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EXPERIMENTAL STUDY OF AVERAGE OVERTOPPING PERFORMANCE ON STEEP LOW-CRESTED STRUCTURES FOR SHALLOW WATER CONDITIONS

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ABSTRACT

Wave overtopping is a key design parameter of the sea defence structures. A good knowledge of the overtopping process is required to assess the safety of coastal structures and to improve the design guidelines. The scientific literature available about wave overtopping is extensive, although there are still knowledge gaps to be filled. Wave overtopping data available for steep low-crested structures are limited and the recent research carried out at Ghent University (Belgium) has been focused on these type of structures in deep water conditions. Wave overtopping for steep low-crested structures in shallow water conditions remains however a knowledge gap. Therefore we performed 2D physical model tests for steep low-crested structures in shallow water conditions, obtaining the new dataset 'UG15'. This paper summarizes the recent developments of wave overtopping with a focus on shallow water conditions, describes the physical model tests, discusses the average overtopping results and compares these new results with the existing prediction formulae, drawing conclusions about the behavior of wave overtopping in depth-limited conditions. The most recent overtopping formulae predict accurately the overtopping rates although presenting some inaccuracies. The shallow water effects increase the overtopping rates for very steep slopes and for vertical walls with large values of the relative crest freeboard.

KEWORDS: coastal structures, wave overtopping, steep low-crested structures, shallow water, experimental modelling

1 INTRODUCTION

Wave overtopping is a governing process in the protection against coastal flooding, being also a key design parameter of the sea defence structures. Due to climate change, the sea level is rising together with an increase of the storminess. This results in an increase of wave attack and wave overtopping which supposes a risk to people and infrastructure located near the coast. To assess the safety of the coastal structures and to improve their design guidelines a detailed knowledge of the wave overtopping average rates and individual overtopping volumes under different wave conditions that may pass the sea defence structure is required.

The scientific literature available about wave overtopping is extensive. The EurOtop (2007) manual summarizes the wave overtopping knowledge of various wave conditions and coastal structures types. However, there are still gaps on wave overtopping knowledge that should be filled to improve the understanding of the overtopping process in all wave conditions and for all structural parameters. The wave overtopping knowledge for steep and very steep low-crested structures (including vertical walls) is very limited and thus at Ghent University (Belgium) different physical experiments have been carried out.

Victor and Troch (2012a, 2012b) performed overtopping experiments on steep structures with small crest freeboards, resulting in the dataset 'UG10'. To extend this dataset towards the limit of the vertical wall and towards the zero freeboard condition, Troch et al. (2015) performed experimental tests, forming the dataset 'UG13'. Both datasets UG10 and UG13 were obtained on deep water wave conditions. However, the overtopping knowledge is also limited in the case of steep low-crested structures in shallow water conditions. As a transition between both depth conditions, Gallach-Sánchez et al. (2014) obtained the dataset 'UG14' featuring overtopping data for very steep slopes and vertical walls with small, very small and zero freeboard. The dataset UG14 included data both for deep water and shallow water conditions, giving a first approximation of the differences in overtopping behaviour due to shallow water effects. However the number of tests in shallow water conditions was limited and therefore the conclusions obtained from the analysis of the results are weakened a more detailed study. Gallach-Sánchez et al. (2015) analyzed the main differences between the UG13 and the UG14 dataset, and therefore between deep water and shallow water conditions.

To increase the knowledge of wave overtopping and to confirm the previous results obtained, we performed experimental model tests for steep low-crested structures in shallow water wave conditions at Ghent University. These tests form the so-called dataset 'UG15' which is an extension towards the shallow water wave conditions of the dataset UG14. The new dataset UG15 has a range of slope angles α from steep to vertical walls, and a range of relative crest freeboards R_c/H_{m0} (where R_c is the crest freeboard and H_{m0} the incident significant wave height) from large to small.

This paper first summarizes the existing knowledge about wave overtopping of steep low-crested structures, focusing on the EurOtop (2007) and van der Meer and Bruce (2014) overtopping prediction formulae. The paper also presents the experimental test set-up and the test programme of the new dataset UG15, the average overtopping rates of this dataset, and a comparison of the results with the dataset UG14 and with the overtopping prediction formulae. Finally it and discusses the accuracy of the existing formulae and provides conclusions..

2 EXISTING KNOWLEDGE OF WAVE OVERTOPPING

Many authors have studied wave overtopping and have proposed average overtopping prediction formulae. The EurOtop (2007) manual summarizes all the formulae available for various wave and structural parameters. It includes average overtopping prediction formulae for sea dikes and sea walls, also including formulae for individual overtopping distribution. The EurOtop (2007) overtopping prediction formula for mild slopes (probabilistic design) is described in Eq. (1).

$$\frac{q}{\sqrt{gH_{m0}^3}} = \frac{0.067}{\sqrt{\tan\alpha}}\gamma_b \cdot \xi_{m-1,0} \cdot \exp\left[-4.75\ \frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right] \qquad \text{(breaking waves)} \qquad (1a)$$

$$\text{with a maximum of } \frac{q}{\sqrt{gH_{m0}^3}} = 0.2 \exp\left[-2.6\ \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right] \qquad \text{(non-breaking waves)} \qquad (1b)$$

In this equation, q is the average overtopping rate, H_{m0} is the spectral wave height, α is the slope angle, R_c is the crest freeboard, $\xi_{m-1,0}$ is the breaker parameter and $\gamma_b, \gamma_f, \gamma_\beta, \gamma_v$ are the different correction factors for a berm, the roughness of the slope, oblique wave attack and a vertical wall on the slope, respectively. The constant coefficients 4.75 and 2.6 are normally distributed stochastic parameters with an associated standard deviation of σ=0.5 and σ=0.35 respectively. The range of application of Eq. (1) is rather limited, being only valid for mild slopes ($1 \leq \cot\alpha \leq 4$) and values of the relative crest freeboards between $0.5 \leq R_c/H_{m0} \leq 3.5$. Most of the tests of the UG15 dataset are outside the range of application of this formula, extending the overtopping data towards the vertical wall limit case and to smaller relative crest freeboards. Also, the formula is applicable to deep water conditions while the UG15 dataset features tests with shallow water wave conditions.

Within the EurOtop (2007) revision process, van der Meer and Bruce (2014) presented new overtopping formula (Eq. 2) fitted partly through the dataset UG10 obtained at Ghent University. These formulae extend the range of application of Eq. (1) to also include steep slopes, very steep slopes and vertical walls, for all the range of relative crest freeboards R_c/H_{m0} from zero to large. The van der Meer and Bruce (2014) (Eq. 2) describes the overtopping process not only as a function of R_c/H_{m0} but also as a function of the slope angle α, as opposed to the EurOtop (2007) formula.

$$\frac{q}{\sqrt{gH_{m0}^3}} = a \cdot exp\left(-\left(b\ \frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta}\right)^{1.3}\right) \qquad (2a)$$

with the following expressions for the coefficients a and b:

$$a = 0.09 - 0.01\ (2 - \cot\alpha)^{2.1} \quad and\ a = 0.09\ for\ \cot\alpha > 2 \qquad (2b)$$

$$b = 1.5 + 0.42\ (2 - \cot\alpha)^{1.5} \quad with\ a\ maximum\ of\ b = 2.35; \quad and\ b = 1.5\ for\ \cot\alpha > 2 \qquad (2c)$$

The van der Meer and Bruce (2014) formula was fitted through overtopping data in deep water conditions, and therefore the accuracy of the formulae in shallow water conditions is unknown. Only Gallach-Sánchez et al. (2014) have partially addressed the question by comparing the results of dataset UG14 with Eq. (2).

Nørgaard et al. (2014) investigated the wave overtopping behaviour (both average overtopping rates and individual wave overtopping volumes) of permeable and rough structures in deep water and in shallow water wave conditions. The test set-up consisted of a rubble-mound breakwater with a crown wall, and only a single value of slope angle was tested. Tests were performed for a single value of the peak wave period T_p and for two target values of the relative wave height H_{m0}/h (where h is the water depth at the toe of the structure): 0.2 for deep water and 0.5 for shallow water. Nørgaard et al. (2014) suggest correction factors on the individual overtopping distribution formulae developed by Victor et al. (2012) to improve the prediction of individual overtopping volumes in shallow water conditions.

3 EXPERIMENTAL TEST SET-UP

We performed physical model tests in the wave flume of the Department of Civil Engineering of Ghent University (Belgium). The wave flume is 30 m long, 1 m wide and 1.2 m high. It is equipped with a piston type wave paddle with a maximum stroke length of 1.5 m and it uses an active wave absorption system to compensate the reflected waves that reach the wave paddle. Behind the test section an overtopping measurement device (called overtopping box) was placed to capturing all the waves overtopping the structure which was situated in front of the device. Beneath the overtopping box, the test section and the foreshore a return flow channel was constructed. This return flow channel allowed the recirculation of the overtopping water to the front section of the wave flume in order to maintain a constant water level during the test. The return flow channel was wide enough to assure a low velocity flow that would not affect the incoming waves.

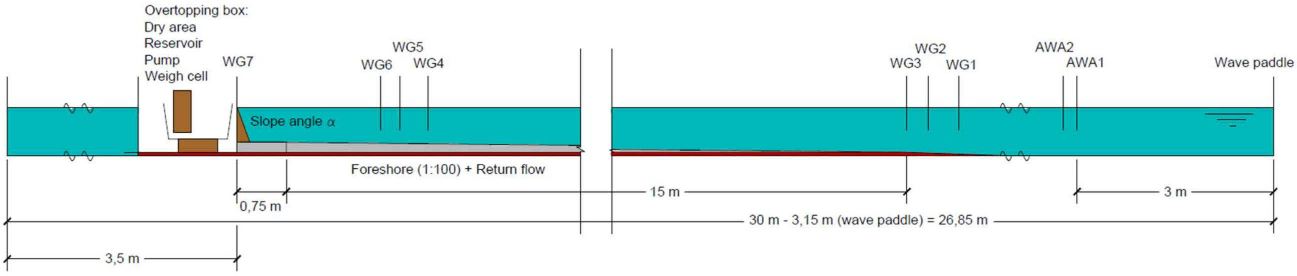

Figure 1. Sketch of the wave flume set-up for the dataset UG15 featuring a 1:100 foreshore slope.

For the UG15 dataset, the foreshore featured a 1:100 slope with a length of 15 m starting at 7.6 m from the wave paddle and ending in a horizontal part of 0.75 m at the toe of the structure (Figure 1). This foreshore matches the one used by Nørgaard et al. (2014) during their research on individual overtopping volumes on shallow water wave conditions. The test set-up of the dataset UG15 is the same as the test set-up of the dataset UG14 (Gallach-Sánchez et al., 2014) in order to avoid model effects that could affect the direct comparison of the overtopping and wave measurements.

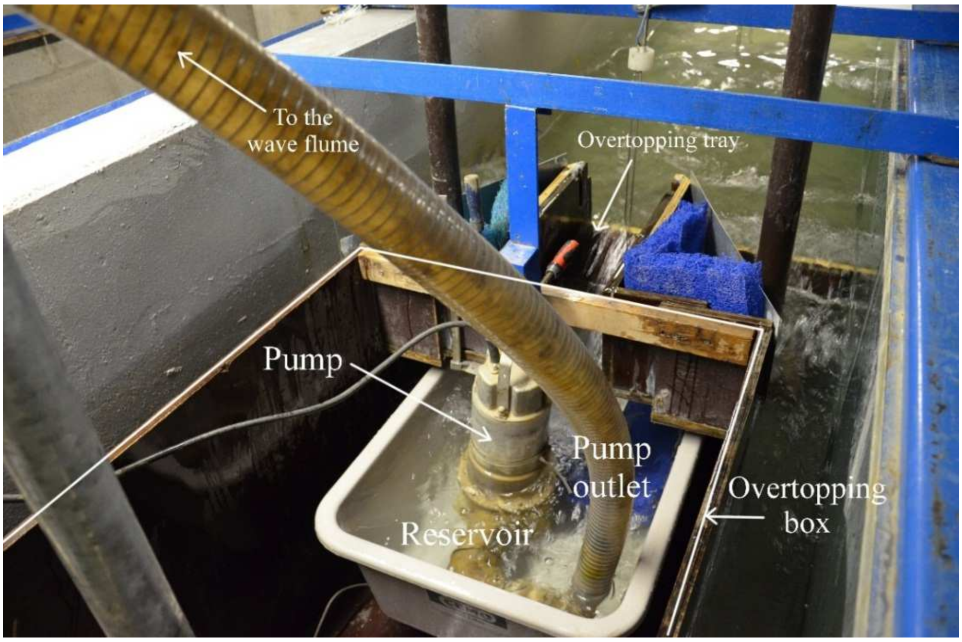

Figure 2. The overtopping box captures the overtopped water through a tray to the reservoir, where it is measured by a weigh cell. The pump returns the water to the wave flume when the weigh cell reaches a maximum value.

The overtopping box (Figure 2) was developed by Victor and Troch (2010) to measure with a high accuracy the individual overtopping volumes, and therefore the average overtopping rates. It measures the overtopping using the weigh cell technique described by Schüttrumpf (2001). The box is constructed in plywood and it is formed by a dry area containing the necessary equipment to measure wave overtopping. This equipment consists of a reservoir to capture the overtopped water through a 0.1 m overtopping tray located at the crest of the model structure, a weigh cell to measure the mass of the overtopped water inside of the reservoir and a pump that returns the water from the reservoir to the wave flume when the weigh cell reaches a fixed value. The average overtopping rate is calculated by a MATLAB™ script that reads the 5 Hz signal of the weigh cell and calculates the amount of water inside the reservoir as a function of the time and therefore the average overtopping rate.

The wave heights are measured by wave gauges (WG) of the resistive type placed in three sets in the wave flume. The first set was formed by two WG as part of the active wave absorption system (AWA 1 and 2 in Figure 1). The second (WG 1, 2, 3 in Figure 1) and third sets (WG 4, 5, 6 in Figure 1) were each one composed of three wave gauges with a distance between them according to Mansard and Funke (1980). The last two sets were used to calculate the incident wave heights and the reflection coefficient at different locations in the wave flume (for WG 1, 2 and 3 before the foreshore slope begins; and for WG 4, 5 and 6 before the model structure) using the 3-point method described in Mansard and Funke (1980). Another wave gauge (WG7 in Figure 1) was placed on top of the model structure to detect incoming waves in order to calculate the individual overtopping volumes.

4 EXPERIMENTAL TEST PROGRAMME

We performed physical model tests to increase the knowledge of wave overtopping in shallow water wave conditions, extending the dataset UG14 obtained at Ghent University. The tests are described by different structural parameters (slope angle α, crest freeboard R_c) and wave parameters (average overtopping rate q, incident significant wave height H_{m0} at the toe of the structure, peak wave period T_p) as seen in Figure 3. Other important parameters can be derived from these ones: the relative crest freeboard R_c/H_{m0}, the relative wave height H_{m0}/h where h is the local water depth at the toe of the structure, the wave steepness $s_{m-1,0}$ and the breaker parameter $\xi_{m-1,0}$. The average overtopping rate q and the individual overtopping volumes Vi were obtained after processing the weigh cell and WG signals. During the experiments approximately 1000 irregular waves were generated in each test using a JONSWAP spectrum with a shape parameter of γ = 3.3.

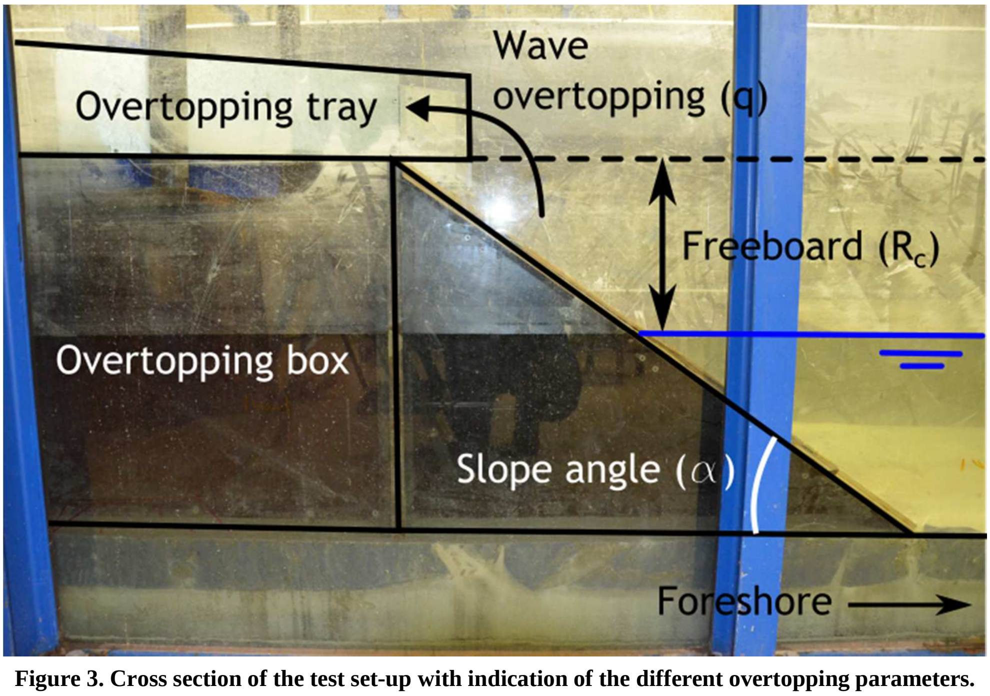

Figure 3. Cross section of the test set-up with indication of the different overtopping parameters.

The different values of the structural and wave parameters for UG14 and UG15 datasets are summarized in Table 1. Both datasets included steep slopes ($0.27 < \cot\alpha < 1.43$), very steep slopes ($0 < \cot\alpha \leq 0.27$), and vertical walls ($\cot\alpha = 0$). The relative crest freeboards were large ($R_c/H_{m0} > 0.8$) and small ($0.8 > R_c/H_{m0} > 0.11$) for UG15 dataset and large, small, very small ($0.11 > R_c/H_{m0} > 0$) and zero ($R_c = 0$) for the UG14 dataset. Due to extreme wave conditions not possible to test in the wave flume at Ghent University, the tests for the UG15 dataset with small and zero freeboards were not carried out. The water depth conditions were assessed by the relative wave height at the toe of the structure, which is the ratio between the incident spectral wave height and the local water depth at the toe of the structure H_{m0}/h. Deep water conditions were considered when $H_{m0}/h \leq 0.2$, while shallow water conditions were considered when $H_{m0}/h > 0.2$, as stated by Nørgaard et al. (2014). For both datasets fixed target values of H_{m0}/h were considered. As seen, the UG14 dataset features not only tests in shallow water conditions but also in deep water conditions, while the UG15 dataset only features tests in shallow water conditions as an extension of UG14. All the tests of the UG14 and UG15 datasets were with non-braking wave conditions, as $\xi_{m-1,0} > 2$.

Table 1. Overview of UG14 and UG15 structural and wave parameters

	UG14	**UG15**
Slope angle α (°)	35, 45, 60, 70, 75, 80, 85, 90	35, 45, 60, 70, 75, 80, 85, 90
cot α (-)	1.43, 1.00, 0.58, 0.36, 0.27, 0.18, 0.09, 0	1.43, 1.00, 0.58, 0.36, 0.27, 0.18, 0.09, 0
Crest freeboard R_c (m)	0, 0.02, 0.045, 0.076, 0.12, 0.2	0.02, 0.045, 0.076, 0.12, 0.2
Spectral wave height H_{m0} (m)	0.061 – 0.225	0.107 – 0.220
Relative crest freeboard R_c/H_{m0} (-)	0 – 2.92	0.11 – 1.87
Peak wave period (target) T_p (s)	1.022, 1.534, 2.045	1.534, 2.045, 2.534
Relative wave height (target) H_{m0}/h (-)	0.20, 0.30, 0.40, 0.50	0.30, 0.40, 0.50
Wave steepness $s_{m-1,0}$ (-)	0.01 – 0.06	0.01 – 0.05
Breaker parameter $\xi_{m-1,0}$ (-)	2.8 - 90	3.3 - 82

5 RESULTS

The dataset UG15 consists of 197 overtopping tests performed at the wave flume of the Department of Civil Engineering of Ghent Univeristy with a test set-up described in Section 3 and a test programme described in Section 4. After performing the tests, we obtained the average overtopping rate of each test of the dataset.

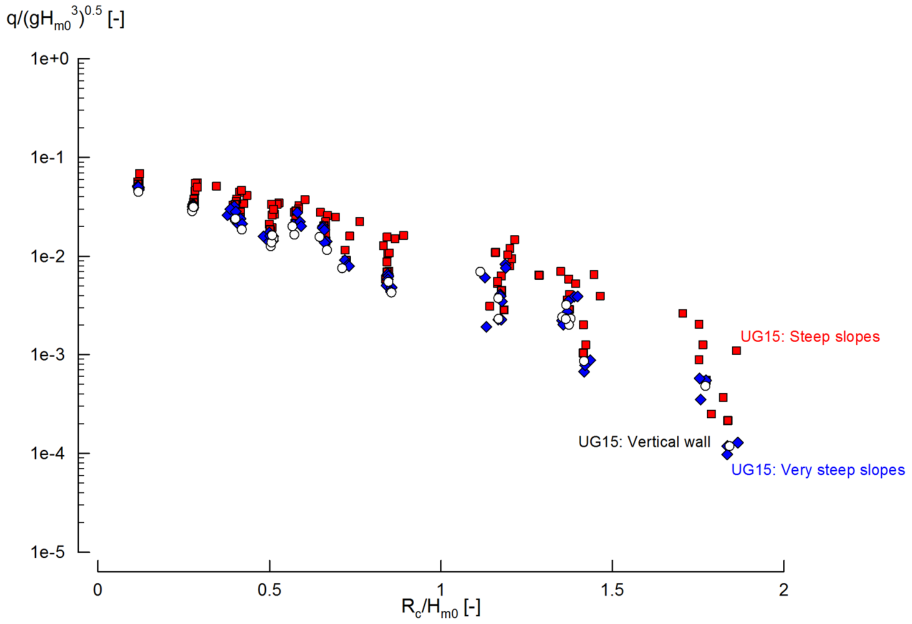

Figure 4. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative crest freeboard R_c/H_{m0} for the complete dataset UG15.

For the UG15 dataset, the relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ decreases for increasing values of the relative crest freeboard R_c/H_{m0} (Figure 4) following the normal behaviour of the overtopping process extensively described in literature. Also the slope angle α has an influence on the overtopping rate: $q/\sqrt{gH_{m0}^3}$ decreases for decreasing values of $\cot\alpha$ (i.e. for steeper slopes), as was previously reported for the UG10, UG13 and UG14 datasets. The scatter of the data is larger for large values of the relative crest freeboard R_c/H_{m0} than for small values, as the influence of the variation of slope angle α is more important for larger values of R_c/H_{m0}.

The overtopping results of the UG15 dataset are aligned with the results of the UG14 dataset (Figure 5). Considering both UG14 and UG15, the number of overtopping tests for steep low-crested structures in shallow water wave conditions is 616. Most of the UG15 overtopping results are below the 90% confidence band of the EurOtop (2007) non-breaking overtopping prediction formula (Eq. 1b). As previously stated, most of the UG15 dataset is outside the range of application of this formula (Figure 5) and therefore the overprediction of the overtopping rates is an expected result. However, for the test conditions lying within the application range of the formula the overtopping results are correctly predicted by the formula.

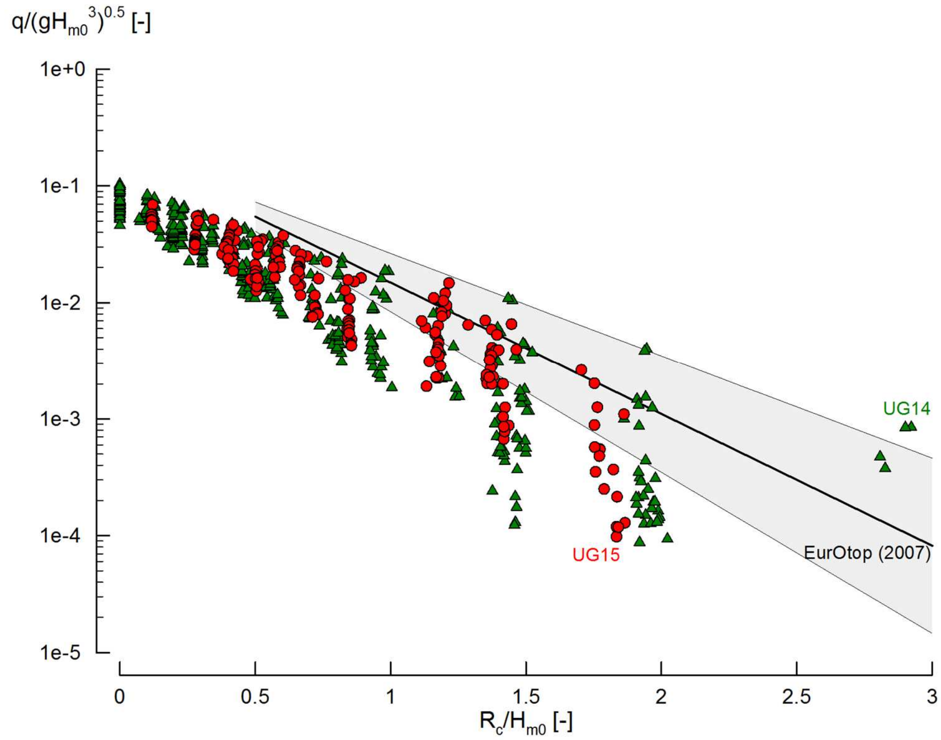

Figure 5. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative crest freeboard R_c/H_{m0} for datasets UG14 (green triangles) and UG15 (red circles), compared to the EurOtop (2007) overtopping prediction formula with its 90% confidence band.

Steep low-crested structures such as the structures considered in the UG14 and UG15 datasets exceed the range of application of the EurOtop (2007) formula. Van der Meer and Bruce (2014) presented new overtopping prediction formulae (Eq. 2) as part of the revision process of the EurOtop (2007) manual. This new formula extends the range of application to very steep slopes towards the vertical wall limit, and to small relative crest freeboards towards the zero freeboard case. The van der Meer and Bruce (2014) formula depends on the slope angle α and therefore there is a different prediction curve for each one of the tested slopes.

Figure 6 shows the overtopping data of the steep slope 35° ($\cot\alpha$ = 1.43) of the UG14 and UG15 datasets compared to the van der Meer and Bruce (2014) prediction formula corresponding to the same slope. In general, the van der Meer and Bruce (2014) formula predicts with a good accuracy the overtopping results. For relative crest freeboards $R_c/H_{m0} < 1$, the formula predicts very accurately the overtopping values of the corresponding slope except for the zero freeboard case $R_c = 0$ where the formula is slightly underpredicting the results. For $R_c/H_{m0} > 1$ some of the overtopping results are slightly underpredicted by the formula. The shallow water effects are not influencing the overtopping results for the case of the 35° slope as the results of the UG13 dataset in deep water conditions are very similar (Gallach-Sánchez et al., 2015).

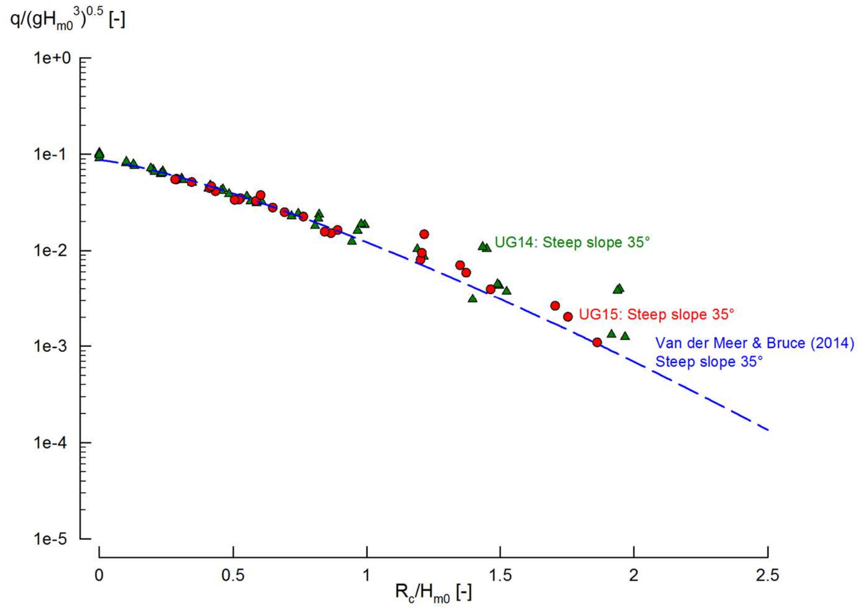

Figure 6. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative crest freeboard R_c/H_{m0} for the steep slope 35° ($\cot\alpha$ = 1.43) of the datasets UG14 (green triangles) and UG15 (red circles), compared to the van der Meer and Bruce (2014) formula.

The overtopping results of the vertical wall (α = 90°, $\cot\alpha$ = 0) of the datasets UG14 and UG15 are not predicted with the same accuracy by the van der Meer and Bruce (2014) for vertical walls (Figure 7). For relative crest freeboards R_c/H_{m0} <1 the average overtopping rates are correctly predicted by the formula, although for the case of zero freeboard R_c = 0 the overtopping rates are slightly underpredicted as it occurred for the steep slope case (Figure 6). However, for R_c/H_{m0} >1 the van der Meer and Bruce (2014) is clearly underpredicting the overtopping rates as seen in Figure 7. For the UG13 dataset (in deep water conditions) this underprediction of the formula was not present (Gallach-Sánchez et al., 2015). This may indicate that the shallow water effects are increasing the overtopping rates for values of relative crest freeboard R_c/H_{m0} > 1. Comparing Figure 6 for a steep slope and Figure 7 for the vertical wall reveals a clear difference in the accuracy of the prediction of the van der Meer and Bruce (2014) formula when R_c/H_{m0} > 1. This indicates a different influence of the shallow water effects depending on the slope angle α.

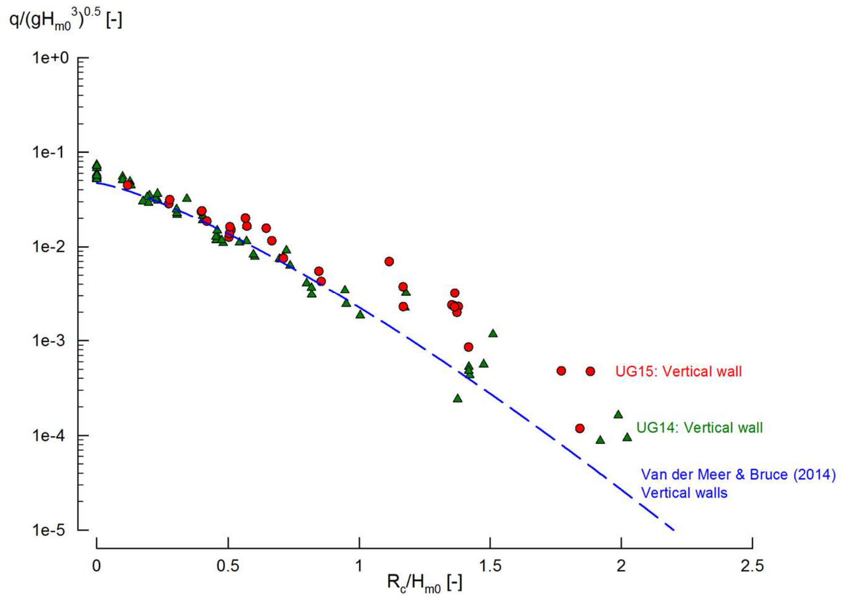

Figure 7. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative crest freeboard R_c/H_{m0} for the vertical wall ($\cot\alpha$ = 0) of the datasets UG14 (green triangles) and UG15 (red circles), compared to the van der Meer and Bruce (2014) formula.

For the steep slopes (α = 35°, 45°, 60° and 70° with corresponding $\cot\alpha$ = 1.43, 1, 0.58 and 0.36 respectively) tested in the UG14 and UG15 datasets, the overtopping results show no difference with the UG13 dataset (deep water conditions) and a good accuracy with the van der Meer and Bruce (2014) formulae. Therefore the shallow water effects for steep slopes for relative crest freeboards $R_c/H_{m0} > 1$ are negligible. For the very steep slopes (α = 75°, 80° and 85° with corresponding $\cot\alpha$ = 0.27, 0.18 and 0.09 respectively) and the vertical wall ($\cot\alpha = 0$) tested in the UG14 and UG15 dataset, the overtopping results for $R_c/H_{m0} > 1$ are larger than the results obtained in the UG13 dataset in deep water conditions and also the van der Meer and Bruce (2014) formulae consistently underpredict the results. Therefore the shallow water effects for very steep slopes and vertical walls with $R_c/H_{m0} > 1$ are increasing the overtopping rates for the same conditions of slope angle α and relative crest freeboard R_c/H_{m0} in deep water.

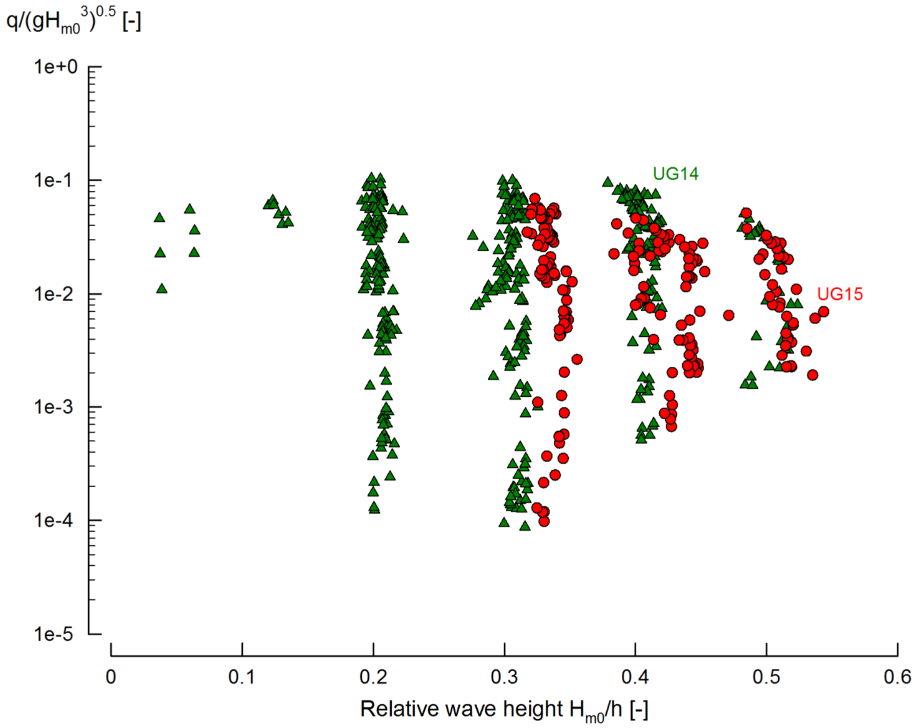

Figure 8. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative wave height H_{m0}/h for datasets UG14 (green triangles) and UG15 (red circles).

Figure 8 shows the relative average overtopping rates $q/\sqrt{gH_{m0}^3}$ as a function of the relative wave height H_{m0}/h for the complete datasets UG14 and UG15. The values of H_{m0}/h gather around the target values of H_{m0}/h = 0.2, 0.3, 0.4 and 0.5. The dataset UG14 includes 13 tests with values $H_{m0}/h < 0.2$ in deep water conditions as an overlap with the dataset UG13. No clear trend is seen in Figure 8, only an increase of the minimum $q/\sqrt{gH_{m0}^3}$ when the value of H_{m0}/h is increasing (i.e. more shallow water conditions) possibly indicating influence of the shallow water effects. A characterization of these values according to the structural parameters slope angle α and relative crest freeboard R_c/H_{m0} is necessary to fully understand the shallow water effects.

The study of the overtopping tests for very steep slopes with relative crest freeboards $R_c/H_{m0} > 1$ (Figure 9) confirms the shallow water effects previously described. The relative wave height H_{m0}/h is the main parameter used in this paper to assess the water depth condition of a test. A deep water wave condition occurs when $H_{m0}/h \leq 0.2$, and a shallow water wave condition when $H_{m0}/h > 0.2$. The UG13 dataset was obtained mainly in deep water conditions, the UG14 dataset featured tests both in the limit condition for deep water and in shallow water conditions and the UG15 dataset featured only tests in shallow water conditions. Focusing only in very steep slopes (α = 75°, 80° and 85° with corresponding $\cot\alpha$ = 0.27, 0.18 and 0.09 respectively) and vertical walls ($\cot\alpha = 0$), the dataset UG13 maximum target relative wave height is $H_{m0}/h = 0.1$ (deep water conditions) while for the datasets UG14 and UG15 the target relative wave height is $0.2 \leq H_{m0}/h \leq 0.5$.

For steep slopes and vertical walls with $R_c/H_{m0} > 1$ in deep water conditions ($H_{m0}/h \leq 0.2$) the overtopping rates remain approximately constant considering the relative wave height H_{m0}/h although with some scatter of the data. However for shallow water conditions ($H_{m0}/h > 0.2$) there is a clear trend: $q/\sqrt{gH_{m0}^3}$ increases for increasing values of the relative wave height H_{m0}/h (Figure 9). There is a clear influence of H_{m0}/h, and therefore of the water depth condition, in the average overtopping rate. Moreover, the average overtopping rate increases when changing from deep water conditions to shallow water conditions for similar values of the slope angle α and relative crest freeboard R_c/H_{m0}. The average overtopping rate in shallow water conditions can be up to a factor 10 higher than in deep water conditions. This result confirms the conclusion obtained previously from Figure 7.

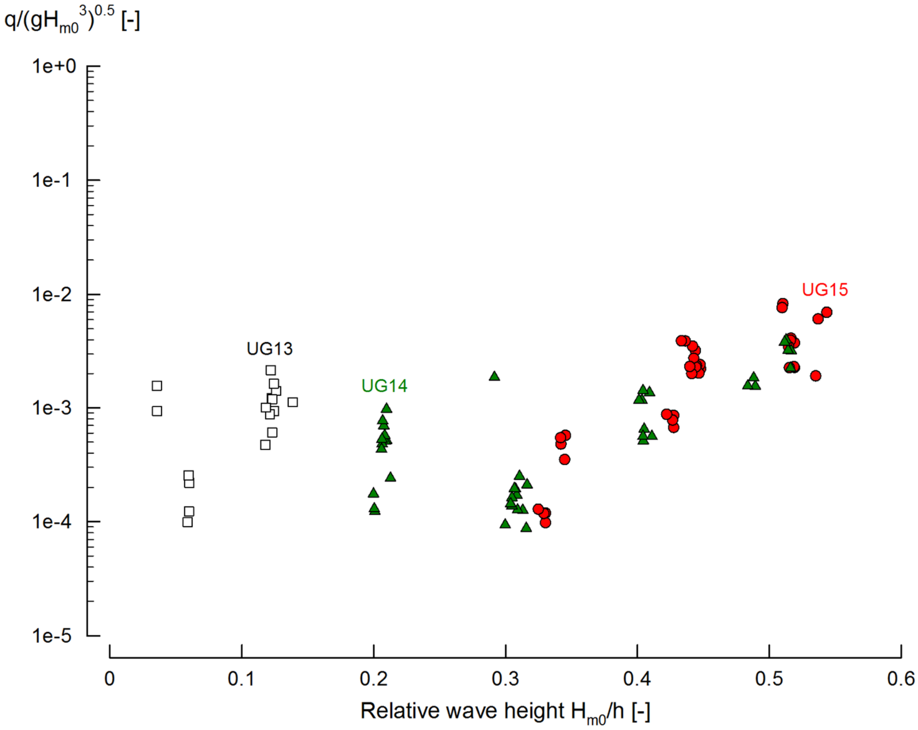

Figure 9. Relative average overtopping rate $q/\sqrt{gH_{m0}^3}$ against relative wave height H_{m0}/h for very steep slopes and vertical walls with $R_c/H_{m0} > 1$ for datasets UG13 (white squares), UG14 (green triangles) and UG15 (red circles).

6 CONCLUSIONS

The dataset UG15 is formed by 197 overtopping tests performed at Ghent University on shallow water conditions, with values of the relative wave height at the toe H_{m0}/d from 0.3 to 0.53. This new dataset extends the dataset UG14 also obtained at Ghent University although featuring not only tests on shallow water conditions but also on deep water conditions. The overtopping results of the UG15 dataset align with the UG14 dataset therefore confirming all the results and conclusions of the dataset UG14 for shallow water conditions. By comparing this two datasets with a overtopping dataset featuring tests on deep water conditions, like the UG13 dataset, it is possible to analyse the influence of the shallow water effects on wave overtopping.

The datasets UG14 and UG15 exceed the range of application of the EurOtop (2007) formulae as it does not include the steep low-crested structures case. For those test conditions inside the range of application of the EurOtop (2007) formula predicts with accuracy the overtopping results. Van der Meer and Bruce (2014) presented new formulae to update and extend the range of application of the EurOtop (2007) formulae towards steep low-crested structures. When compared to the datasets UG14 and UG15, the new formulae predicts with accuracy the overtopping rates except for some cases. For the zero freeboard $R_c = 0$ case, the formulae slightly underpredict the overtopping results. Also for relative crest freeboards $R_c/H_{m0} > 1$ the van der Meer and Bruce (2014) formulae underpredict the results, in particular for very steep slopes and vertical walls.

The effect of the shallow water wave conditions on the average overtopping rate for steep slopes ($\cot\alpha > 0.27$) is negligible as the overtopping results are similar than for deep water conditions. For very steep slopes ($\cot\alpha \leq 0.27$) and the vertical wall ($\cot\alpha = 0$) there is an increase of the overtopping rate compared to a test with the same value relative crest freeboard R_c/H_{m0} in deep water conditions. However, this influence of the shallow water effects in very steep slopes and vertical walls does not occur for the whole range of relative crest freeboards.

For small relative crest freeboards $R_c/H_{m0} < 1$ the shallow water effects do not significantly affect the average overtopping rate on very steep slopes and vertical walls. In this conditions of crest freeboards smaller than the incident wave height, the overtopping rate is not affected by an increase in the relative wave height H_{m0}/d due to the small crest freeboard of the structure. For large relative crest freeboards $R_c/H_{m0} > 1$ the shallow water effects on very steep slopes and vertical walls produce an increase in the average overtopping rates compared to the same value of relative crest freeboard on deep water conditions. In this case, the crest freeboard of the structure is larger than the incident wave height and an increase in the relative wave height (H_{m0}/h) leads to a larger average overtopping rate. For shallow water wave conditions the wave characteristics are affected by the sea bottom, increasing the average overtopping rates for very steep and vertical walls with large relative crest freeboards ($R_c/H_{m0} > 1$). Due to this increasing of the average overtopping rates for very steep slopes and vertical walls with $R_c/H_{m0} > 1$, the van der Meer and Bruce (2014) formulae underpredict the results as these formulae were fitted only through data in deep water conditions.

The future steps of this research are to analyze the individual overtopping volumes of the UG15 dataset to study the influence of the shallow water wave conditions on the individual volume distribution, comparing it with the distribution of individual volumes in deep water conditions. Also, the datasets UG14 and UG15 in shallow water conditions will be used to improve the van der Meer and Bruce (2014) formulae suggesting new coefficients that improve their accuracy.

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