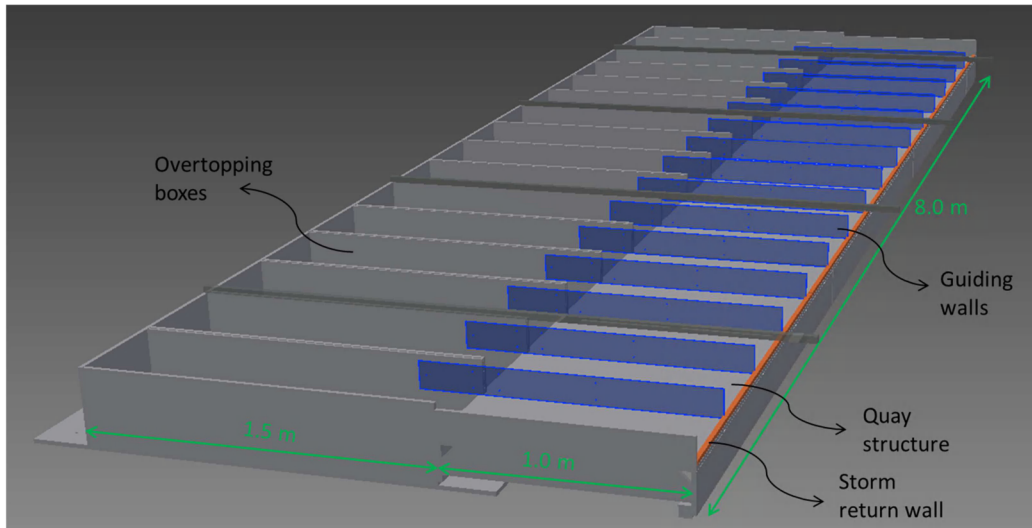

Figure 1. The structure used to simulate the reduction on overtopping for very oblique waves.
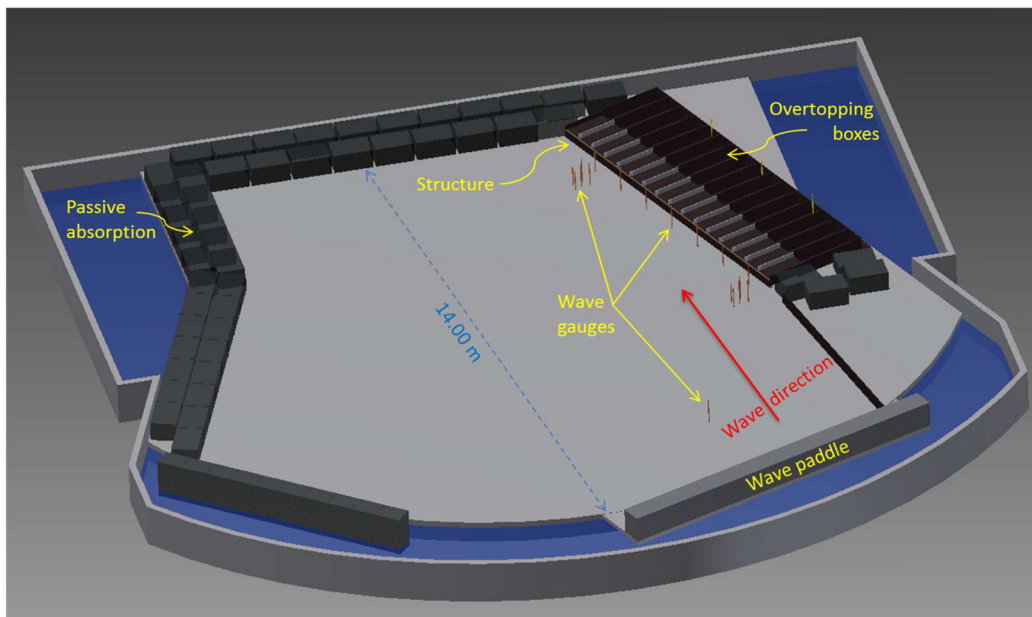

Figure 2. The wave tank, the position of the structure and of the instruments.

4

2.4 Test program

A test program was elaborated in order to investigate the reduction of overtopping related to the very oblique wave angle. A number of 71 tests were made with the target prototype values 1.5, 2.25 and 3.0 m for the wave height, 5.8 and 12 s for the wave period, 0, 5, 25 and 25 m distance respect to the quay edge for the position of the storm return wall, two heights of the storm return wall 1.0 and 2.0 m, two configurations of the quay, vertical and sloping dyke (slope 1:25) and three water levels -0.75, 0.0 and +1.0 m respect to the quay level. The wave conditions are similar with those for the Oostende and Blankenberge harbors (Gruwez *et al.,* 2011; Suzuki *et al.,* 2012).

3. Results

The results of the experimental campaign carried out at FHR are presented in the study. The effects of the wave obliqueness and of the storm return wall on top of the dike have been quantified and the results of the tests have been compared with those from CLASH for similar layouts. A value for the reduction coefficient of wave obliqueness (γ_β) for the 80° case is suggested. The analysis of the results is mainly focused on the vertical quay configuration (61 tests), comparing the measured with the calculated overtopping for a wave angle of 80° with respect to the structure normal. The effect of a slope in front of a dyke was also investigated (10 tests). The analysis of the results was made differently for the vertical quay wall than for the sloping dyke. Several tests led to 0 overtopping discharge, but only the cases that produced overtopping rates are included in the following analysis. The wave gauges along the dike were used to measure the total wave height at the structure's toe, while the 3D arrays, as described in the previous sections, have been used to calculate the incident wave height and period. Thereby reflection analysis has provided the incident wave characteristics which were used as input for predicting the overtopping discharge using EurOtop formulae.

3.1 Vertical quay wall

The results for the vertical quay layout and comparison with CLASH data and EurOtop Manual prediction formulae are discussed in this sub-section. The overtopping discharge per each box and the measured total wave height along the structure are shown in Figure 3. For few tests the number of wave gauges along the structure was limited and for those tests the wave height is 0. The calculation of the mean overtopping discharge started from the collected overtopping volume and it follows a geometrical rule summarized as follows:

- For each test the berm length has been calculated as a distance between the edge of the quay (sea dike) and the crown wall.

- For each angle the projection of the berm length along the wave direction has been assessed: this represents the effective berm length that the wave has to run before reaching the wall.

- Starting from the first corner of the dike, the projection of the effective berm along the quay gives the minimum distance before which no wave reaches the wall.

- The width considered to calculate the mean overtopping for the entire quay is equal to the quay length minus the calculated distance.

5

- In the case without crown wall or with crown wall on the edge of the quay, the entire quay length (8.0 m) has been considered.

- It has been verified by video recording that the peaks in the overtopping volume in the last overtopping boxes are not due to model effects (boundary reflection), but they represent the real distribution due only to the wave attack.
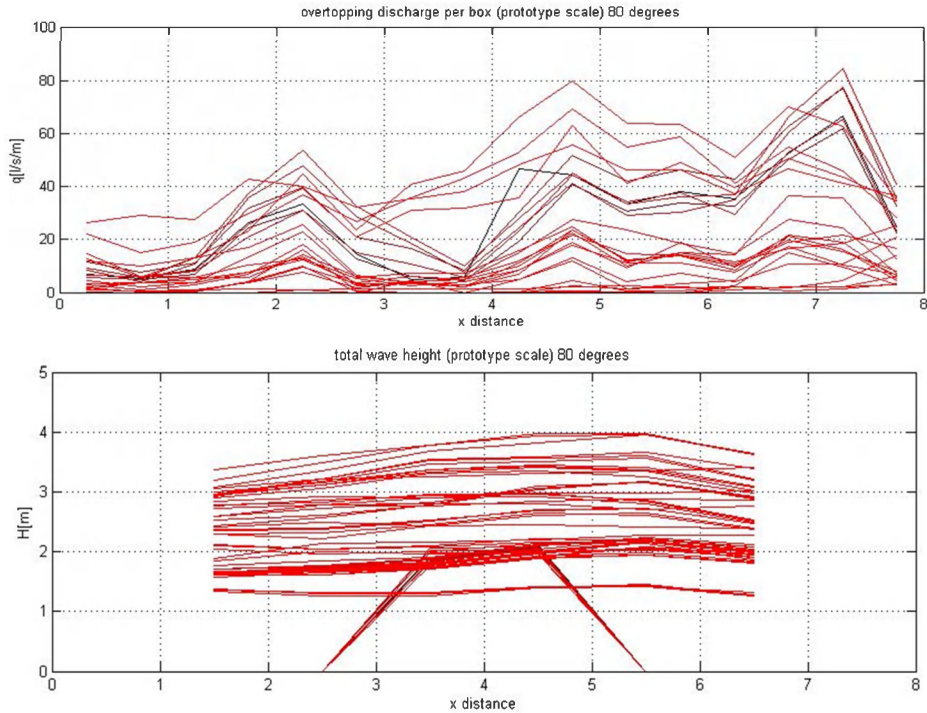

Figure 3. Overtopping discharge per box along the quay and total wave height along the structure.

The comparison between measured overtopping discharge in the present study and predicted overtopping discharge using EurOtop formula for 80° wave angle is shown in Figure 4. For a correct comparison a distinction has to be made between configurations with the storm return wall on the edge (or without wall) and configurations with a berm before the storm wall. The latter ones have less overtopping discharge than the predictions due to the presence of the berm. The former ones are identical to vertical sea dikes as described in the EurOtop Manual. However, the results show that for both layouts with and without berm, the EurOtop formulae overestimate the measured overtopping discharges. This is mainly due to the assumption of keeping the same γ_β for 80° and as for 45°.

Starting from the measured data an evaluation of the reduction factor for 80° has been made. Only data without berm have been considered in order not to introduce any influence of the berm length on the reduction factor so calculated. The resulting measured reduction factor $\gamma_\beta.WL$ has been defined as:

- $\gamma_\beta.WL,80 = 0.2847$ (reduction factor for 80°obliqueness)

Since the number of data is somewhat limited, the value is rounded to 0.3. The EurOtop Manual reports a value of 0.72 both for 45° and 80°, so the overestimation of the reduction factor is very large and consequently the overtopping discharges estimation.

It is noticeable the fact that the difference in the reduction factor between 0.72 and 0.3 causes a difference in the calculated discharge of 1 order of magnitude (10 times) in the selected data range. The standard deviation calculated from the FHR results for 80° is 0.0322.
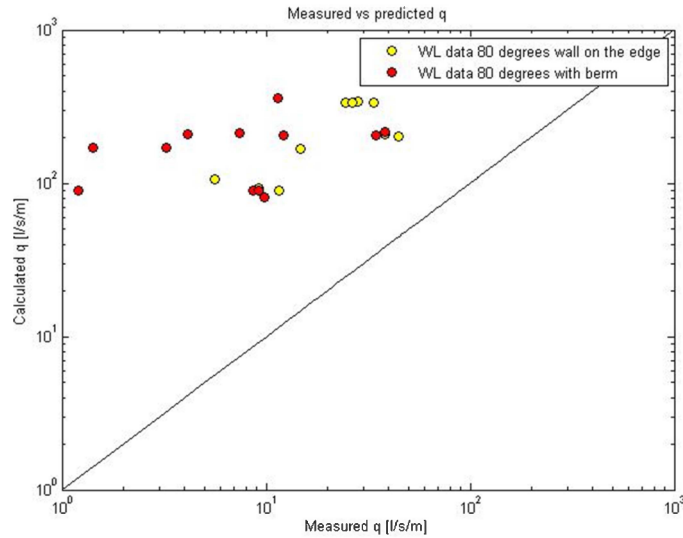

Figure 4. Measured vs. calculated overtopping discharge for 80° wave angle.

In Figure 5 the WL data (data from experimental results at FHR) have been included together with the CLASH database data. Only configurations without storm return wall or with storm return wall on the edge of the quay are plotted.

It is evident how the application of the EurOtop reduction factor still overestimates the measured values, where the use of the measured reduction factor leads to a reasonable fit of the data with the overtopping formula.

After the obliqueness effect has been quantified, a preliminary analysis of the effects of the berm length (wall distance from the edge) and wall height was carried out. Figure 6 summarizes all the results labeling them in function of the wall height, berm length and water depth.

Even though the scatter of the data is quite large and is difficult to identify a clear relationship between the aforementioned quantities, there are clear differences between short or no berm layout (L_{berm}= 0 and 5 m) and long berm layout (L_{berm}=25 and 50 m): the effective berm length which is calculated based on angle and L_{berm} are comparable with the wave length).

The configurations without berm (circles) and with short berm length, 5m in prototype (triangles), show a quite similar behavior leading to higher overtopping discharge than the configurations with larger berms (25 and 50 m in prototype).

An important role is played by the water level in front of the structure, so the freeboard with respect to the quay (A_c = quay elevation – water depth). Positive values of A_c correspond to water level below the quay level, negative values correspond to water level on the top of the

quay. It can be noticed that positive A_c for 80° do not produce overtopping discharges for all the tested cases.

3.2 Sloping (1:2.5) sea dike

The results for the sloping dike configuration are discussed in this sub-section. In order to compare clearly with the EurOtop predictions, a distinction is made between configurations with short berm length and long berm length. In fact the EurOtop formulae do not consider the influence of a berm on the top of the dike. A reduction coefficient γ_w for crown wall is suggested in EurOtop Manual (equation 5.31). It has been estimated equal to 0.648 in the cases tested at FHR and it is applied when the berm length is not zero. It has been noticed that for 80° the cases with long berms do not lead to any significant overtopping discharge. Starting from the measured data a coarse evaluation of the reduction factor for 80° has been made. Only data with short or no berm have been considered in order not to introduce any influence of the berm length on the reduction factor so calculated. A preliminary value of the reduction factor $\gamma_{\beta}.WL$ (further research is still ongoing) has been calculated and assumes the following values:

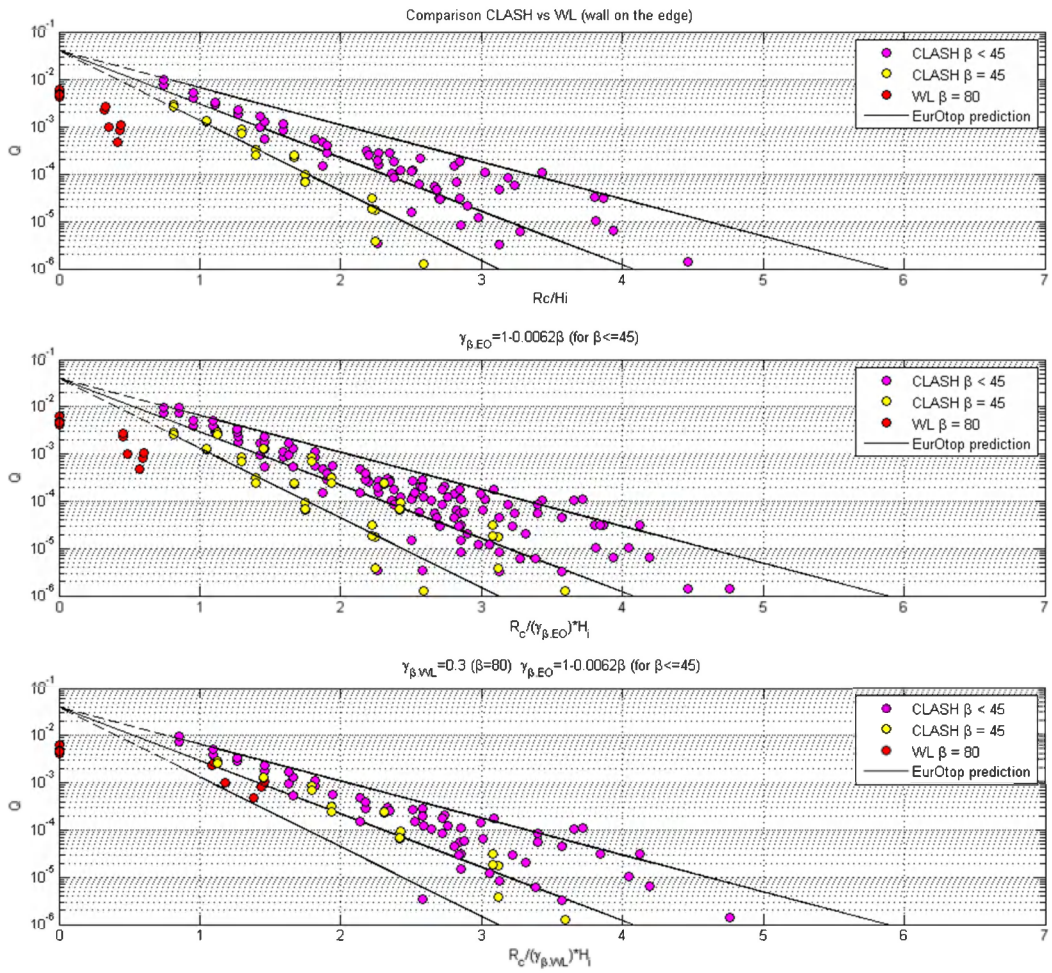- $\gamma_{\beta}.WL,80$ = 0.38 (reduction factor for 80°obliqueness)

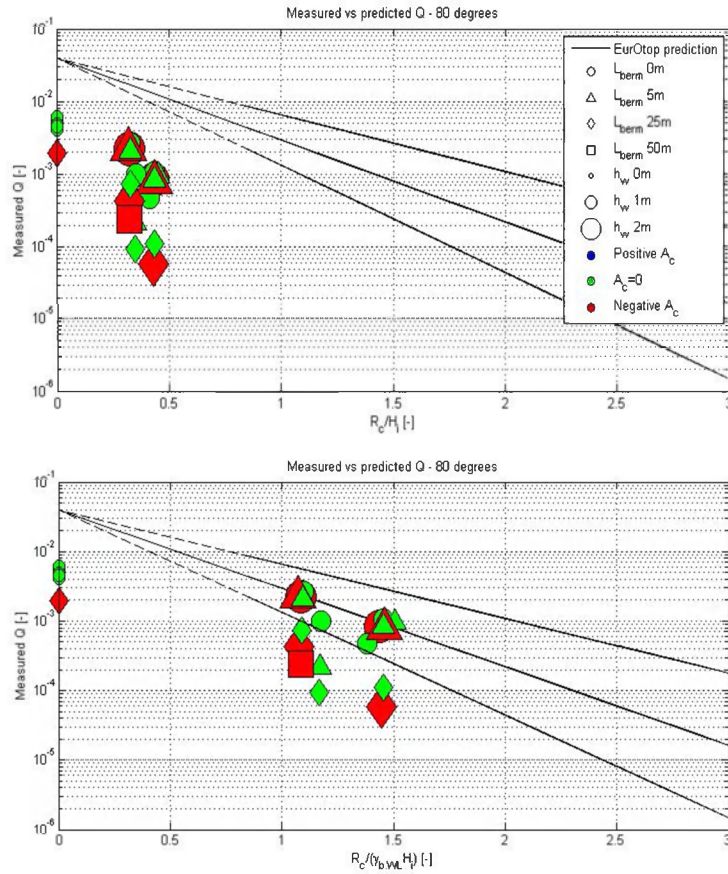Figure 5. CLASH and FHR data vs. EurOtop Manual predictions (FHR data without a berm).

Figure 6. FHR data vs. EurOtop Manual predictions.

4. Conclusions

The results of a physical model tests carried out at FHR on wave overtopping for very oblique waves are shown in the present study. The main objective of this study was to investigate the overtopping reduction for very oblique waves attacking a vertical and/or sloping structure. The physical results were compared with similar cases from the CLASH database (2005) and predictions through the formulations proposed in the European Overtopping Manual (2007). The analysis of the results for the vertical quay layout leads to the following conclusions:

1. The EurOtop formula overestimates the overtopping discharge for the wave angle of 80° with respect to the structure normal.

2. The reduction factor calculated using the FHR data is approximately γ_β.WL = 0.3 for 80° wave angle and vertical walls. This is a significant improvement for the formulae used to predict the overtopping since the EurOtop Manual suggests to assume the same reduction coefficient for all the angles larger or equal to 45° with respect to the structure normal and this coefficient is γ_β = 0.72.

3. The high obliqueness combined with long berms (comparable with the wave length) leads to very low or no overtopping discharge.

10

4. The berm length has a stronger influence on the overtopping reduction than the wall height.

5. It has been noticed a certain reduction also for sloping dikes, different than what was proposed in the EurOtop.

Further investigations on the overtopping reduction due to the oblique wave attack will be extended to other wave directions: control 0° and 45° to check the compatibility with the previous experiments, and intermediary 60° to 70° to define reduction coefficients for the rest of oblique wave directions.

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