EXPERIMENTAL STUDY OF OVERTOPPING PERFORMANCE FOR THE CASES OF VERY STEEP SLOPES AND VERTICAL WALLS WITH VERY SMALL FREEBOARDS

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This article describes the investigation of average wave overtopping performance for sloping coastal structures characterised by very steep slopes (typically $\cot \alpha < 0.5$) and very small freeboards. Based on experimental tests, performed in the large wave flume of Ghent University, the influence of the relevant hydraulic and geometrical parameters on overtopping is examined. Test set-up and test parameters are presented and discussed in detail in this paper. Furthermore, the established dataset, called UG13 dataset, is compared to prediction formulae from existing literature, including the limiting cases of zero freeboard and vertical wall.

Keywords: Wave overtopping; steep low-crested slopes; zero freeboard; vertical wall

INTRODUCTION

Overtopping is a governing process in the protection against flooding. Coastal defence structures should be built from an economic and aesthetic point of view. Therefore, a decent knowledge of the volumes of water that may pass the coastal structures is required. There is still research going on to predict the overtopping rates for all kinds of structures and in all kinds of situations. This article extends earlier research of Victor & Troch (2012a, 2012b), who investigated the cases of steep slopes and small freeboards for smooth sloping coastal structures. The extension presented here covers the cases of very small to zero freeboard (transition towards the limiting case of zero freeboard) and very steep slopes to vertical walls (transition towards the limiting case of vertical wall, i.e. in the range $0 < \cot \alpha < 0.5$), which were not yet fully covered.

The main goal of the research presented in this paper is to extend the existing overtopping datasets to steep slopes and vertical walls for the case of relatively deep water wave conditions by performing additional overtopping experiments in the wave flume of Ghent University using a set-up as presented in detail in Victor & Troch (2010). The dataset obtained in this investigation is called 'UG13'. Only the average overtopping rates will be evaluated within this paper. Further research on individual wave overtopping volumes is also planned at a later stage.

LITERATURE STUDY

There is extensive literature on prediction formulae for average overtopping rates under different conditions. The EurOtop 2007 manual (Pullen et al., 2007), see section 2.1, provides formulations for a range of wave conditions and structure types, both for average and individual wave overtopping rates q and V_i respectively. Nevertheless, for the case of very steep slopes and small relative freeboards, the EurOtop 2007 manual has suggested average overtopping rates which are considered too conservative. Victor & Troch (2012b) presented a correction for a more accurate overtopping prediction in those cases. Van der Meer & Bruce (2013), see section 2.3, used the UG10 dataset from Victor & Troch (2012b) and the CLASH dataset (Steendam et al., 2004) to extend the range of application of the traditional EurOtop prediction formulae to very steep slopes and very small freeboards.

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EurOtop 2007 formula

The ranges of application for the EurOtop 2007 formulae are, for the slope angle: $1 \leq \cot \alpha \leq 4$, and for the relative crest freeboard: $0.5 \leq R_c/H_{m0} \leq 3.5$. For this application here, usually the EurOtop 2007 formula for non-breaking waves is applicable:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2\,exp\left[-2.6\frac{R_c}{H_{m0}}\right] \tag{1}$$

where H_{m0} is the spectral incident wave height at the toe of the structure, and R_c is the crest freeboard of the structure.

Victor & Troch (2012b) formula

In Victor & Troch (2012b), a classification is proposed based on slope angle and relative crest freeboard, indicating the significant effect of the slope angle for steeper slopes, and four zones have been defined in which the following prediction formulae are used:

Z1: $$\frac{q}{\sqrt{gH_{m0}^3}} = (0.033\cot\alpha + 0.062)\,exp\left[(1.08\cot\alpha - 3.45)\frac{R_c}{H_{m0}}\right] \tag{2.a}$$

Z2: $$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2\,exp\left[(1.57\cot\alpha - 4.88)\frac{R_c}{H_{m0}}\right] \tag{2.b}$$

Z3: $$\frac{q}{\sqrt{gH_{m0}^3}} = 0.11\,exp\left[-1.85\frac{R_c}{H_{m0}}\right] \tag{2.c}$$

Z4: $$\frac{q}{\sqrt{gH_{m0}^3}} = 0.2\,exp\left[-2.6\frac{R_c}{H_{m0}}\right] \tag{2.d}$$

where α is the slope angle of the structure, and see Table 1 for the classification.

Table 1. Classification for zones

	small freeboard $\frac{R_c}{H_{m0}} < 0.8$	large freeboard $\frac{R_c}{H_{m0}} > 0.8$
steep: cot α < 1.5	Z1	Z2
mild: cot α > 1.5	Z3	Z4

Van der Meer & Bruce (2013) formula

Recently, van der Meer & Bruce proposed a generic formula extending the existing EurOtop formula towards steep slopes and vertical walls for relatively deep water:

$$\frac{q}{\sqrt{gH_{m0}^3}} = A\,exp\left[-\left(B\frac{R_c}{H_{m0}}\right)^{1.3}\right] \tag{3.a}$$

with the following expressions for the coefficients A and B:

$$A = 0.09 - 0.01(2 - cot\,\alpha)^{2.1} \quad and\ A = 0.09\ for\ cot\,\alpha > 2 \tag{3.b}$$

$$B = 1.5 + 0.42(2 - cot\,\alpha)^{1.5} \quad \begin{matrix} with\ a\ maximum\ of\ B = 2.35 \\ and\ B = 1.5\ for\ cot\,\alpha > 2 \end{matrix} \tag{3.c}$$

and where the fit of those coefficients has been based mainly on the UG10 dataset presented in Victor & Troch, 2012b.

TEST SET-UP

The experiments were performed in the wave flume of the Department of Civil Engineering at Ghent University (Belgium), which has a width of 1 meter, a height of 1.2 meters and a length of 30 meters. It is equipped with a piston type wave paddle with a maximum stroke length of 1.5 m. The test set-up, as used by Victor & Troch (2010) in the wave flume of Ghent University, is re-used to determine the average overtopping rates for two cases, a general case and a case for zero freeboard and vertical walls. It was developed specifically to measure large individual wave overtopping volumes with high accuracy. The structure itself consists of a wooden uniform slope and a dry area behind it, which contains the reservoir, submersible pump and the load cell for the overtopping measurements (Figure 1). In the wave flume, irregular waves according to a JONSWAP spectrum with $\gamma = 3.3$ (total no. of waves around 1000) are generated for a range of structural parameters like slope angle and crest freeboard.

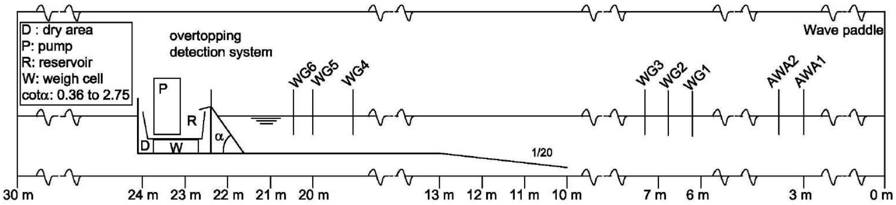

Figure 1. Cross section of the experimental test set-up, as used in Victor & Troch (2010).

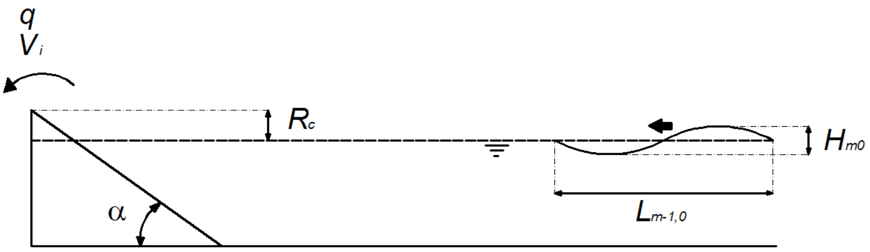

Figure 2. Definition sketch of the governing parameters for the test matrix.

WAVE CONDITIONS

Using the set-up described in Section 3, experiments were performed based on different structural (slope angle α and crest freeboard R_c of the structure) and wave parameters (wave height H_{m0}, and peak wave period T_p), Figure 2. All the parameters were chosen to include an overlap with pre-existing datasets such as CLASH database (Steendam et al., 2004) or datasets obtained at Ghent University such as UG10 (Victor & Troch, 2012b). The ranges of the governing parameters have been summarized in Table 2 (table data are in model units). The UG13 dataset covers the “gap” between 70° and 90° (vertical wall) and the “gap” between R_c/H_{m0} = 0.27 and 0 (zero freeboard), for relatively deep water conditions.

Table 2. Overview of UG10 and UG13 datasets

	UG10	UG13
Slope angle α (°)	20, 25, 30, 35, 40, 45, 50, 60, 70	25, 35, 45, 60, 75, 80, 85, 90
Crest freeboard R_c (m)	0.020, 0.045, 0.070	0.000, 0.005, 0.010, 0.020, 0.045, 0.070
Spectral wave height H_{m0} (m)	0.02 – 0.185	0.02 – 0.185
Peak wave period T_p (s)	1.022 – 2.045	1.022 – 2.045
Foreshore	Horizontal	Horizontal

DATA ANALYSIS

First results regarding average wave overtopping derived from the experiments corresponding to the UG13 dataset are presented and discussed in the following. The data analysis is performed in three parts. First of all the general case of steep slopes with $0 \leq \cot \alpha \leq 2.14$ and $0 \leq R_c/H_{m0} \leq 2$ is considered, where α is the slope angle, R_c is the crest freeboard and H_{m0} is the incident wave height. Secondly, a closer look is given at the asymptotic cases of zero freeboard and vertical wall.

General case

The gathered data of this newly established “UG13” wave overtopping data set feature a number of characteristics. In general, the influences of the parameters as discussed by Victor (2012) also apply for very small freeboards ($0 \leq R_c/H_{m0} \leq 0.1$) and very steep slopes ($0 \leq \cot \alpha \leq 0.27$). The influence of the slope angle on the dimensionless average overtopping rate is largest for $0.27 \leq \cot \alpha \leq 2.14$ and fades out, as expected for vertical walls, for $\cot \alpha \leq 0.2$. The two UG10 and UG13 data sets are shown in Figure 3, illustrating the extended ranges.

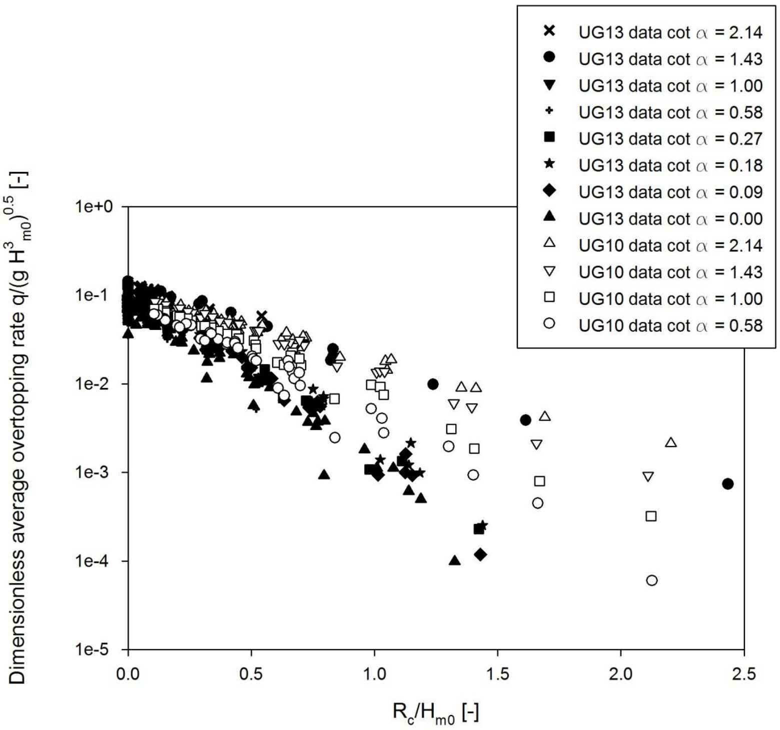

Figure 3. Dimensionless average overtopping rate $q/(gH^3_{m0})^{0.5}$ versus the relative freeboard R_c/H_{m0} for UG13 (black symbols) and UG10 data (Victor, 2012) (white symbols).

Wave period T_p and wave steepness s_0 appear to have no significant effect on the average overtopping rate. The same was observed for the breaker parameter $\xi_{m-1,0} > 20$, but for $\xi_{m-1,0}$ below 20 a specific maximum of the dimensionless average overtopping rate was found.

When looking at the existing prediction formulae in literature, the formula of EurOtop (2007) for nonbreaking waves is not an accurate fit for the steeper slopes $\cot \alpha \leq 1$ and smaller freeboards $R_c/H_{m0} \leq 0.5$, see Figure 4. The formulae of Victor & Troch (2012b) predict the average overtopping rate good (not shown in Fig. 4 for clarity as formula varies with slope angle) although the formulae slightly underestimate the average overtopping rate for the steeper slopes.

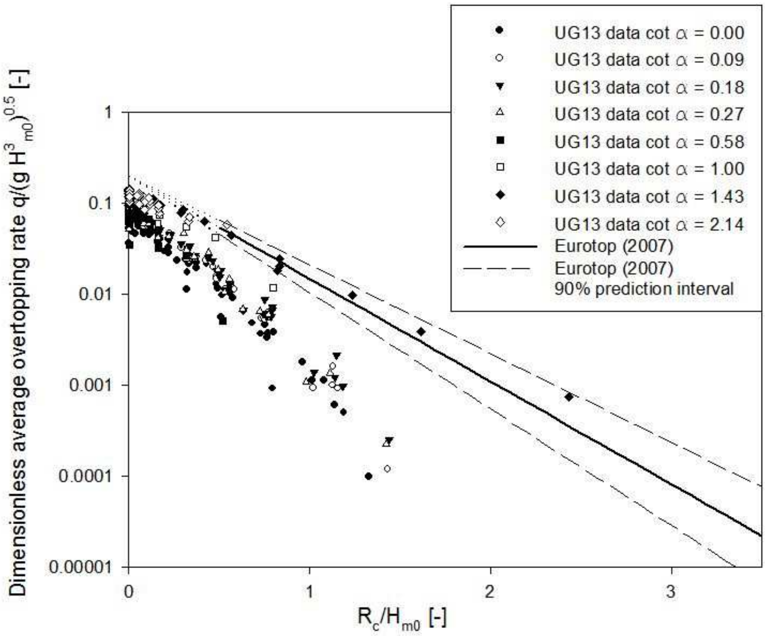

Figure 4. Dimensionless average overtopping rate $q/(gH^3_{m0})^{0.5}$ versus the relative freeboard R_c/H_{m0} for UG13 compared to the EurOtop (2007) overtopping prediction formula

Zero freeboard

The limit case of overtopping with zero freeboard was also investigated separately. The most relevant parameters appeared to be the slope cot α and to a lesser extent the wave height H_{m0}. With increasing H_{m0} and cot α an increase in the dimensionless average overtopping rate $q/\left(gH_{m0}^3\right)^{0.5}$ is observed for this case.

When comparing the UG13 test data for zero freeboard with the existing literature, the prediction formula of Schüttrumpf (2001) shows the opposite trend when comparing the dimensionless average overtopping rate as a function of $\xi_{m-1,0}$ for the UG13 data. The expression according to Smid et al. (2001) gives a constant value for $q/\left(gH_{m0}^3\right)^{0.5}$ of 0.062 which is in good agreement with the UG13 data for a vertical wall. There is however some spreading of the UG13 data around the constant value of 0.062

Vertical wall

The other limit case which is investigated here, is the situation of a vertical wall. The influence of the parameters as discussed for the general behaviour is the same as in case of a vertical wall. When comparing the UG13 experimental data for cot α with available prediction formulae from literature, both the formulae of Victor & Troch (2012b), eq. (2), and van der Meer & Bruce (2013), eq. (3), (see Figure 5) succeed in giving an accurate prediction of the non-dimensional overtopping rate $q/\left(gH_{m0}^3\right)^{0.5}$. It is observed in Figure 5 that Victor & Troch (2012b) is performing slightly better for very small and zero freeboards, and for large relative freeboards (larger than say 0.8).

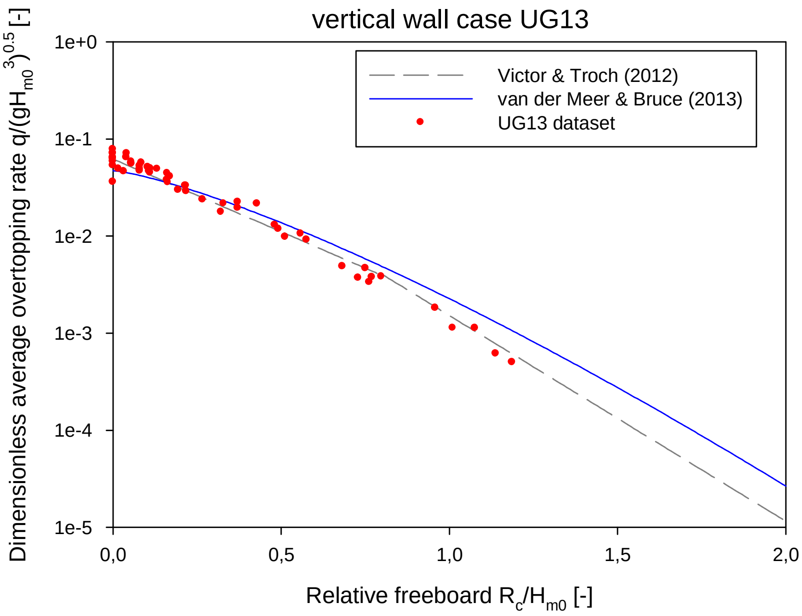

Figure 5. Dimensionless average overtopping rate $q/(gH^3_{m0})^{0.5}$ versus the relative freeboard R_c/H_{m0} for UG13 data with a vertical wall, compared to the formulae of Victor & Troch (2012b) and van der Meer & Bruce (2013).

CONCLUSIONS

This research investigated the average overtopping rate for structures with steep slopes and a limit for zero freeboard and vertical wall. The test set-up, the applied test matrix and the resulting established dataset UG13 have been presented. First data analysis results have been presented, indicating similar trends as in the UG10 dataset of Victor and Troch (2012b) and thereby covering the gaps for the slope angles $0 \leq \cot \alpha \leq 0.5$ and the relative crest freeboards $0 \leq R_c/H_{m0} \leq 0.27$. Finally, the focus of this research was the average overtopping rate but also the individual overtopping volumes were measured during the experimental tests. Further research is recommended for the behaviour of individual overtopping volumes for structures with very steep slopes and very low relative freeboard, and for shallow water cases.

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