Distribution of overtopping wave volumes caused by crossing seas

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Abstract: In the European research project *HYDRALAB+* physical model tests have been performed in 2018 in the large wave basin of Deltares on crossing seas and wave overtopping over a 1:3 smooth slope. Crossing seas are defined as two sea states coming simultaneously from different directions. One could be a sea state developed by local winds, where the other one might be swell with a longer period coming from elsewhere from the ocean. The *CrossOver* project performed 170 tests on wave overtopping with different wave loadings (wave heights, periods, angles and spreading). Tests included "sea only" and "swell only" calibrations tests, and tests with sea and swell crossing, with sea obliquities ranging from -85° to +60° and swells from -75° to +60°. The influence of crossing seas on the distribution of overtopping wave volumes has been analysed using a Weibull distribution to describe such distribution and compared with the known theory for single sea states. The results agree well.

Keywords: Wave overtopping, crossing seas, sea and swell, individual overtopping volumes, overtopping distributions

1 Introduction

Wave overtopping may cause severe problems on the crest and rear slope of the coastal structures (damage), on property behind it and to people visiting the structure during storm conditions. An important parameter used to design coastal structures is the average wave overtopping discharge q. However, this parameter does not fully describe the overtopping process. The volume that overtops the structure's crest for each overtopping wave (individual wave overtopping volume) is different from the mean overtopping discharge (Van der Meer and Janssen, 1994). A distribution of overtopping wave volumes shows the largest overtopping volumes which most likely can cause damages to the structures during a specific event. This has also been recognized in EurOtop 2018, where guidance has been given for allowable overtopping using the overtopping discharge as well as maximum overtopping wave volumes. There are several studies about probability distribution functions for individual wave overtopping volumes (Franco et al. 1994, Van der Meer and Janssen 1994, Besley 1999, Victor et al. 2012, Hughes, et al. 2012, Zanuttigh et al. 2013). Such distribution is described by a two-parameter Weibull distribution as given in Equations 1 and 2:

$$P_V(V_i \leq V) = 1 - e^{\left[-\left(\frac{V}{a}\right)^b\right]} \tag{1}$$

$$P_{V\%}(V_i \geq V) = e^{\left[-\left(\frac{V}{a}\right)^b\right]} \times 100\% \tag{2}$$

Where P_v is the probability that individual wave volumes will be less than a specified volume V, and $P_{V\%}$ is the percentage of wave volumes that will exceed V. The parameter a is the scale parameter that normalises the distribution, and the parameter b is the shape parameter (shape factor) that defines the extreme tail of the distribution. The Weibull plotting formula is used to compute the exceedance probability of each overtopping volume which is a function of the number of overtopping waves N_{ow} (Goda, 2010).

$$P_V = 1 - \frac{i}{N_{ow}+1} \tag{3}$$

Where i is the rank of the individual volume. The value of b indicates the type of distribution which represents the overtopping volumes, see Figure 1. A value of 2 means a Rayleigh-distribution and a value of 1 an exponential distribution, which is a much steeper distribution with less and large extreme volumes. Large b-values ($b>2$) are found for very large overtopping discharges or for submerged structures (Hughes and Nadal, 2009). Van der Meer and Janssen (1994) found a constant shape parameter ($b=0.75$) for low to moderate overtopping volumes in structures with smooth mild slopes (1:3 and 1:4), which gives a distribution that is even steeper than an exponential distribution.
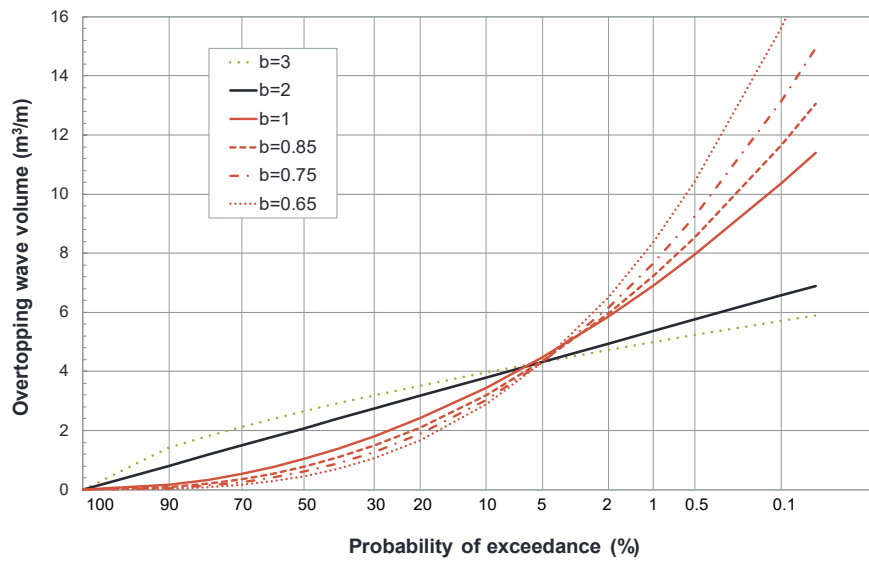

Figure 1   Various distributions on a Rayleigh scale graph. A straight line (b = 2) is a Rayleigh distribution, b = 1 an exponential distribution.

Victor et al. (2012) proposed an equation to compute the shape parameter b for smooth mild structures with large overtopping discharges. The formula is based on 364 overtopping wave tests on structures with different relative freeboards R_c/H_{m0} ($0.11 \leq R_c/H_{m0} \leq 1.69$) and slope angles ($0.36 \leq cot\alpha \leq 2.75$) performed in a wave flume. It relates the shape parameter with the relative freeboard and slope angle α:

$$b = e^{\left(-2.0\frac{R_c}{H_{m0}}\right)} + (0.56 + 0.15 \times cot\alpha) \tag{4}$$

Hughes et al. (2012) analysed the data from Victor et al. (2012) and their own data to create a new prediction formula for the shape parameter. Their data included tests with very high relative freeboard and with negative relative freeboard. The new proposed formula expanded the validation from negative to positive relative freeboard, see Equation 5, and it only depends on the relative freeboard:

$$b = \left(e^{\left(-0.6\frac{R_c}{H_{m0}}\right)}\right)^{1.8} + 0.64 \tag{5}$$

Zanuttigh et al. (2013) compared the shape parameters from wave overtopping tests on rubble mound structures with the proposed equation from Hughes et al. (2012). They observed that the equation based on the relative freeboard does not predict approximate b-values for rubble mound structures. Therefore, they proposed a new prediction formula to calculate the shape parameter for smooth and rubble mound structures based on the relative discharge $q/(g*H_{m0}*T_{m-1,0})$. This formula is also reported in EurOtop 2018:

$$b = 0.73 + 55 \left(\frac{q}{g \times H_{m0} \times T_{m-1,0}} \right)^{0.8} \tag{6}$$

Waves coming from one direction only have been used in the studies about wave overtopping on coastal structures, but the effect of waves coming from two different directions on wave overtopping is still unknown. This situation may happen when swell waves coming from a long distance combined with sea waves generated locally by wind creating a crossing seas condition. Studies such as Young et al. (1995), Petrova et al. (2013) and Petrova and Guedes (2014) describe crossing seas (bimodal seas) with sea states from different wave directions. Van der Werf and Van Gent (2018) analysed wave overtopping discharges over coastal structures with crossing seas. The *CrossOver* project was created to fill the absence of guidance on the influence of crossing seas upon wave overtopping at a coastal defence. The present study used a part of the *CrossOver* data to analyse the distribution of overtopping wave volumes under crossing seas conditions.

2 Physical Model Tests

The CrossOver project has performed 170 physical model tests in the Delta Basin of Deltares, Delft, see Figures 2 and 3. This large basin is equipped with two multi-directional wave generators with an active reflection compensation system. The tested structure was 30 m long and had a simple smooth slope of 1:3 with a crest level of 1.15m. Most tests were in a water depth of 0.95m (R_c=0.20m), with some larger sea cases at a lower depth of 0.90m (R_c=0.25m). Behind and in the middle of the structure, six overtopping boxes were arranged to collect the overtopping volumes. Inside of each box a gauge and a pump were installed to measure the water level and to pump out the water when the boxes were completely full. A wave detector (*c04*) was placed on the crest of the structure to record the presence of wave overtopping. Waves were measured in front of each wave generator with a directional wave gauge (*GRSM*) and in front of the toe of the structure with a directional wave gauge and an array of eight wave gauges (*WHM*). Figure 2 illustrates the model set-up in the Delta Basin:
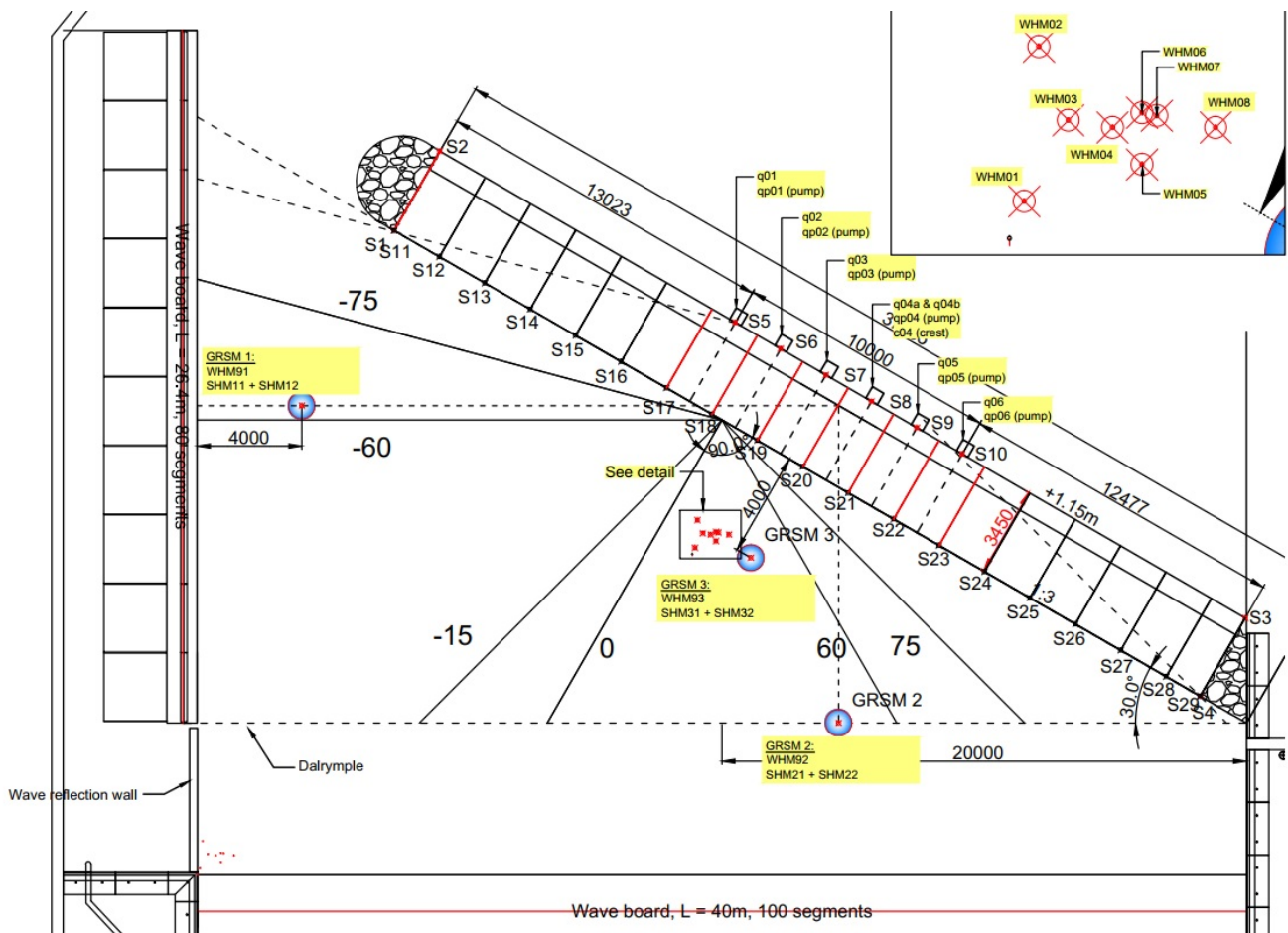

Figure 2   Directions -15° to 75° possible with the new generator (below) and -60° to -75° with the old generator (left).

2.1 Test conditions

The general strategy was to use the newer wave generator with 100 wave paddles (along the lower side of the basin as seen in Figure 3) to generate sea-only, swell-only and combined sea+swell (bimodal) conditions for sea and swell obliquities ranging from -15° to +60°. The older wave generator with 80 wave paddles was only brought into use as a wave generator for the large negative obliquities of -60° and greater. The wave height varied from $H_{m0} = 0.065$ to 0.12 meters for sea waves and from $H_{m0} = 0.05$ to 0.12 meters for swell waves in the tests. The wave period ranged from $T_{m-1,0} = 1$ to 1.6 seconds for sea waves and from $T_{m-1,0} = 2.5$ to 3.5 seconds for swell waves. Most tests performed in the Delta Basin were short-crested (spreading angles of 30° for swell waves and 10° for sea waves), but also some long-crested tests were generated. Table 1 shows the main wave conditions tested during the tests.
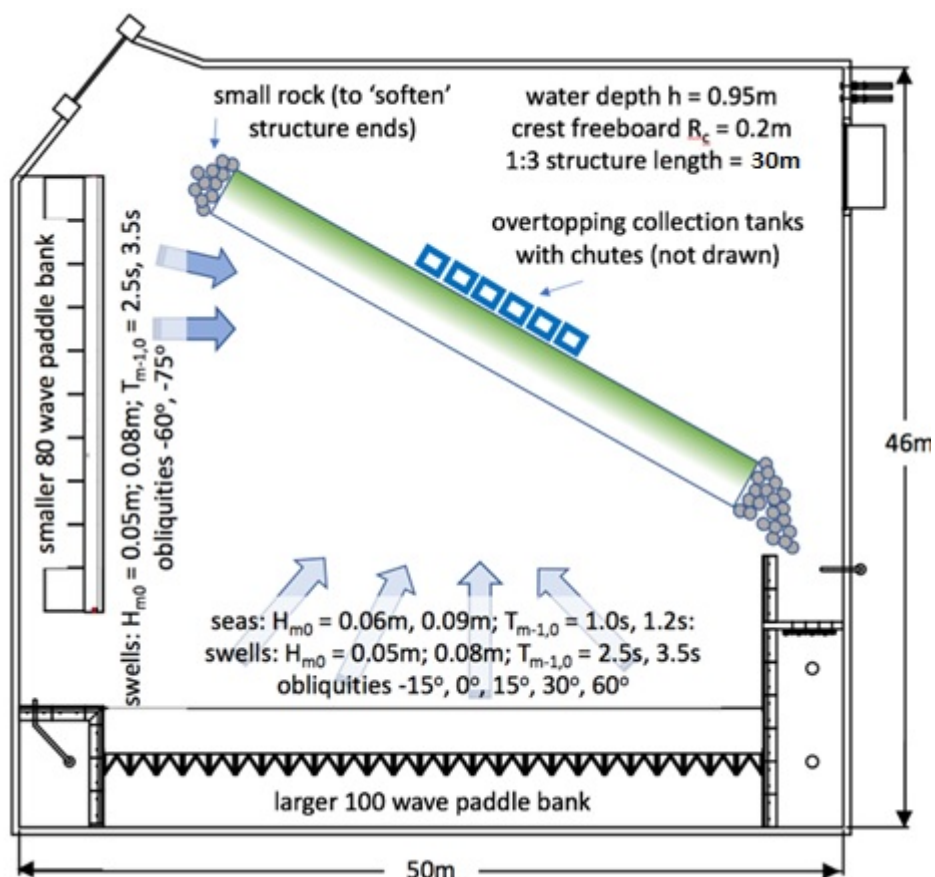

Figure 3 Sketch of the layout of the structure in the Delta Basin (not to scale) Bruce, et al. (2019).

Table 1 The main test conditions (nominal/ target values)

Sea state	Wave height, H_{m0} (m)	Wave period, $T_{m-1,0}$ (s)	Wave steepness $S_{m-1,0}$ (-)	Spreading σ (°)	
sea	0.12	1.4	0.04	30	plus some σ = 0° tests
sea	0.09	1.2	0.04	30	plus some σ = 0° tests
sea	0.08	1.1	0.04	30	plus some σ = 0° tests
sea	0.08	1.6	0.02	30	plus some σ = 0° tests
sea	0.065	1.0	0.04	30	plus some σ = 0° tests
swell	0.12	3.5	0.006	10	-
swell	0.12	2.5	0.012	10	-
swell	0.08	3.5	0.004	10	plus some σ = 0° tests
swell	0.08	2.5	0.008	10	plus some σ = 0° tests
swell	0.05	3.5	0.002	10	plus some σ = 0° tests

The combination of the single sea states generated six different crossing seas conditions (sea normal and swell oblique, swell normal and sea oblique, swell and sea same direction, crossing sea and swell

oblique, swell-swell, and sea-sea) based on the wave systems and wave angle attack related to the structure.

3 Distribution of Overtopping Wave Volumes

The distribution of overtopping wave volumes for single sea states is well represented by a Weibull distribution for dike type structures (Van der Meer and Janssen, 1994). This distribution is made with the individual overtopping wave volumes and their probability of exceedance (Equation 3). This chapter used the Weibull distribution to analyse such distributions for crossing seas states. The measured information from box number 4 was used to compute the overtopping volumes for each test due to the wave detector that was present only for this box. Two measurements were used to calculate the overtopping wave volumes: the cumulative water level in the box and the time of each overtopping wave reaching the detector.

3.1 Overtopping wave volumes

Using a MATLAB script, a cumulative water elevation for all the tests was determined based on the water level record from the gauge installed inside of the box and the pump characteristics. A lowpass filter was applied to remove the high-frequency response present in the cumulative water level record. A more stable signal was obtained in this way to compute the overtopping volumes.

The number of waves reaching the structure with crossing seas is not the sum of the individual number of waves for each sea state (sea or swell). The real number of waves is somewhere in between the two individual numbers of waves. The script also identifies the overtopping waves. It analyses the wave detector record identifying the sudden peaks based on a certain period which was the smallest wave period present in the test (see, Figure 4). Therefore, when the script identifies a peak, the next one will be identified after one wave period avoiding finding two peaks from the same wave.
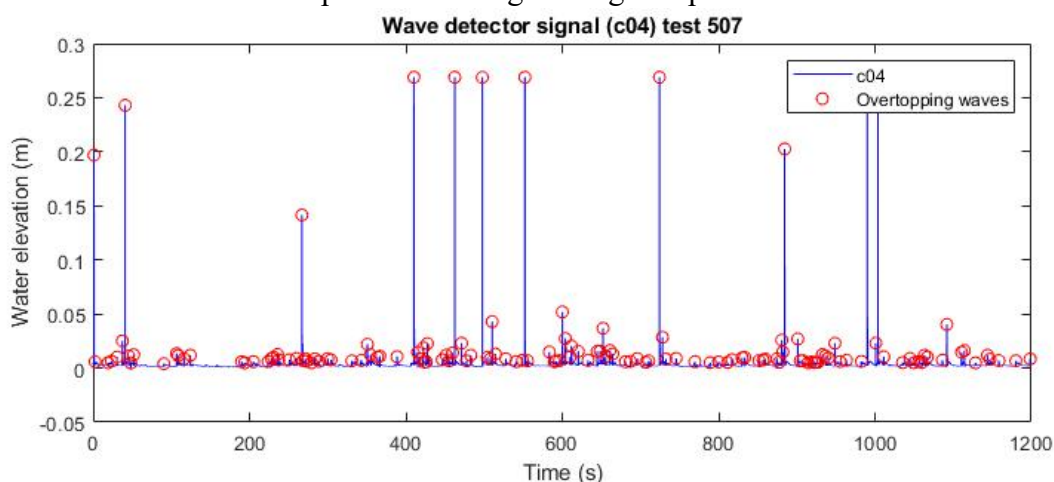

Figure 4   A part of the wave detector record (c04) and the overtopping waves detected (red cross).

With the cumulative water level and the time of the overtopping waves, a step graph was made to compute each overtopping volume based on the difference of water level between two overtopping waves. The step graph was made averaging the last 1 second of the water level measurements before the next overtopping wave. This was done to eliminate the water oscillation inside the box. Thus, the overtopping volumes were computed multiplying the difference of water level between two overtopping waves by the horizontal cross-section area of the collection box.

3.2 Shape parameter (b)

A distribution on a Weibull scale graph was drawn to compute the shape parameter b, see Figure 5. Here $P(V)$ is the probability of exceedance and V_{bar} is the average of all overtopping wave volumes. The upper part of the overtopping volumes usually presents a different inclination from the lower part. As the focus on this study is the largest overtopping volumes which is the most important part to predict, the distributions were fitted using the extreme values. The value of the shape parameter b is based on

the inclination of the fitted line. Figure 8 shows the difference between fitted lines using the upper values (red line) and all values (blue line).
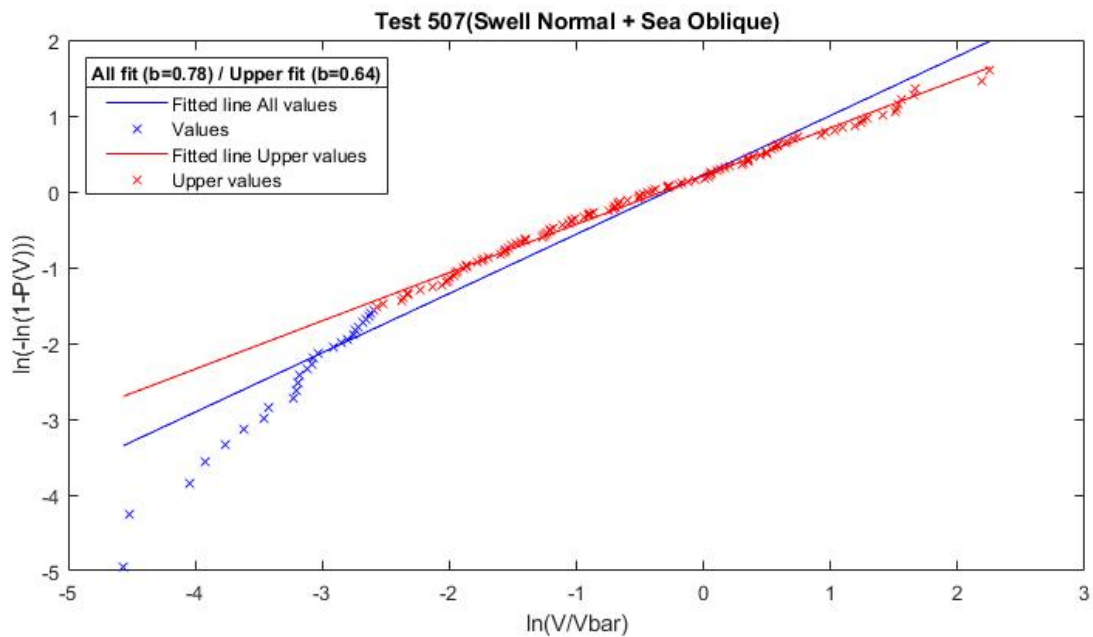

Figure 5   Fitting to the largest (red line) and all (blue line) overtopping volumes on a Weibull plot.

After fitting a line on the Weibull plot, a distribution curve was plotted to check if the extreme values chosen in the fitting on Weibull scale cover the largest overtopping volumes. Figure 6 clearly illustrates that the upper fit covers better the overtopping volumes than the other fit. It is therefore very important to fit the b-value for the largest overtopping wave volumes.
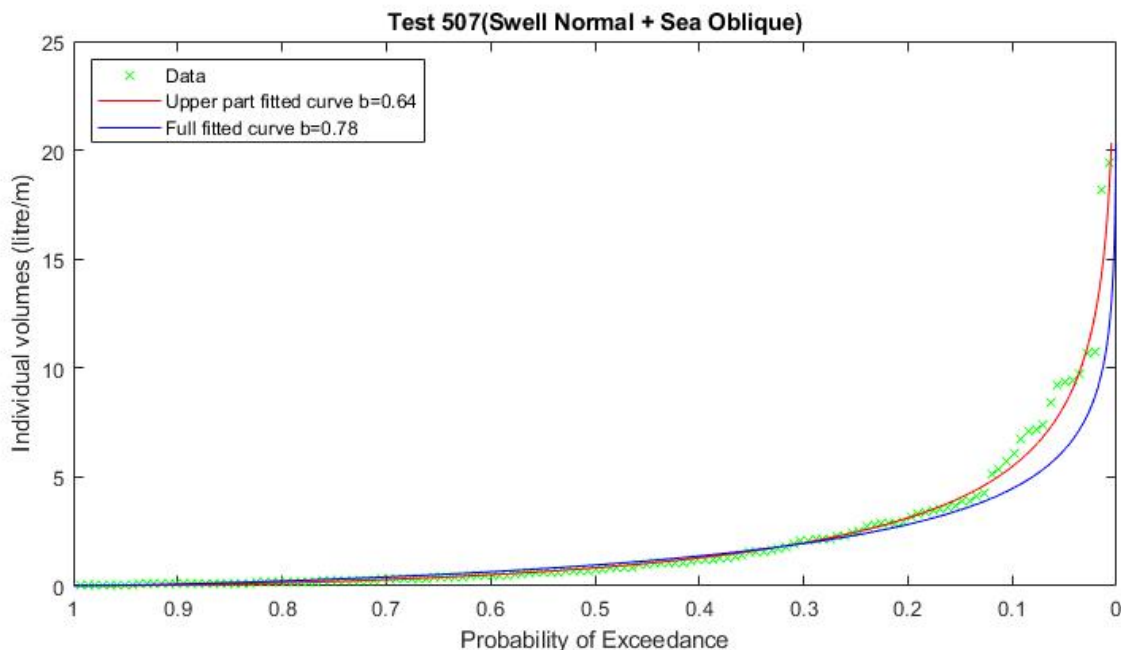

Figure 6   Distribution of overtopping wave volumes on linear scale in ascending order; upper values (red line) and all values (blue line).

The shape parameters were computed for the tests with more than 10 overtopping waves and relative overtopping discharges ($q/sqrt(g*H_{m0}^3)$) larger than 10^{-6}. Relative discharges lower than 10^{-6} should be regarded as no overtopping (EurOtop, 2018). This criterion was adopted after checking the tests with low relative discharge and their number of overtopping waves. In total 118 shape parameters were obtained from 170 tests, and 52 tests did not generate enough overtopping waves. Most of the tests that had not enough overtopping waves were from the single sea state tests (sea only and swell only).

4 Analysis of Results

The computed shape parameters in this study have been compared with the theoretical formulae proposed by Hughes et al. (2012) and Zanuttigh et al. (2013) to see how the shape parameters for crossing seas relate to the single sea. To better interpret the shape parameters they were divided into 8 groups (sea only, swell only, sea normal + swell oblique, swell normal + sea oblique, sea and swell same direction, crossing sea + swell oblique, swell + swell, and sea + sea) based on the wave system and the wave attack angle in relation to the structure. The wave periods used to compute the theoretical shape parameter for the tests (Eq. 6), were the ones measured by the wave gauges during the tests. These were consistent for all tests. It is more difficult to measure the incident wave heights with crossing seas and reflection from a structure. Analysis is ongoing. Most of the single sea states could be measured (and processed and analysed) in a reliable way. These wave heights were used to calculate the combined incident wave height for crossing seas. It is very important to make an analysis on the reliability of the measured and processed incident wave heights, but that is not part of this paper.

4.1 Prediction formula proposed by Hughes et al. (2012)

The first comparison was done with the proposed formula from Hughes et al. (2012). This formula (Equation 5) computes the shape parameter based on the relative freeboard R_c/H_{m0} for smooth sloped structures. The validity range of Eq. 5 is from $-1 < R_c/H_{m0} < 4$, which means from crests deep under water up to no or hardly overtopping and with b-values up to 3.5. The computed shape parameters from the tests are in the relative freeboard range of 1.2 to 3 and in the b-values range of 0.4 to 1.2 and give only a part of the full range of Hughes et al. (2012). Therefore, only the range where b-values have been determined, have been plotted with the prediction line proposed by Hughes et at. (2012), as shown in Figure 7 It shows that the shape parameters for single sea states (sea only and swell only) are around the line as expected. The majority of shape parameters for crossing seas states (except sea +sea tests) are below the prediction line. Moreover, the b-values show a more or less horizontal trend in the area where the line is increasing. This means that the prediction formula proposed by Hughes et al. (2012) to compute shape parameters for single sea states gives slightly higher b-values for crossing seas states than the measured ones.
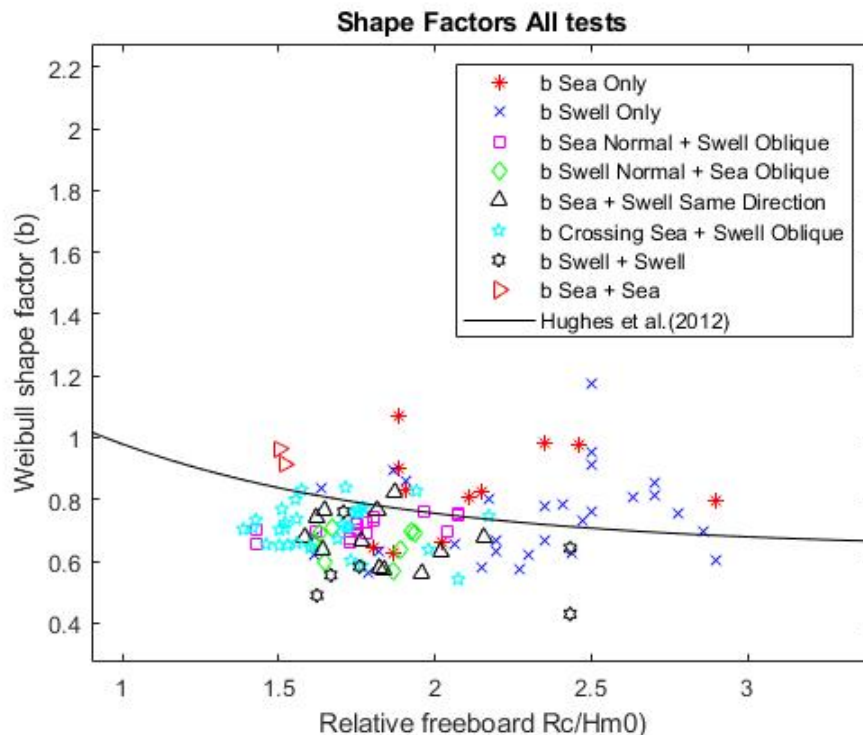

Figure 7   Weibull shape b-values compared with Hughes et al (2012), Eq. 5.

4.2 Prediction formula EurOtop proposed by Zanuttigh et al. (2013)

The prediction formula given in the EurOtop 2016 and proposed by Zanuttigh et al. (2013) to compute the shape parameter for smooth structures (Equation 6) were plotted with the shape parameters obtained in the tests (see, Figure 8). Also, here only the range of measurements is shown with the formula, not the whole range of validity (where we would have no new data). This formula computes the shape parameter based on the relative discharge and not on the relative freeboard. The graph below shows the b-values are close to b-values predicted by the formula, and they are located in the straight part of the prediction line where the values are around 0.75. The largest scatter is obviously found for the small overtopping discharges (relative discharge smaller than 10^{-5}). These tests have a small number of overtopping waves (around 20 overtopping waves), and their wave overtopping volumes are not well distributed, which affects the calculation of b-values. This means that if the wave parameters are unreliable (which still may be the case in this project), they will not influence the shape parameters computation as the shape parameters are located in a more or less horizontal line.
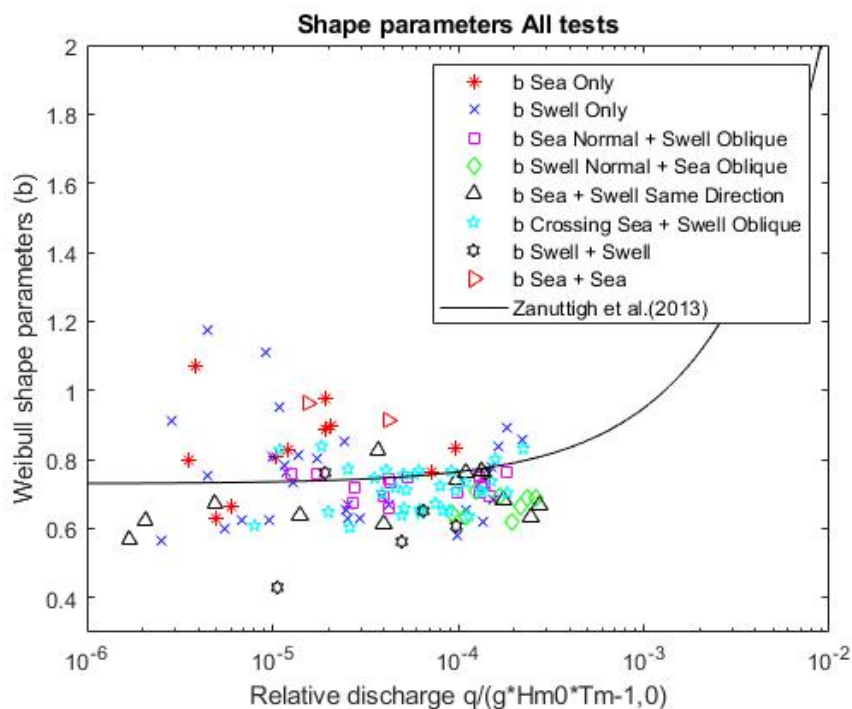

Figure 8   All shape parameters as a function of the relative discharge compared to Zanuttigh, et al. (2013) formula (solid line).

Figure 8 shows that there is a more or less horizontal trend for the shape parameter b for increasing values of relative discharge. Most of the shape parameters computed are concentrated in a relative discharge range of 10^{-5} to 10^{-3} and in a b-value range of 0.6 to 0.8. The shape parameters for single sea states (sea only and swell only) slightly deviate the prediction line as expected. This difference may be due to the single sea tests have small overtopping volumes and number of overtopping waves (relative discharge lower than 10^{-5} and N_{ow} lower than 50) which affect the computation of the shape parameter.

The average of the crossing seas shape parameters was calculated to compare with b=0.75 for single sea and small values of q proposed by Van der Meer and Janssen (1994). The mean b for the crossing seas test was b=0.71 which is close to the proposed for single sea. To know the reliability of the prediction formulae for the crossing seas shape parameters the *rmse* (root mean square error) has been computed and compared. The lower the *rmse* value, the more reliable the formula is. For two formulae used in this analysis, the following *rmse* values have been computed: 0.10 for the prediction formula from Zanuttigh, et al. (2013) and 0.13 for the prediction formula from Hughes, et al. (2012). Therefore, the Zanuttigh, et al. (2013) formula predicts more approximate values of shape parameters for crossing seas states than the other one. Figure 9 illustrates all shape parameters computed for smooth structures present in the EurOtop 2018 (Fig. 5.58) with the shape parameters computed in the *CrossOver* project compared with the prediction formula proposed by Zanuttigh, et al. (2013).
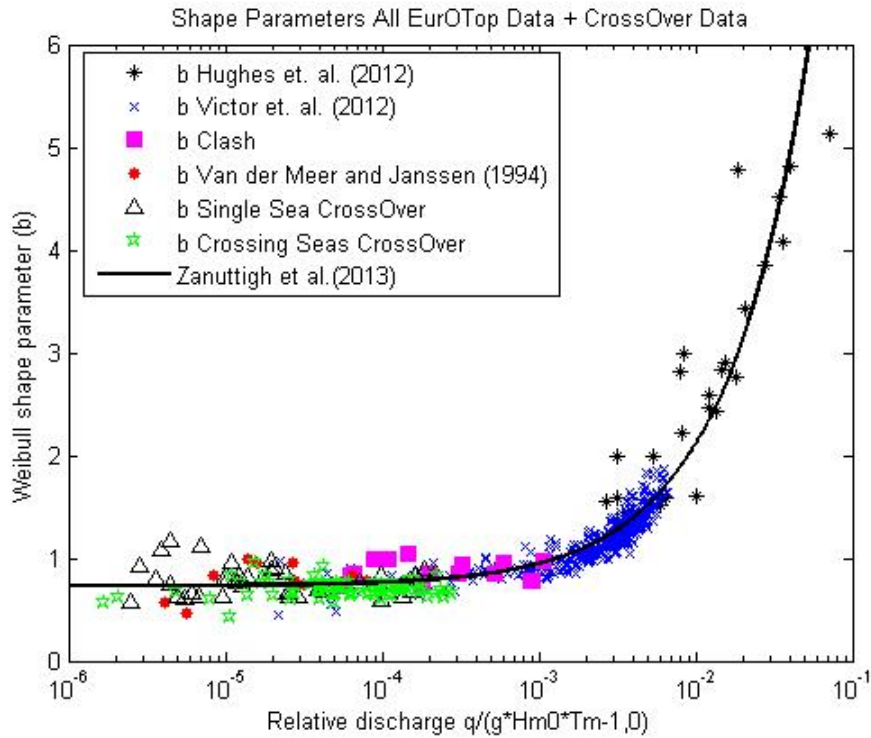
Figure 9   All shape parameters present in the EurOtop 2018 (Fig 5.58) with the CrossOver shape parameters compared with Eq.6.

5 Conclusions

From 170 physical model tests performed in the Delta basin at Deltares, 118 tests showed enough wave overtopping to compute the shape parameters b (41 of the single sea and 77 of crossing seas). The computed shape parameters were compared with the prediction formulae proposed by Zanuttigh, et al. (2013) and Hughes, et al. (2012) for single sea states.

The proposed formula by Zanuttigh, et al. (2013) (Equation 6) to compute the shape parameters for single sea states predicted approximate values of shape parameters for single sea and crossing seas states. The shape parameters computed from the tests are located in the flat part of the prediction line (relative discharge smaller than 10^{-3}) where the values are around 0.75. The root mean square error (*rmse*) was computed for the crossing seas shape parameters to know the reliability of the prediction formula, and the *rmse* obtained for the crossing seas shape parameters is 0.10.

The prediction formula proposed by Hughes, et al. (2012) (Equation 5) to compute the shape parameters b for single sea states gave approximate values of shape parameters for single sea and crossing seas states, but it predicted higher values of shape parameters for crossing seas than the prediction formula proposed by Zanuttigh, et al. (2013). The prediction line of Hughes, et al. (2012) formula starts increasing fairly quickly at the relative freeboard value of 2 and most of the crossing seas shape parameters are located between relative freeboard values of 1.5 to 2. The *rmse* obtained for the crossing seas shape parameters computed by Hughes, et al. (2012) formula is 0.13.

The prediction formula to calculate the shape parameter based on the relative discharge (Zanuttigh, et al., 2013) gave slightly more precise values of shape parameters for crossing seas states than the prediction formula based on the relative freeboard (Hughes, et al., 2012). This means that for crossing sea states it is important to consider the wave period in the prediction formula, like in the formula of Zanuttigh, et al. (2013).

The mean b-value ($b=0.75$) for small overtopping volumes q (relative discharge smaller than 10^{-4}) for single sea states proposed by Van der Meer and Janssen (1994) is close to the mean b-value ($b=0.71$) computed for crossing seas shape parameters.

This paper did not analyse the reliability of the wave parameters, as this is another part of the project, but if they are a little unreliable, it does not influence the shape parameter prediction, as the shape

parameters are located along a more or less horizontal line. An analysis of the wave parameters should be done for further studies on overtopping discharges.

Acknowledgements

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