EXPERIMENTAL STUDY OF OVERTOPPING BEHAVIOUR OF STEEP LOW-CRESTED COASTAL STRUCTURES

by

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1 INTRODUCTION

Climate change is causing a sea level rise and an increase in the storminess, supposing a risk to the coastal communities. The existing sea defence structures should remain equally effective in protecting those communities against future storms. Therefore, a good knowledge of the coastal processes is required to correctly assess the safety of the existing sea defence structures in this new scenario and to improve the design guidelines of these structures. The main coastal processes involved are, among others, wave overtopping over the crest of the structure, wave run-up on sea dykes and wave forces and pressures exerted by the waves attacking the structure.

Wave overtopping (Figure 1) is a key design parameter of sea defence structures as it determines the necessary crest level that limits the amount of water that passes over the structure during wave attack. Traditional research has focused on analysing the average wave overtopping rate over sea defence structures establishing the relation between the average overtopping rate and diverse wave parameters of the sea state (wave height, wave period, wave steepness, etc.) and structural parameters (slope angle, crest freeboard, etc.). Furthermore, physical insights show that the damage on infrastructures and people near the coast during a storm is also related to individual volumes from single wave overtopping events.

Figure 1: Waves attacking and overtopping the breakwater of the harbour of Zeebrugge (Belgium) during a winter storm
Despite the large scientific literature available for wave overtopping, there are still knowledge gaps to be covered in order to improve the understanding of wave overtopping under different conditions. This knowledge gap consists of overtopping data for very steep slopes and vertical walls, with a crest freeboard ranging from very small to zero. Improving the knowledge on various processes related to wave overtopping will eventually lead to more accurate overtopping prediction formulae with larger ranges of application, and hence to safer coastal defence structures.

To extend the wave overtopping data available in the scientific literature, we performed 2-D physical model tests at the large wave flume of Ghent University (Belgium). The experiments consisted in overtopping tests on smooth impermeable sea defence structures, both with deep and shallow water conditions. During the tests, the wave conditions and the overtopping (including the individual overtopping events) were measured. The tests were focused on obtaining average and individual wave overtopping data for a range of slope angles \( \alpha \) from steep to vertical walls and for a range of relative crest freeboards \( R_c/H_m0 \) (where \( R_c \) is the crest freeboard of the structure and \( H_m0 \) is the spectral wave height) from large to zero. Three different datasets resulted from the physical model tests: dataset ‘UG10’ on mild and steep slopes with small crest freeboard [Victor & Troch, 2012], dataset ‘UG13’ on very steep slopes and vertical walls with very small and zero crest freeboards on deep water conditions [Troch et al., 2015] and dataset ‘UG14’ also on steep low-crested structures although with tests featuring shallow water conditions [Gallach-Sánchez et al., 2014].

This paper explains the set-up used during the experiments in the wave flume at Ghent University and summarises the various parameters of the datasets UG10, UG13 and UG14. It also focuses on the main results obtained in these three datasets, presenting the overtopping results for very steep slopes and vertical walls, for very small and zero crest freeboard. The paper also introduces the results of the probability distribution of the individual overtopping volumes during a storm event.

2 PREVIOUS RESEARCH ON WAVE OVERTOPPING

Physical modelling on wave overtopping is widely reported in the scientific literature. An important effort was made in the CLASH project [van der Meer et al., 2009] to compile the existing overtopping knowledge and to perform physical modelling in those structural and wave conditions not previously reported in literature. Part of the CLASH data was included in the EurOtop (2007) manual, an overtopping manual extensively describing the overtopping process on various types of structures, providing also empirical formulae both on average wave overtopping and individual overtopping volumes. This manual is widely used to assess the wave overtopping and other coastal processes during the design of a sea defence structure.

Among the formulae featured in the EurOtop (2007) manual, the overtopping prediction formulae for mild slopes is widely used to assess the average overtopping rates. It has an exponential shape and it is only dependant on the relative crest freeboard \( R_c/H_m0 \). However, the formula is valid for a limited range of application only including mild slopes and large relative crest freeboards. For overtopping data inside the range of application, the formula predicts with a high accuracy the overtopping rates. Outside the range of application (i.e. for steep slopes and very small relative crest freeboard) the formula needs an updated version.

Van der Meer & Bruce (2014) presented a new formula (which will be included in the next EurOtop manual revision) that extends the range of application towards very steep slopes and vertical walls with very small and zero freeboard. It features an exponential function not only depending on the relative crest freeboard \( R_c/H_m0 \) but also on the slope angle \( \alpha \). This new formula was fitted through the UG10 dataset obtained at Ghent University for steep slopes data, and through a selection of CLASH datasets for vertical walls and mild slopes. However, the formula was neither fitted through overtopping data with very small and zero relative crest freeboard, nor through very steep slopes. Therefore, the datasets UG13 and UG14 could improve the accuracy of the formula by extending the data towards very steep slopes and vertical walls with very small and zero relative crest freeboard, in deep and shallow water wave conditions.

The exceedance probability of each overtopping volume (the volume of water that passes over a sea defence structure at each overtopping event) follows a two-parameter Weibull distribution, according to the EurOtop (2007) manual. This distribution features a scale factor \( a \) and a shape factor \( b \). The scale factor \( a \) is proportional to the average overtopping rate, scaling the individual volumes (larger values of the individual volumes correspond to larger values of \( a \)). The shape factor \( b \) determines the shape of the distribution. If \( b = 2 \) the exceedance probability follows a Rayleigh distribution which is a special case of the Weibull distribution. The EurOtop (2007) manual suggests a constant value of the shape factor of \( b = 0.75 \) for all types of structures in all kinds of conditions. However, recent research by Hughes et al. (2012) shows that the shape factor \( b \) is dependent on the relative crest freeboard \( R_c/H_m0 \), while research by Victor et al. (2012) shows that is dependent both on \( R_c/H_m0 \) and the slope angle \( \alpha \). This conclusion was extracted from analysing the dataset UG10 obtained at Ghent University.
3 EXPERIMENTAL TEST SETUP

We performed physical model tests in the large wave flume of the Department of Civil Engineering of Ghent University (Belgium). The wave flume (Figure 2) has a length of 30 m, a width of 1 m and a height of 1.2 m, and 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. The test setup installed in the wave flume was very similar for the three datasets UG10, UG13 and UG14 (Figure 3). In all the three datasets it consisted of a smooth impermeable structure forming a certain slope angle $\alpha$ with the foreshore. Behind the structure an overtopping box was placed, containing the necessary equipment to measure wave overtopping. Beneath the structure 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 is wide enough to assure a low velocity flow that does not affect the incoming waves.

The wave conditions (significant wave height $H_m0$ and peak wave period $T_p$) in the wave flume during a test are measured by two different sets of three wave gauges (WG 1 to WG 6 in Figure 3) installed at different locations in the wave flume to also study wave transformation during the wave propagation.

The overtopping box (Figure 4) was developed by Victor & Troch (2010) to measure with a high accuracy the individual overtopping volumes. During the UG10, UG13 and UG14 tests the individual wave overtopping volumes were measured and analysed, together with the average overtopping rates for every test (Figure 5). The overtopping box uses the weigh cell technique to measure the overtopping. It is constructed in plywood and it is formed by a dry area containing a reservoir to capture the overtopped water through a 0.2 m wide tray located at the crest of the model structure, a weigh cell to measure the water mass inside 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 based on the acquired readings of the weigh cell at a 5 Hz rate.

Figure 2: Large wave flume at the Department of Civil Engineering at Ghent University

Figure 3: Test setup of dataset UG13. For datasets UG10 and UG14 the foreshore was slightly different.

Figure 4: 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.

Figure 5: A wave attacks the structure (with a very steep slope and a small crest freeboard) and overtops during a test, resulting in a large individual overtopping volume.
4 EXPERIMENTAL TEST PROGRAMME FOR DATASETS UG10, UG13 AND UG14

We performed the physical model tests using the described setup with various structural parameters (slope angle $\alpha$, crest freeboard $R_c$) and wave parameters (incident spectral wave height $H_{m0}$ at the toe of the model structure, relative wave height $H_{m0}/h$, where $h$ is the local water depth at the toe of the model structure, and peak wave period $T_p$), as seen in Figure 6, with different values for UG10, UG13 and UG14 datasets. The average overtopping rate $q$ and the individual overtopping volumes $V_i$ were obtained after processing the weigh cell and WG signals. During the experiments, approximately 1,000 irregular waves were generated each test using a JONSWAP spectrum with a shape parameter of $\gamma = 3.3$.

An overview of the different wave and structural parameters of the UG10, UG13 and UG14 datasets is presented in Table 1. As explained before, the dataset UG10 contains overtopping data for mild and steep slopes with small relative crest freeboards. The UG13 and UG14 datasets are the extension of the UG10 dataset towards very steep slopes and vertical walls with very small and zero freeboards. The water depth conditions of the experiments is determined by the relative wave height. If the relative wave height is smaller than 0.2, the experiment is in deep water conditions; and if the relative wave height is larger than 0.2, the experiment is in shallow water conditions. It is clear then that the datasets UG10 and UG13 feature overtopping data in deep water conditions while the dataset UG14 is the extension of the UG13 dataset towards shallow water conditions.

5 RESULTS

After performing the experiments to obtain the UG10, UG13 and UG14 datasets, we have analysed wave overtopping for the different tested wave and structural conditions. The main overtopping results obtained from this research are for the following conditions:

(i) mild and steep slopes
(ii) very steep slopes and vertical walls
(iii) small relative crest freeboards
(iv) very small and zero relative crest freeboards
(v) individual overtopping volumes for all the mentioned conditions

In this section we will present the results relative to conditions (ii), (iv) and (v) individual overtopping volumes.

<table>
<thead>
<tr>
<th>Slope angle $\alpha$ (°)</th>
<th>UG10</th>
<th>UG13</th>
<th>UG14</th>
</tr>
</thead>
<tbody>
<tr>
<td>20, 25, 30, 35, 40, 45, 50, 60, 70</td>
<td>25, 35, 45, 60, 75, 80, 85, 90</td>
<td>35, 45, 60, 70, 75, 80, 85, 90</td>
<td></td>
</tr>
<tr>
<td>$\cot \alpha$ (-)</td>
<td>2.75, 2.14, 1.73, 1.43, 1.19, 1.00, 0.84, 0.58, 0.36</td>
<td>2.14, 1.43, 1.00, 0.58, 0.27, 0.18, 0.09, 0</td>
<td>1.43, 1.00, 0.58, 0.36, 0.27, 0.18, 0.09, 0</td>
</tr>
<tr>
<td>Crest freeboard $R_c$ (m)</td>
<td>0.020, 0.045, 0.070</td>
<td>0, 0.005, 0.01, 0.02, 0.045, 0.07</td>
<td>0, 0.02, 0.045, 0.076, 0.12, 0.2</td>
</tr>
<tr>
<td>Significant wave height $H_{m0}$ (m)</td>
<td>0.02 – 0.19</td>
<td>0.02 – 0.185</td>
<td>0.061 – 0.225</td>
</tr>
<tr>
<td>Relative crest freeboard $R_c/H_{m0}$ (-)</td>
<td>0.11 – 1.69</td>
<td>0 – 2.43</td>
<td>0 – 2.92</td>
</tr>
<tr>
<td>Peak wave period $T_p$ (s)</td>
<td>1.000 – 2.000</td>
<td>1.022 – 2.045</td>
<td>1.022, 1.534, 2.045</td>
</tr>
<tr>
<td>Relative wave height $H_{m0}/h$ (-)</td>
<td>0.04 – 0.39</td>
<td>0.03 – 0.39</td>
<td>0.20, 0.30, 0.40, 0.50</td>
</tr>
</tbody>
</table>

Table 1: Overview of UG10, UG13 and UG14 wave and structural parameters
Figure 7 shows the relative average overtopping rate $q/\sqrt{gH_{no}^3}$ against the relative crest freeboard $R_c/H_{no}$ for the condition no. (ii): very steep slopes (cot$\alpha$ ≤ 0.27) and vertical wall (cot$\alpha$ = 0) of the datasets UG13 and UG14. The overtopping data in this range of slopes not present in traditional literature is following the expected behaviour: decrease in average overtopping for increasing relative crest freeboard. However, in the range of very steep slopes and vertical walls, there is a strong dependence of the average overtopping with the slope angle $\alpha$, as stated before by Victor & Trach (2012) and van der Meer & Bruce (2014). The average overtopping rate decreases for increasing values of cot$\alpha$ (i.e., for steeper slopes).

The difference between the UG13 dataset (deep water conditions) and UG14 (shallow water conditions) is the increase of the average overtopping for relative crest freeboards $R_c/H_{no} > 1$ for shallow water conditions. For smaller values of $R_c/H_{no}$ the influence of the water depth is not noticeable in the overtopping rate. The EurOtop (2007) overtopping prediction formula (solid line) is also plotted in Figure 7 with its 90% confidence band. The overtopping data of datasets UG13 and UG14 for very steep slopes and vertical walls is exceeding the range of application of the EurOtop (2007) and therefore the formula is over-predicting all the overtopping results. The new van der Meer & Bruce (2014) formula (dashed line in Figure 7 for the vertical wall case) successfully extends this range of application towards very steep slopes and vertical walls, improving the accuracy of the prediction.
Figure 8 shows the relative average overtopping rate \( q \sqrt{gH_{mo}^3} \) against the cotangent of the slope angle \( \alpha \) \([\cot \alpha]\) for the condition no. (iv): very small relative crest freeboards \( R_c/H_{mo} \leq 0.11 \) and zero freeboard \( R_c = 0 \) of the UG13 and UG14 datasets. The average overtopping rate is mildly increasing for increasing values of \( \cot \alpha \), i.e. for milder slopes, in the range of considered \( R_c/H_{mo} \). However, for very steep slopes \( (\cot \alpha \leq 0.27) \) and vertical wall \( (\cot \alpha = 0) \) this trend is not significant enough where the average overtopping rates seem to be constant. More experiments would be valuable to confirm these results.

Figure 9 shows the shape factor \( b \) of the individual overtopping distribution of each UG13 test, as a function of the relative crest freeboard \( R_c/H_{mo} \). It is clear that the \( b \) values in the UG13 dataset decrease for increasing \( R_c/H_{mo} \). This is the same trend as found by Victor et al. (2012) for the UG10 dataset. For large values of the relative crest freeboard \( R_c/H_{mo} > 1 \) the \( b \) values are tending asymptotically towards the value suggested by the EurOtop (2007) manual \( b = 0.75 \). For relative crest freeboards \( R_c/H_{mo} < 1 \) the shape factors \( b \) show larger values than \( b = 0.75 \), indicating that this latter value is only valid for large relative crest freeboards.

### 6 CONCLUSIONS

To check the safety of the existing sea defence structures and to improve the design guidelines it is important to increase the knowledge of wave overtopping. Even though wave overtopping has been widely reported in the scientific literature, there are still knowledge gaps that should be covered. At Ghent University we performed experimental model tests with wave overtopping measurements to cover the existing gaps for steep, very steep slopes and vertical walls; and for small, very small and zero freeboard. These experiments resulted in the datasets UG10, UG13 and UG14. The UG10 dataset is the starting point of this research for steep slopes and small freeboards, while the datasets UG13 and UG14 extended the experiments towards very steep slopes and vertical walls with very small and zero freeboard. Dataset UG13 focuses on overtopping data for deep water conditions while the dataset UG14 focuses on shallow water conditions.

The average overtopping rates for this range of slope angles \( \alpha \) and relative crest freeboards \( R_c/H_{mo} \) follow the expected behaviour: decreasing average overtopping for increasing \( R_c/H_{mo} \). The slope angle \( \alpha \) has an influence in the overtopping rate for the range of steep slopes to vertical walls: the average overtopping decreases for steeper slopes. In the range of very small and zero freeboards, the influence of the slope angle \( \alpha \) is also present although for very steep slopes this influence is rather limited. For the dataset UG14 there is an increase of the average overtopping rates for large relative crest freeboards, indicating an influence of the shallow water conditions. The tested conditions of very steep slopes and vertical walls with very small and zero freeboard is outside the range of application of the EurOtop (2007) overtopping prediction formula. As an update, van der Meer & Bruce (2014) presented a new formula with an extended range of application suitable for datasets UG10, UG13 and UG14.

![Figure 9: Shape factor b of the individual overtopping distribution of the dataset UG13 (deep water) against the relative crest freeboard R_c/H_{mo}, and value b = 0.75 suggested by EurOtop (2007).](image)
The determination of the individual overtopping volumes is also an important part of this research. The shape factor $b$ of the probability distribution of the individual volumes for each test in the dataset UG13 decreases for increasing values of the relative crest freeboard $R_c/H_{m0}$ towards an asymptotic value of $b = 0.75$ for large $R_c/H_{m0}$, which matches the value suggested by the EurOtop (2007) manual for all types of slopes.

The research presented here is ongoing and the next steps will be to analyse the individual overtopping volumes of the dataset UG14, and to perform more tests in shallow water to confirm the influence of this conditions in the average overtopping rates.

REFERENCES


SUMMARY

Wave overtopping can affect persons, buildings and infrastructures located behind a sea defence structure. A detailed knowledge of the wave overtopping process is necessary to improve the accuracy of the overtopping prediction formulae and to design safer coastal defence structures. However, there is still a knowledge gap on wave overtopping of steep low-crested structures in the scientific literature. To cover this knowledge gap, a wide range of 2-D physical model tests on steep low-crested structures, both with deep water and shallow water wave conditions, have been performed in the large wave flume at the Department of Civil Engineering at Ghent University (Belgium).

This paper summarises the existing knowledge about wave overtopping for these conditions, describes the newly performed physical model tests, discusses the obtained average overtopping results and compares these new results with the existing traditional overtopping prediction formulae. The various traditional overtopping prediction formulae tend to underpredict the (experimentally obtained) overtopping rates for zero freeboards while there is an observed increase of the overtopping rates in the experimentally obtained data for large relative crest freeboards due to shallow water effects. The new data can be used to improve the accuracy of the existing overtopping prediction formulae.
RÉSUMÉ

Le franchissement des vagues peut impacter les personnes, les bâtiments et les infrastructures situées derrière des ouvrages de protection. Une connaissance détaillée des mécanismes de franchissement des vagues est nécessaire pour améliorer les formules de prédiction des franchissements et concevoir des ouvrages de défense des côtes plus sûrs. Cependant, il reste une lacune dans la littérature scientifique concernant le franchissement des ouvrages de faibles hauteurs et à pente raide. Pour combler cette lacune, une campagne d’essais sur modèle physique 2D a été réalisée dans le grand canal à houle du département de génie civil de l’Université de Gand (Belgique). Des conditions de faible profondeur et aussi de grande profondeur ont été testées au cours de ces essais sur modèle physique 2D. Cet article résume la connaissance existante sur les franchissements dans ces conditions, décrit ces essais sur modèle physique, discute les résultats moyens de franchissement de ces essais et les compare aux formules existantes usuelles de prédiction des franchissements. Les diverses formules usuelles de prédiction des franchissements ont tendance à sous-estimer les taux de franchissement (obtenus expérimentalement) avec une revanche de crête nulle alors que pour les résultats expérimentaux, on observe une augmentation due aux effets de faible profondeur, des taux de franchissement pour des rapports revanches de crête sur hauteur de houle élevés. Ces nouvelles données peuvent être utilisées pour améliorer la qualité des formules existantes de prédiction des franchissements.

ZUSAMMENFASSUNG


RESÚMEN

Los rebases pueden afectar a personas, edificaciones e infraestructuras situadas tras una estructura de defensa costera. El conocimiento detallado del comportamiento de estas situaciones resulta necesario para mejorar la precisión de las fórmulas de cálculo del rebase y poder diseñar de esta manera estructuras de defensa costera más seguras. Existe aún en la literatura científica un cierto desconocimiento a la hora de valorar los rebases sobre estructuras con baja cota de coronación. Para tratar de cubrir este campo, en el Departamento de Ingeniería Civil de la Universidad de Gante (Bélgica) se han llevado a cabo un conjunto de ensayos en modelo físico 2D para estructuras costeras con baja cota de coronación, en condiciones de oleaje representativas tanto de aguas profundas como de aguas someras. Este artículo resume el estado del arte del cálculo de rebases en estas condiciones, describe los modelos físicos llevados a cabo, analiza los resultados de rebase medio obtenidos y compara estos nuevos datos con las fórmulas tradicionales de cálculo de rebase. Dichas fórmulas tradicionales tienden a infravalorar las tasas de rebase (frente a las obtenidas en los ensayos) en situaciones en las que la coronación de la estructura coincide sensiblemente con el nivel del mar (francoline cero), a la vez que se observa un incremento en las tasas de rebase medidas en laboratorio a medida que se eleva la coronación en condiciones de aguas someras. Estos nuevos datos pueden servir para mejorar la fiabilidad de las formulaciones existentes de cálculo de rebases.