

WAVE OVERTOPPING CHARACTERISTICS FOR A DOUBLE VERTICAL WALL AND THE EFFECT OF PARAPETS

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The mean wave overtopping discharge and extreme overtopping volumes were assessed for a double vertical wall solution, including the combined effect of the mutual distance and effect of parapets, also known as wave return walls or bullnoses. New empirical functions were derived for predicting the mean overtopping discharge and maximum overtopping volumes applicable for this design case. This study demonstrates the importance of analyzing the statistical characteristics of extreme overtopping volumes, especially for cases with low number of overtopping waves and steep volume distributions. It is argued that derivation of these statistics is essential for design of coastal structures and required drainage system at the hinterland. The analysis has shown that performing repetition tests is valuable, especially with cases of low number of overtopping waves. Generating more data allows for the derivation of more reliable statistics and in turn enables better quantification of the associated uncertainties. Statistical parameters of wave overtopping volumes showed that it provides critical design input for drainage and enable the generation of synthetic overtopping events with realistic distributions of wave overtopping volumes.

Keywords: overtopping; individual overtopping volumes; statistical distribution of wave overtopping; double vertical wall; parapet; wave return wall; bullnose wall; synthetic timeseries

INTRODUCTION

For the design of an offshore artificial island, approximately 40 kilometers off the coast of Belgium, a spatially efficient perimeter protection was required to strongly limit the wave overtopping. The artificial island will serve as energy hub for offshore wind energy and will have an interconnector function for other countries. The proposed design concept of the perimeter protection includes a double vertical wall, consisting of an outer seawall on the seaward edge of a caisson and a secondary wave wall that protects the island area. This creates a multi-purpose intermediate buffer zone that will also serve as catchment and drain excessive overtopping water in extreme situations.

This paper presents the assessment of the wave overtopping and the combined effect of the buffer zone width and effect of parapets on the wave overtopping performance, including analysis of mean overtopping discharge and individual overtopping volumes.

Design concept

The planned energy island will be located on top of the western ‘Hinder Banken’ in the Belgian North Sea, amid the Princess Elisabeth windfarm zone. The island concept design has a rectangle shape, where a small CTV harbor for berthing and safe crew transfer is included in the northeast corner of the island, see Fig 1. The island is subject to waves from all sides, although they are predominantly from the north and southwest. An unprotected quay area is located along the southeastern section of the island, taking advantage of the island’s natural sheltering.

The island will accommodate critical infrastructure that requires high safety levels and hence the admissible overtopping into the land area is low: $q < 1$ l/s/m with an exceedance probability of 1/1000 years. Given that the island is subject to extreme wave action with waves reaching up to $H_s = 8.3$ m (return period of 1000 years), limiting the wave overtopping while minimizing the footprint of the structure was challenging.

The land area will be protected by the perimeter protection, consisting of a caisson with a double vertical wall being 20~30m apart, including a parapet on top on both walls, creating a buffer zone that can catch and drain overtopping water towards the eastern side of the island during extreme events, see Fig 2. The required dimensions of the walls and the buffer zone depends on the overtopping rate and maximum volumes at the outside perimeter (1st wall), the subsequent drainage capacity and the amount of secondary overtopping and spray reaching over the 2nd (inner) wall at the end of the buffer zone.

For the dimensioning of the perimeter protection and the required drainage capacity of the buffer zone an assessment of overtopping discharge and volumes has been performed.

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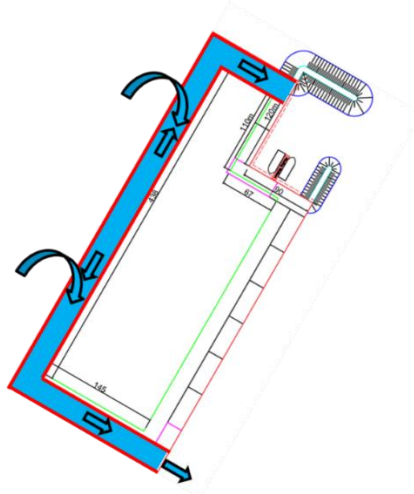


Figure 1. Island layout and principle of drainage of buffer zone.

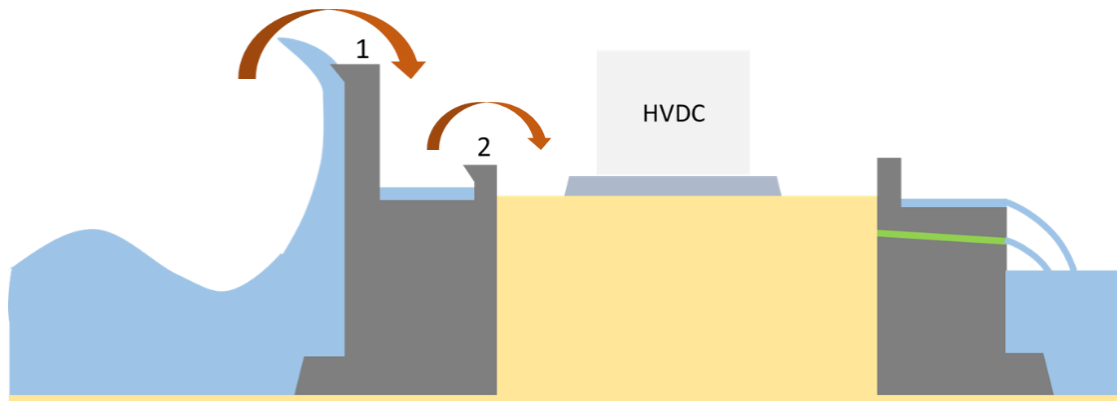


Figure 2. Design concept of double vertical wall with parapets and buffer zone, indicating 1st and second 2nd wave return wall.

METHODS

Physical model tests were performed in the 30 m long 2D wave flume at Ghent University. The double vertical wall design has been included on a Froude length scale of 1 in 48. At the structure the flume has been split in half to measure the mean overtopping discharge both at the 1st (outer) and 2nd (inner) wall simultaneously, while the individual overtopping volumes were measured only at the 1st wall. A schematic overview of the test setup is shown in Fig. 3.

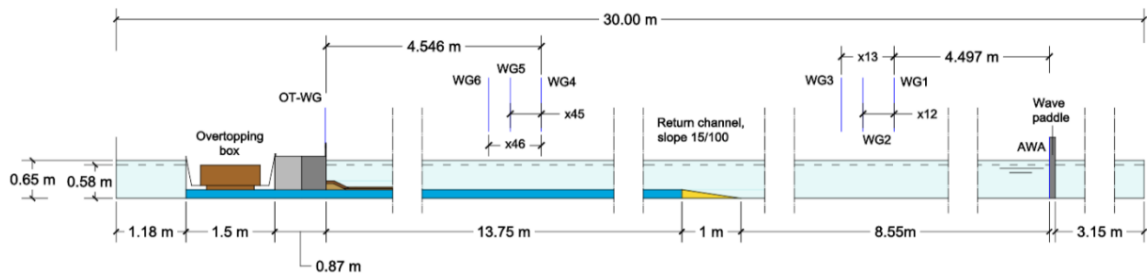


Figure 3. Schematic overview of test setup (model scale) in the Ghent University wave flume facility

Table 1 provides a summary of the test conditions that were applied (prototype scale).

Test No.	H _{m0} [m]	T _P [s]	Water level (m+LAT)
T1	5.5	10.3	6.5
T2	6.5	11.2	6.5
T3	7.7	12.2	6.5
T4	8.3	12.7	6.5
T5	6.5	11.2	5.5
T6	7.7	12.2	5.5
T7	8.3	12.7	5.5
T8	8.3	12.7	4.0
T9	8.3	12.7	3.0
T10	8.3	12.7	6.7
T11	7.7	12.2	7.5
T12	7.7	12.2	8.5
T13	8.3	12.7	8.5
T14	5.5	10.3	8.5
T15	6.5	11.2	8.5
T16	7.7	12.2	9.5
T17	8.3	12.7	7.5

Seven design scenarios were tested in the flume and applied in this study, with varying height of the 1st wall, buffer zone width (20 to 40 m), parapets (none, 1:1 and 1:2 shape) and the foreshore slope. Table 2 provides a summary of the design scenarios that are tested and specifies which test conditions were applied for each scenario. For all design scenarios the 2nd wall height was at +12 m LAT and the caisson top level at +10 m LAT. The parapet wall, or bullnose, was triangular shaped with dimensions specified in the table below. A horizontal sea bed is applied (except for DS6) at -17.5 m LAT, while including a 2 m thick scour protection and toe construction with top level at -10.3 m LAT in front of the structure, see Fig 4. To save valuable time, the height of the 1st wall remained the same from DS3 onwards (to avoid (re)construction works), but the water level was varied to represent different wall heights; as can be seen in the list of test conditions.

Design scenario	1 st wall height	Buffer zone width	Parapet 1 st wall	Parapet 2 nd wall	Test conditions	Remark
DS1	+19 m LAT	40 m	-	-	T1 – T10	-
DS2	+21 m LAT	40 m	-	-	T1 – T10	-
DS3	+19 m LAT	40 m	1m width x 1m height	-	T1 – T4, T6, T8, T11 – T16	-
DS4	+19 m LAT	40 m	1m width x 2 m height	-	T1 – T4, T6, T12, T13	-
DS5	+19 m LAT	40 m	1m width x 1m height	1m width x 1m height	T11 – T17 (T12 was repeated 5 times)	-
DS6	+19 m LAT	20 m	1m width x 1m height	1m width x 1m height	T11 – T17	-
DS7	+19 m LAT	20 m	1m width x 1m height	1m width x 1m height	T2-T4, T8, T9, T17	Same as DS6, with conservative siltation slope (~1:30) in front of the caisson

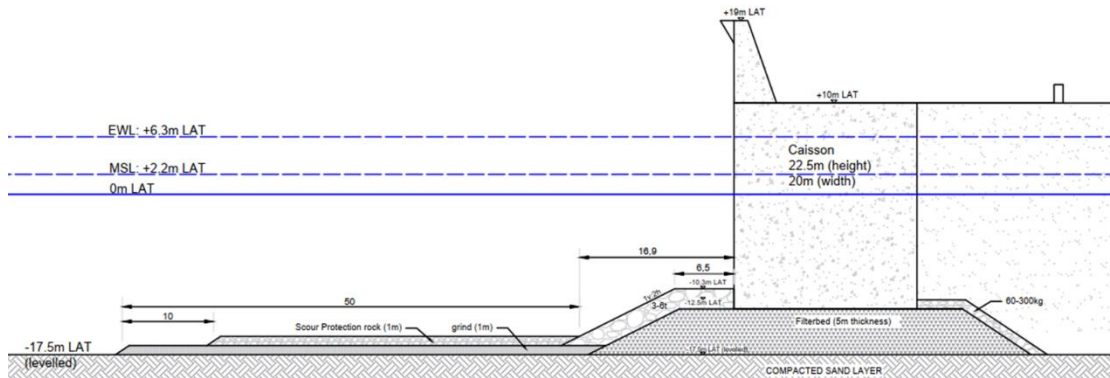


Figure 4. Concept drawing of the basic design configuration at the north/west/south side of the island

The method for analysis is based on two general design formulae for mean overtopping discharge for vertical walls for non-impulsive conditions as presented in EurOtop (2018), hereafter referred to as the manual. Two different formulas are considered: mean discharge without influencing foreshore (eq. 7.1 and 7.2 of the manual) and mean discharge with influencing foreshore (non-impulsive - eq. 7.5 and 7.6 of the manual). Due to the relation between the depth and the wave period no impulsive conditions were expected and also not observed during the tests. The relationship used for fitting the mean overtopping discharge for influencing foreshore is given by:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.05 \cdot \exp\left(-\alpha \cdot \frac{R_c}{H_{m0}}\right) \quad (1)$$

The relationship used for fitting the mean overtopping discharge for non-influencing foreshore is given by:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.047 \cdot \exp\left(-\left(\beta \cdot \frac{R_c}{H_{m0}}\right)^{1.3}\right) \quad (2)$$

Consistent fitting procedures have been adopted to derive the α and β parameter in the equations above. Least square logarithmic error fitting is used to derive the mean fit. Applying quantile regression technique the 5th and 95th percentile lines are fitted.

Comparison is made with the methods presented in Pearson et al. (2005) and TAW (2003) for the effectiveness of the parapet walls. The analysis of the overtopping volumes for parapet walls was based on, and has been compared to, the methods of (statistical) analysis for plain vertical walls presented in the manual.

RESULTS

Mean overtopping discharge double plain vertical wall without parapets

The results for the double vertical wall without a parapet is shown in Fig. 5, which includes the test data from DS1 and DS2. In black the test data and fit is shown for the 1st (outer) wall. The data showed good correspondence with the relationship based on the influencing foreshore (Eq.1). The fitted parameter $\alpha=2.93$, which is slightly higher than the manual suggests for plain vertical walls with influencing foreshore ($\alpha=2.78$)

In red the test data and fits are shown for the 2nd (inner) wall. For the inner wall the data showed better fit for the relationship for non-influencing foreshore (Eq. 2). The dashed lines show the 90% confidence band. The fitted parameter $\beta=2.74$ (mean). It is noted that some of the resulting overtopping discharge are relatively low ($<10^{-6}$).

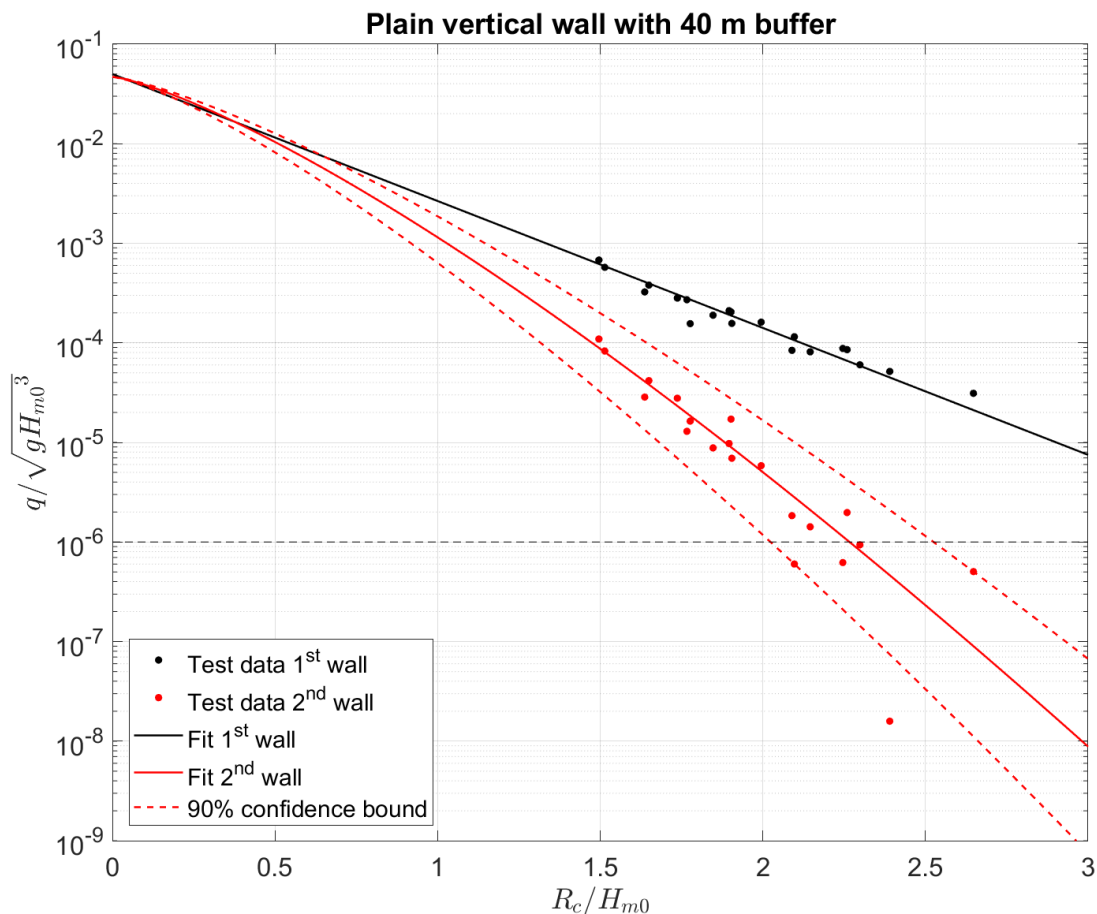


Figure 5. Fitted relations for plain vertical wall (DS 1 and DS 2). In black the test data and fit for the 1st (outer) wall and in red the test data and fits for the 2nd wall, including the 90% confidence bound.

Mean overtopping discharge outer (1st) wall with parapet

All the test data that included a parapet (bullnose) at the outer wall has been aggregated to assess the effect of the parapet on the mean overtopping discharge rate over the 1st (outer) wall. Fig. 6 shows the test data and fits for the relative mean overtopping discharge.

No significant different trend between the considered design scenarios are found: the 1:1 and 1:2 parapet configuration and the foreshore siltation slope. Although it may be argued that the number of tests with a 1:2 parapet are insufficient to draw this conclusion.

The scatter is relatively large, especially in the region where the relative overtopping $< 10^{-6}$. The manual argues that relative overtopping below $< 10^{-6}$ may be used as limit for ‘zero overtopping’ in a laboratory and is therefore omitted in the fitting. One test showed actual zero overtopping.

Although the plain vertical wall results shows similarity with the formula with influencing foreshore (Eq. 1), see the black line in Fig 5, the test results with the parapet show a similar trend as the formula without influencing foreshore (Eq. 2). The fitted parameter $\beta=3.18$ with the 5th and 95th percentile lines, $\beta=3.61$ and $\beta=2.77$ resp. Compared with the fits in Fig 5 it is clear that the parapet significantly reduces the overtopping discharge.

The results with parapet were also compared with two existing methods that are presented in the manual: a reduction factor applied within the basis formulae (TAW, 2003) and the use of a factor describing the ratio between the overtopping discharge with and without parapet (Pearson, 2005). Based on the results it is concluded that both methods underestimate the effect of the parapet, i.e. overestimate the mean overtopping discharge for the tested design scenarios.

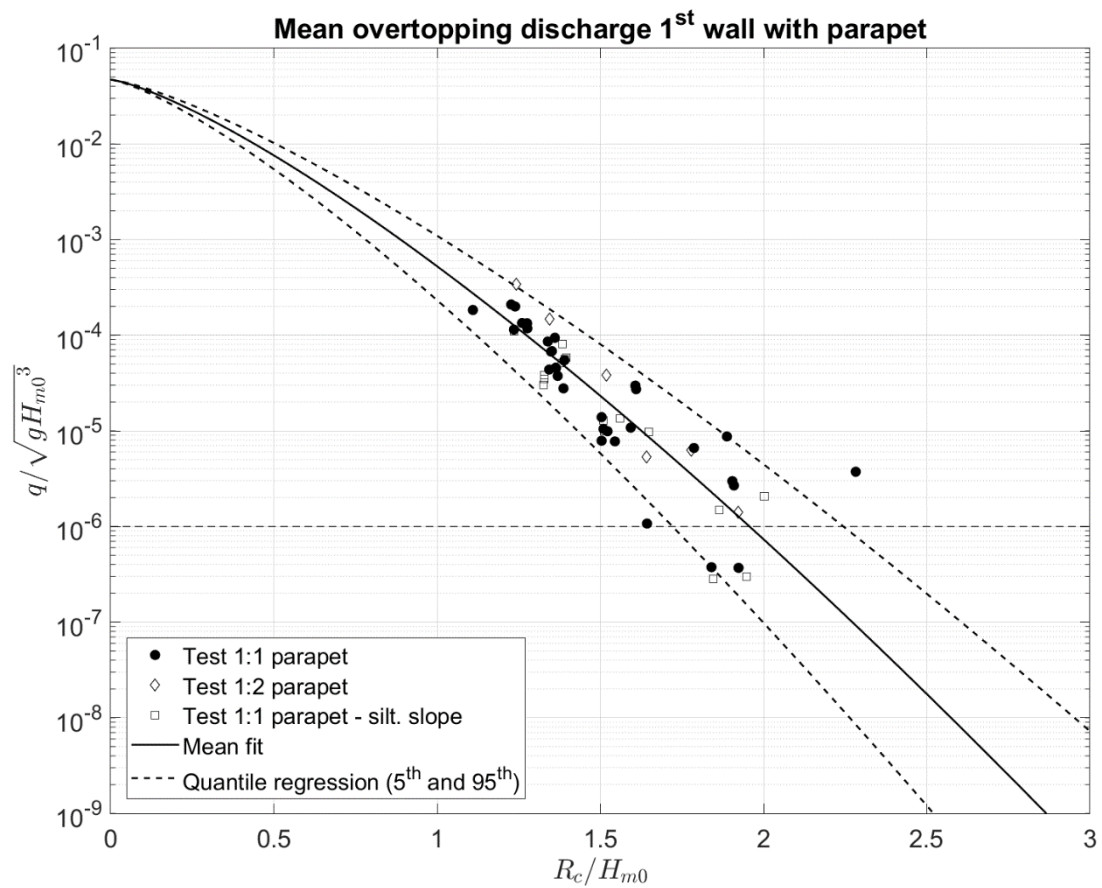


Figure 6. Fitted relations for 1st (outer) vertical wall with the parapet.

Mean overtopping discharge double vertical wall with parapet

The effect of the dimensions of the buffer zone and the impact of a parapet on top of the 2nd wall is assessed by fitting the mean overtopping discharge over the 2nd (inner) wall for each separate design configuration. The following figures (Fig 7, Fig 8 and Fig 9) show the test data and fits for the different configurations. All fits are based on the formula for non-influencing foreshore (Eq. 2). In all the figures below the test data and fit for the 1st (outer) wall from Fig 4. has been plotted in black as reference.

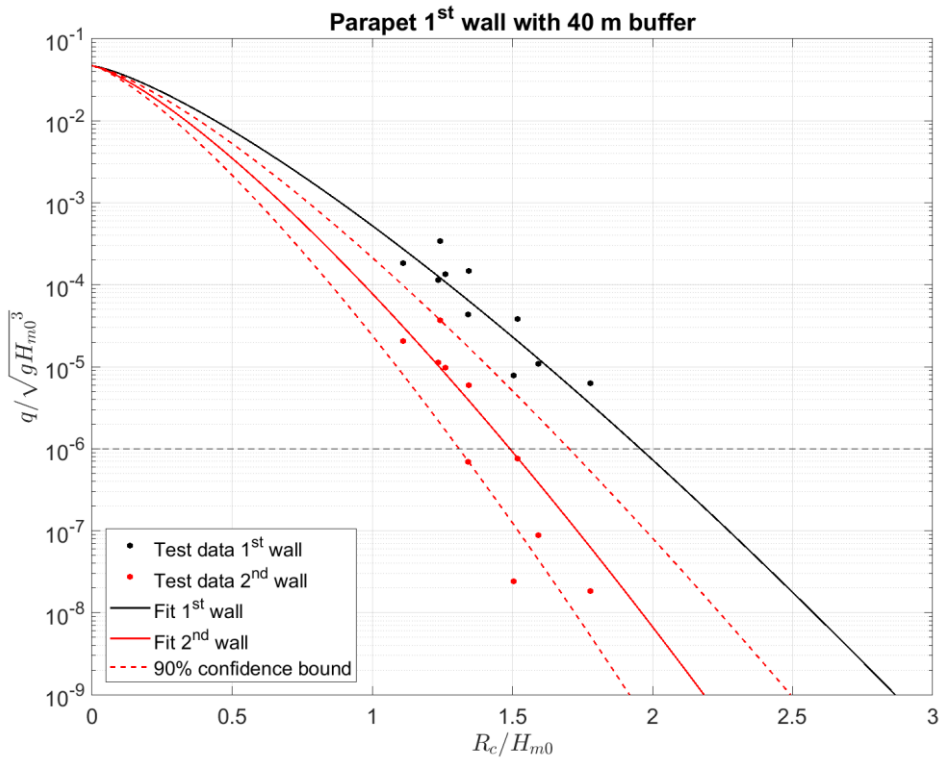


Figure 7. Fitted relation for overtopping discharge 2nd wall for double vertical wall with parapet on 1st (outer) wall, a 40 m buffer zone and plain vertical 2nd (inner) wall of 2 m high.

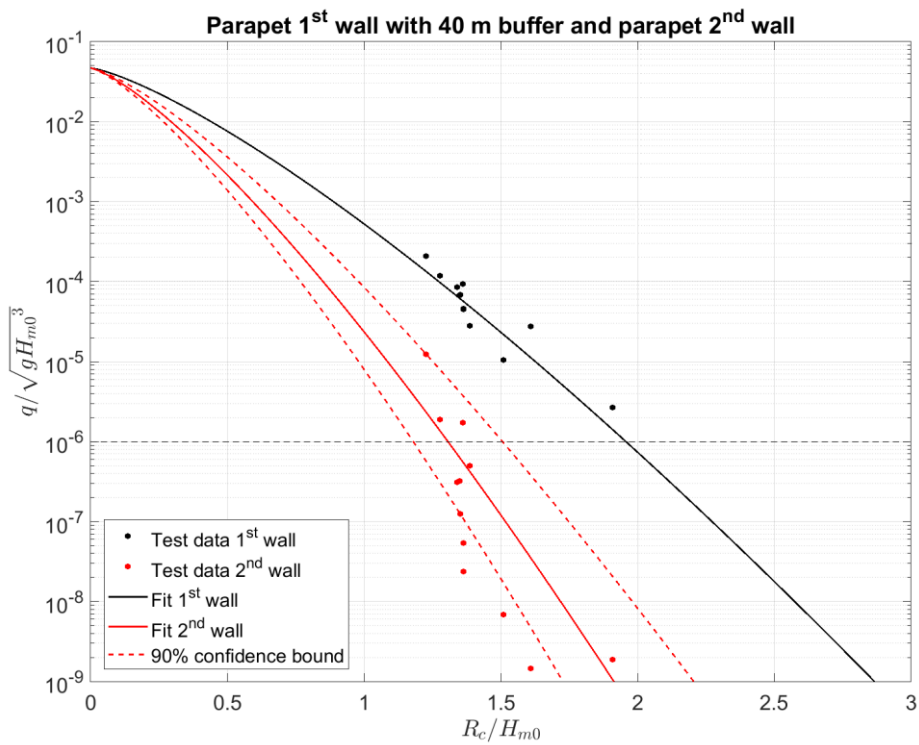


Figure 8. Fitted relation for overtopping discharge 2nd wall for double vertical wall with parapet on 1st (outer) wall, a 40 m buffer zone and a 1:1 parapet on the 2nd (inner) wall of 2 m high.

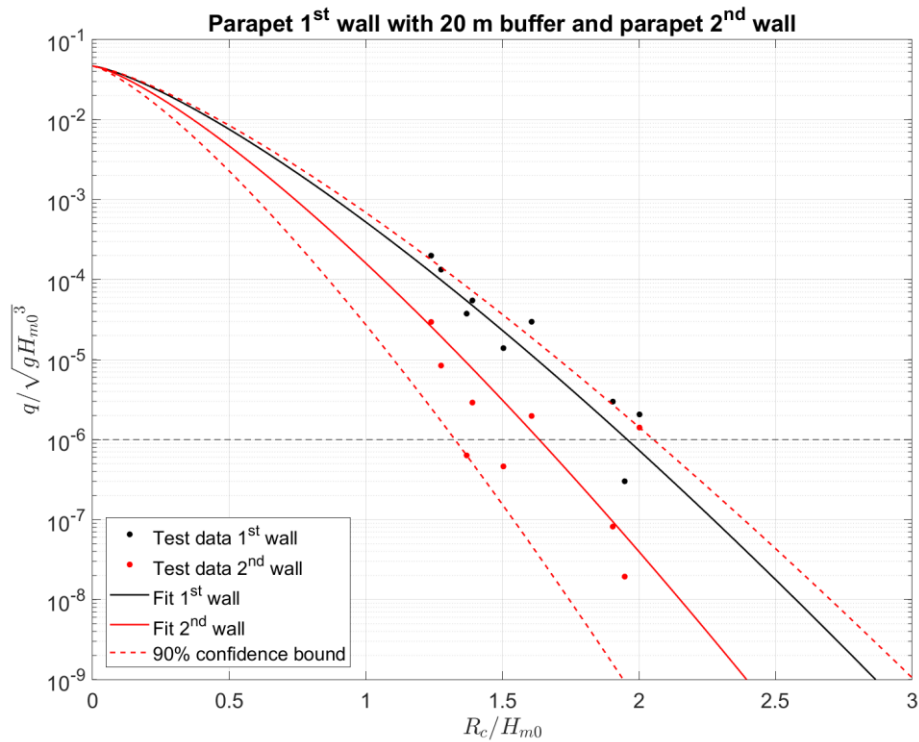


Figure 9. Fitted relation for overtopping discharge 2nd wall for double vertical wall with parapet on 1st (outer) wall, a 40 m buffer zone and a 1:1 parapet on the 2nd (inner) wall of 2 m high.

The figures above show the strong effect of the parapet and buffer zone width on the resulting overtopping discharge over the second wall. Comparing the results in Fig 7 and Fig 8., a parapet on the 2nd wall seems to be very effective. For some cases significant number of tests showed very low overtopping ($<10^{-7}$), especially for the configuration with the parapet on both walls and a buffer zone of 40 m. These tests were not considered for the fit. The results showed the intended impact by strongly limiting the wave overtopping at the land area. Table 3 shows the fitted parameters (β in Eq. 2) for the different design configurations, including the 90% confidence bounds.

Design configuration	Mean	5 th perc	95 th perc
Plain double wall with 40 m buffer	2.74	3.07	2.46
Parapet on 1 st wall and 40 m buffer	4.18	4.75	3.65
Parapet on 1 st and 2 nd wall and 40 m buffer	4.76	5.27	4.13
Parapet on 1 st and 2 nd wall and 20 m buffer	3.80	4.69	3.03

Overtopping volumes

During the tests the individual overtopping volumes at the 1st wall have been measured. The statistics of these individual volumes and there extremes are relevant for the assessment of the required drainage capacity of the buffer zone. The number of overtopping waves, the distribution of the volumes and the expected maximum volume during an event are important parameters for design and safety assessments.

Probability of overtopping

The probability of overtopping (P_{ov}) is derived from the ratio between the number of overtopping waves and the total number of waves during the tested event. The probability of overtopping waves is a exponential function and has the following form:

$$Pov = \exp \left[k \left(\frac{R_c}{H_{m0}} \right)^2 \right] \quad (3)$$

The factor of the exponential function (k) is fitted to the test data to derive an new empirical formula for parapet wall data. The manual suggests a $k=-1.21$ for vertical walls and non-impulsive conditions.

For the fitting an average of $N_w=1180$ number of waves is applied, based on the results of the physical model testing.

Fig. 10 shows the frequency of the overtopping for the test data in relation to the dimensionless freeboard and the fitted relations for the tests with parapet (red) and without parapet (black). The fitted factor (k) for parapet walls is $k=-1.85$ and for the plain vertical wall $k=-0.73$.

There is a clear distinction notable caused by the effect of the parapet. As expected, due to the parapet the number of overtopping waves are significantly lower than for the plain vertical wall. For most test data with the parapet the number of overtopping waves are less compared to the data without parapet.

It seems that the coefficient provided in manual (blue line in Fig. 9) gives a underestimation of the recorded number of overtopping waves for the plain vertical wall in the tested design configuration. The only available formula in the manual that may lead to higher estimations is for impulsive waves. However for the overtopping discharge measurements there was no trend found that these are in fact impulsive waves. Visually also no impulsiveness was observed.

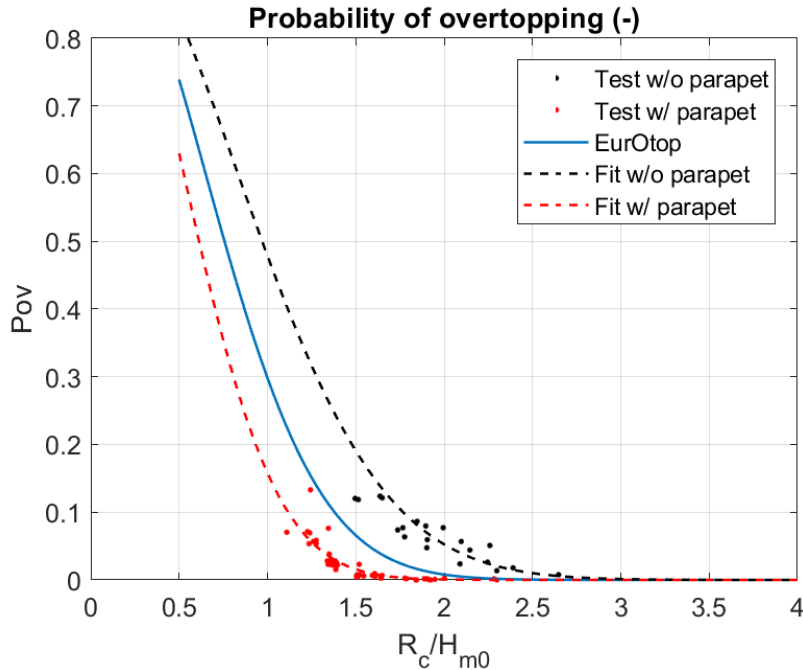


Figure 10. Probability of overtopping and fitted relations

Distribution of overtopping volumes

The distribution of individual overtopping volumes are usually approximated by the two parameter Weibull distribution. The exceedance distribution over overtopping volume is given by:

$$P_V = 1 - \exp \left[- \left(-\frac{V}{a} \right)^b \right] \tag{4}$$

The two parameters of the Weibull distribution are the non-dimensional shape factor, b , and the dimensional scale factor, a . Following the manual the factor a is derived using the following equation:

$$a = \left(\frac{1}{\Gamma(1+\frac{1}{b})} \right) \left(\frac{qT_m}{P_{ov}} \right) \tag{5}$$

Where Γ is the mathematical gamma function. It is noted that the shape factor, b , is also included in the derivation of the scale factor, a . Following the manual, for plain vertical wall the shape factor, b , is empirically found to be $b=0.82$ (non-impulsive waves and steepness of $s_{m-1,0}=0.04$). The scale factor, a , is by the definition in in Eq. 5 unique for every test and event. The shape factor, b , is expected to be unique for every design configuration, although similar for each test with the same design configuration.

Fitting of the volume distributions of each test did not provide consistent results, especially for the data with the parapet. The number of overtopping waves per test was relatively low leading to little data points for accurate fitting and there were too much outliers.

One particular test has been repeated (DS5 – T12) for 5 times, leading to a total of 6 repetition tests with different seeding applied at the wave paddle. By combining the test data of these test, sufficient data points are available for fitting the distribution; see Fig. 11. The shape factor, b , has been fitted on the high volumes to $b=0.52$ and is shown as the dashed black line. The red dashed line shows the $b=0.82$ as suggested by the manual for plain vertical walls as reference. It is clear that the volume distribution has a very steep tail, mostly caused by the parapet wall.

This illustrates the value of performing repetition tests, especially in cases with low number of overtopping waves and thereby generating more data and thus enable to perform better statistical analysis on the data.

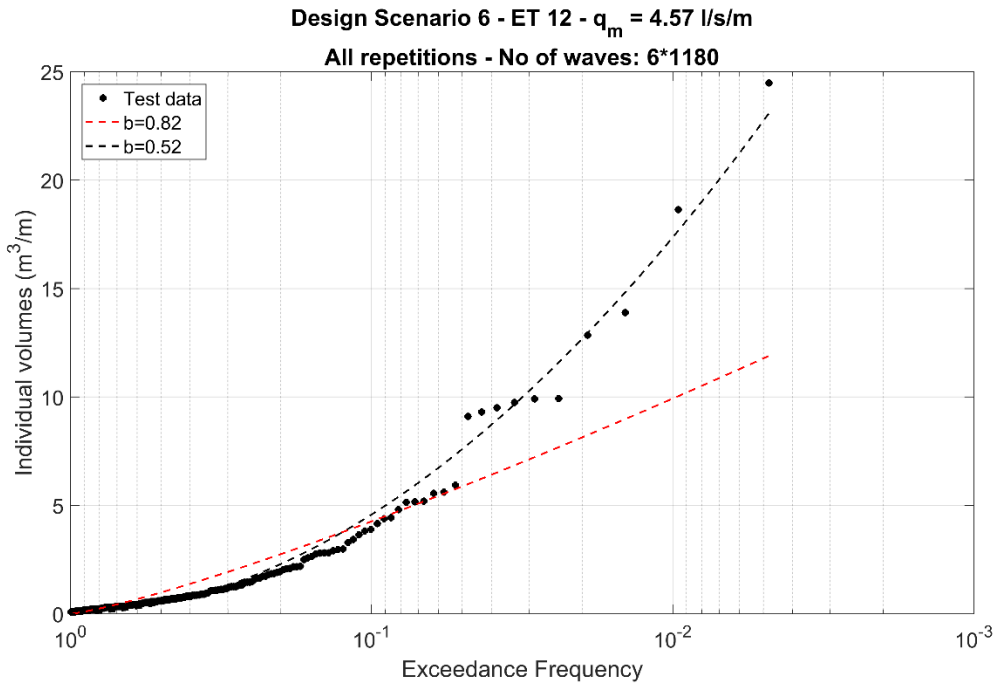


Figure 11. Fitted individual volume distribution on repetition test data for DS 6 – T12,

In order to derive a single shape factor for each design configuration, i.e. with or without parapet wall a fitting procedure has been adopted that uses the maximum volume per test only. For the prediction of the maximum overtopping volume in a given distribution (a and b from Eq. 4) the following formula can be used:

$$V_{max} = a(\ln N_{ov})^{1/b} \quad (6)$$

Where N_{ov} is the number of overtopping waves, derived using the probability of overtopping and the total number of waves per test. The shape factor, b , has been fitted on the measured individual maximum volumes of all tests, using Eq.5 and Eq. 6 and the least square method. The fit is performed on the test data which has a probability of overtopping >0.01 , which implies that it includes at least. 10 data points for a reasonable estimate of the maximum volume per test.

Fig. 12 shows the results of the fitting procedure by comparing the predicted and measured maximum individual volume for the fitted shape factor, b , for both the plain vertical wall and the parapet wall separately.

For the plain vertical wall, the fitted shape factor, $b=0.78$ seems to be reasonable for the prediction of maximum volume for plain vertical walls and is relatively close to the suggested $b=0.82$ from the manual. Also the errors of the fit are reasonable: RMSE = 3.01 m³/m.

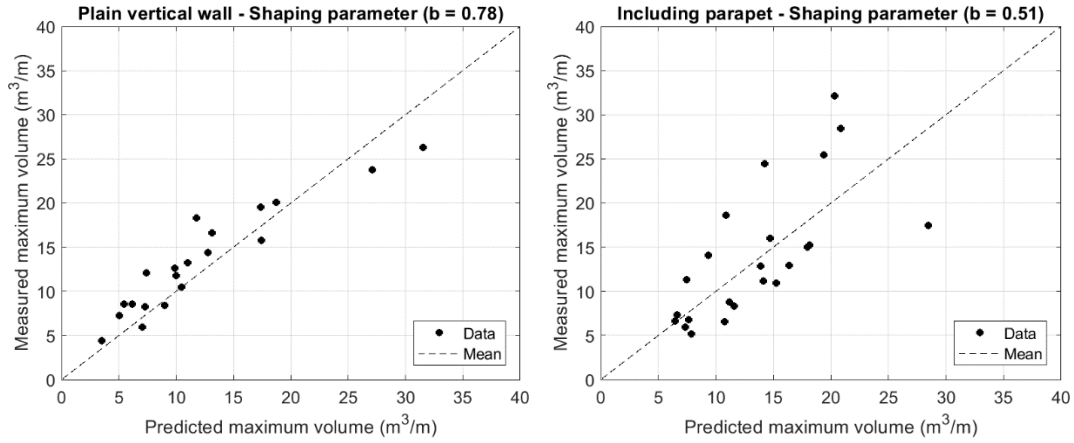


Figure 12. Fitted shape factors, b, on maximum individual volume for plain vertical walls (left) and vertical wall including parapet (right).

The fit for the shape factor for maximum overtopping volume for the wall with parapet is shown in right panel of Fig. 12. The fitted shape factor is $b=0.51$, indicating a much steeper distribution compared to plain wall. The scatter of the maximum overtopping volumes is large for data with a parapet with only limited number of overtopping waves. The accuracy is worse compared to the fit for plain vertical walls and the RMSE = 5.24 m³/m (on the data with $P_{ov}>0.01$). Therefore the uncertainty related to these estimations is relatively large and should be interpreted with care.

Distribution of maximum overtopping volumes

The reason that the scatter is large for the parapet data is a combination of the low probability of overtopping and the steep tail of the distribution of the overtopping volumes. This steep tail makes the uncertainty of the predicted maximum volume significantly larger compared to the maxima associated with flatter tail distribution.

This can be explained by the exceedance distribution of the maxima:

$$P(V_{max} > V)|Dur = 1 - (1 - P(\underline{V} > V))^{N_{ow}} \tag{7}$$

Where $P(\underline{V}_{max} > V)|Dur$ is the exceedance distribution of the maximum volume within a given duration (*Dur*) of an event, $P(\underline{V} > V)$ the exceedance distribution of the individual volume (Eq. 4) and N_{ow} the number of overtopping waves.

Fig 13. shows the distributions of maximum volumes for two different shape factors, $b=0.5$ and $b=0.82$, but with same mean overtopping discharge ($q = 10$ l/s/m) and number of overtopping waves (~38). It shows that the *b*-parameter has significant effect on the distribution of the maximum volume. The predicted maximum volume (derived using Eq. 6) is shown as the dashed black lines. This value is exceeded by a probability of 0.63 and is the mode of the distribution (for narrow distributions), also known as the Most Probable Maximum.

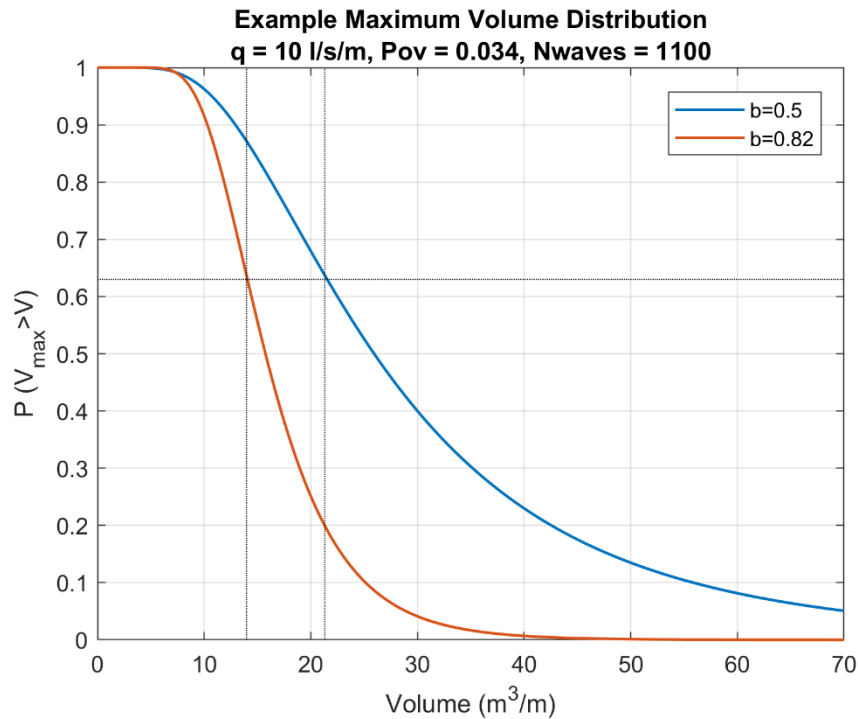


Figure 13. Example of maximum volume distributions for two different shape factors (b) with equal mean overtopping discharge and probability of overtopping waves.

However it should be acknowledged that the presented distributions in Fig. 13 are theoretical distributions and are in reality physically limited., e.g. the tail of the distribution for $b=0.50$ shows unrealistically high overtopping volume in the tail. The physical limitations to the maximum volume distribution is given by the mean overtopping discharge and probability of overtopping that are associated to the event.

To demonstrate that effect, a large number of events have been simulated using the theoretical distributions described in Eq. 4. and Fig. 11. Then the sample events that result in a mean overtopping discharge that deviates too much ($\pm 1\%$) from the mean overtopping discharge that is been used as input have been removed from the sample. From the resulting sample set the empirical distribution has been derived. The resulting distribution for $b=0.50$ is shown in Fig. 14, where the simulated distribution (blue) shows a significantly narrower distribution of the maximum volume distribution compared to the theoretical distribution (red). The predicted maximum still shows the same probability of exceedance (0.63). Here the 90% bound shows that the maximum volume is approximately in between 15 and 40 m^3/m with the most probable value of just above 20 m^3/m .

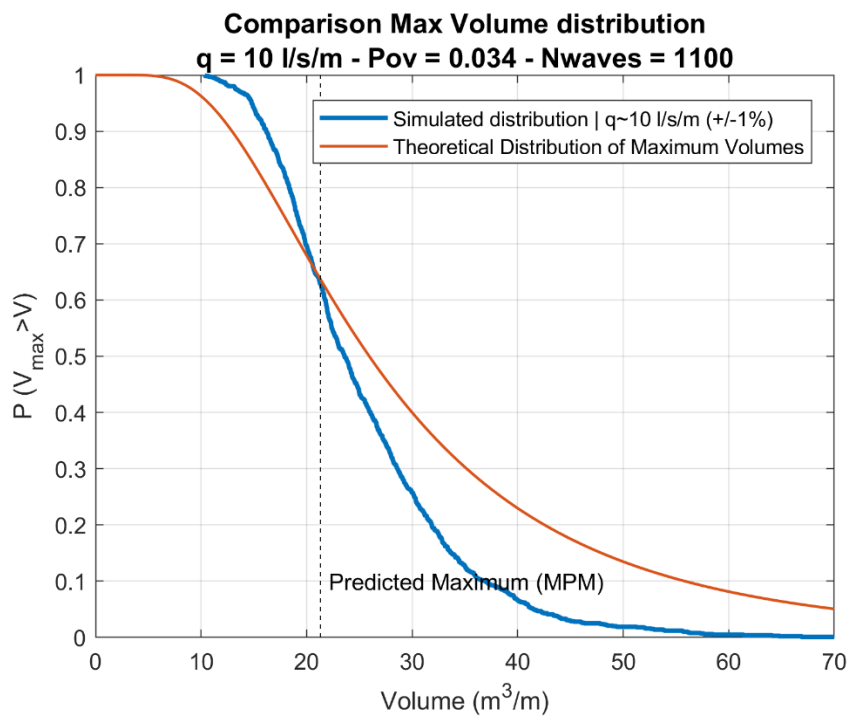


Figure 14. Comparison of physical limited maximum volume distribution and theoretical distribution using shape factor of $b=0.50$.

DISCUSSION

All the derived fits and empirical functions are only applicable for the design configurations as described in this paper and are specifically applied for the dimensioning of the perimeter protection for this artificial island.

Especially for cases with very limited number of overtopping waves, and steep overtopping distributions, which is common for vertical walls with high relative freeboard and parapet walls, it is essential to gain detailed understanding of the distribution of the volumes and their maxima in order to be effectively used for (drainage) design. The analysis of the individual overtopping volumes revealed the added value of performing repetition tests generating more reliable statistics.

The presented distributions demonstrates that the predicted maximum volume using Eq. 4 should be used with care, since the probability that the predicted maximum volume is exceeded during an actual event is relatively large (0.63). The associated uncertainty can be very large as well, especially for steep distributions: in this case over 100%.

The method of deriving the physically realistic distribution (Fig. 14) was found to be very valuable for design and subsequent (drainage) assessments. It enables the quantification of the expected uncertainty bounds related to the expected extreme overtopping volumes. By the generation of sample events of overtopping volumes, realistic synthetic timeseries of overtopping volumes were constructed by combining them with random generated timeseries of waves. These timeseries may form valuable input for drainage models and can be used to assess the effect of variability of overtopping events.

The above analysis of the maximum overtopping waves considers given fixed mean overtopping discharge and number of overtopping waves. It should be acknowledged that these parameters are also stochastic, increasing the associated uncertainty of the parameters even more.

CONCLUSIONS

This paper present the analysis of overtopping characteristics for a double vertical wall and the effects of parapets. Physical model tests were performed for 7 different design configurations, measuring the mean overtopping discharge at both the 1st (outer) and 2nd (inner) wall simultaneously and individual overtopping volumes at the 1st wall only.

Empirical functions were derived for mean overtopping discharge for the design configurations presented in this paper. The results show that a parapet is very effective on both the 1st and 2nd wall in reducing the overtopping and in is for this case more effective than predicted in the EurOtop manual.

Statistical analysis has been performed on the individual overtopping volumes to derive the shape factor, b , of the distributions for the different design configurations. The results of the parapet wall showed both a very steep tail of the distribution and low number of overtopping waves. This both leads to a very wide distribution of maxima and hence large associated uncertainty.

A method has been proposed to derive physically realistic distributions of maximum overtopping volumes allowing to quantify the uncertainty associated with the predicted maximum overtopping volume, which in this case reached over 100%.

This study demonstrates the importance of analyzing the statistical characteristics of extreme overtopping volumes, especially with cases with low number of overtopping waves and steep volume distributions. It is argued that derivation of these statistics is essential for design of coastal structures and required drainage system at the hinterland.

The analysis has shown that performing repetition tests is valuable, especially with cases of low number of overtopping waves. Generating more data allows for deriving more reliable statistics and in turn enables better quantification of the associated uncertainties. Statistical parameters of wave overtopping volumes showed that it provides critical design input for drainage and enable the generation of synthetic overtopping events with realistic distributions of wave overtopping volumes.

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