# WAVE OVERTOPPING PREDICTION OF A GENTLE SLOPED STEPPED REVETMENT

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Stepped revetments are multi-functional coastal structures offering protection against flooding. Despite the fact that these structures have been implemented for more than 60 years, comprehensive design guidance is lacking. Previous research studied overtopping of stepped revetments with slopes ranging between 1:1 to 1:4. To address the knowledge gap of predicting overtopping of stepped revetments with gentler slopes, this paper presents results of physical model tests for a 1:6 sloped stepped revetment with step heights of 0.05 m. The tests were conducted in a 110 m long, 2.2 m wide and 2.0 m deep wave flume. A fit through the overtopping results is compared with the reference curve for a smooth slope of EurOtop (2016), which allows the determination of the influence factor for roughness ($\gamma_f$) of the stepped revetment. A value of $\gamma_f$ = 0.74 ($r^2$ of 0.94) is proposed to be used in combination with the overtopping prediction formula of EurOtop (2016) for slopes under breaking wave conditions. The results of the study indicate a high slope dependency for $\gamma_f$.

*Keywords: coastal structures; wave overtopping; stepped revetments; physical model tests*

## INTRODUCTION

As tourism and recreation continue to play a more pronounced role in coastal areas, the implementation of multi-functional coastal structures becomes increasingly important. A stepped revetment is an appealing example of such a multi-functional coastal structure. The main benefit of a stepped revetment, from a coastal engineering point of view, is that the stepped surface acts as roughness elements which reduce wave overtopping compared to a smooth slope. Other added benefits of stepped revetments are that these structures can be aesthetic coastal solutions that offer safe access to the beach or water areas and promote tourism by offering a place to sit and/or serve as a walkway. Furthermore, stepped surfaces as roughness elements can be applied on dikes to increase energy dissipation. Although literature on stepped revetments include around 30 publications (e.g. Goda and Kishira (1976); Saville (1955); Van Steeg et al. (2018); Kerpen and Schlurmann (2014)), knowledge gaps on the design of stepped revetments with certain boundary conditions still persist.

Stepped revetments as dike cover could be of particular interest around the German coast, where dikes have seaward slopes between 1:4 and 1:7. As previous studies investigated wave overtopping of stepped revetments with slopes ranging from 1:1 to 1:4, the overtopping performance of milder slopes is unknown. The objective of this paper is to present an empirical approach for predicting the wave overtopping discharge of a stepped revetment with a 1:6 slope. To adhere to the widely applied overtopping guidelines of EurOtop (2016), an influence factor for roughness ($\gamma_f$) is proposed that can be applied in the EurOtop formula for breaking wave conditions (Equation 5.10 in EurOtop (2016)).

## PREVIOUS STUDIES

### Overtopping guidelines

The Overtopping Manual provides guidance on the analysis and prediction of wave overtopping for a wide range of structures (EurOtop, 2016). Although the manual is mainly based on European research, it has an international application. EurOtop (2016) presents the following general equations to predict the average wave overtopping discharge for relatively gentle slopes (dikes, levee, embankments):

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} = \frac{0.023}{\sqrt{tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot exp\left[-\left(2.7\frac{R_c}{\xi_{m-1,0} \cdot H_{m0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)^{1.3}\right] \quad (1)$$

$$\text{with a maximum of } \frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot exp\left[-\left(1.5\frac{R_c}{H_{m0} \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma^*}\right)^{1.3}\right] \quad (2)$$

where $q$ represents the average overtopping discharge in [$m^3/s$ per $m$], $g$ is the acceleration due to gravity in [$m/s^2$], $H_{m0}$ is the spectral significant wave height in [$m$], $\alpha$ is the angle between the overall structure slope and the horizontal, $\xi_{m-1,0}$ is the surf similarity parameter [-] and $R_c$ is the crest freeboard of the structure in

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[$m$]. A number of influence factors are presented ( $\gamma_\beta, \gamma_b, \gamma_f, \gamma_v, \gamma^*$ ) of which only the influence factor for roughness, $\gamma_f$, is of interest for this study. A value of 1 is assumed for all other influence factors.

For stepped revetments, Equations 1 and 2 apply under breaking and non-breaking waves respectively. In this study Equation 1 is applicable since only breaking wave conditions are considered. The influence factor for roughness is an indicator for the reduction in wave overtopping compared to a smooth slope due to the structure's permeability and roughness. For stepped revetments, this factor depends on the roughness of the structure's steps. In literature there are currently no guidance on the prediction of $\gamma_f$ for gentle sloped stepped revetments.

### Stepped revetments

A comprehensive literature review by Kerpen and Schlurmann (2016) critically discusses previous studies on stepped revetments as coastal protection measure. The boundary conditions and results of wave run-up and wave overtopping physical model tests were analysed and presented graphically. The results include studies with both regular waves (Saville (1955); Xiaomin et al. (2013); Kerpen and Schlurmann (2014)) and wave spectra (Goda and Kishira (1976); Takayama et al. (1982); Heimbaugh (1988); Ward and Ahrens (1992); Van Steeg et al. (2012)). Kerpen and Schlurmann (2016) found that there is no single study that tested a wide range of hydraulic and geometric boundary conditions and therefore highlight the need for systematic research. Moreover, based on the literature review they recommend a comprehensive analysis for results based on the step ratio ($H_{m0}/S_h$), defined as the wave height related to the step height.

Furthermore, Kerpen (2017) conducted physical model tests on stepped revetments to investigate the underlying system performance ($\cot\alpha$ = 1,2,3; $S_h$ = 0.05 m; 0.30 m). The study presents empirical formulae for wave reflection, wave run-up and wave impacts. Kerpen (2017) proposes the following equations to predict the influence factor for roughness ($\gamma_f$) for wave overtopping on stepped revetments valid for $H_{m0}/S_h < 1$ or $H_{m0}/S_h > 2.5$:

$$\gamma_f = 1 + 0.4 \cdot a^{1.5} \cdot atan\left(\frac{k_h \cdot b}{H_{m0} \cdot \xi_{m-1,0}}\right) \tag{3}$$

$$a = min\left\{1, \frac{H_{m0}}{S_h}\right\} \tag{4}$$

$$b = -\left(1.8 + 0.4 \cdot exp\left[\left(0.015\frac{S_h}{H_{m0}}\right)^{-0.22}\right]\right) \tag{5}$$

where $\gamma_f$ is the influence factor for roughness [-], $S_h$ is the step height of the revetment in [$m$], $a$ and $b$ are factors presenting the influence of the step ratio and $k_h$ is the characteristic step diameter ($k_h = \cos\alpha \cdot S_h$).

Although Equations 3 to 5 are based on a wide range of hydraulic and geometrical boundary conditions, a limited number of tests were conducted with breaking waves while slopes gentler than 1:3 have not been tested. For these reasons, the need is identified to conduct physical model tests to investigate the overtopping performance for stepped revetments with gentler slopes.

## METHODOLOGY

### Test facility

Physical model tests were conducted in the 110 m long Schneiderberg wave flume at the Ludwig Franzius Institute of Leibniz University Hannover. The flume 2.2 m wide, 2.0 m deep and is equipped with a piston type wave maker which can generate both regular and irregular waves. The wave paddle does not compensate for reflections, but the determined reflection coefficients of the structure are low ($C_r$ = 0.10 - 0.18).

### Model setup and instrumentation

The model was constructed from prefabricated steel step elements attached to two adjacent steel frames that stretches across the flume (Fig. 1). The structure had a slope of 1:6 ($cot\alpha = 6$), with a step height ($S_h$) of 0.05 m and a width ($S_w$) of 0.30 m (Fig. 2). At a distance of 73.6 m from the wave board, the model was placed on a horizontal flume bed. A number of four ultrasonic sensors ($US$) were employed to measure the surface elevation. Three of these sensors ($US1-3$) were placed at a distance of 45 m from the wave board and spaced according to the recommendations of Mansard and Funke (1980) to enable the separation of incident and reflected waves. The fourth sensor ($US4$) measured the surface elevation at the toe of the structure.

The water that flows over the crest of the structure is guided by a chute into an overtopping container. The container consists of two shells, with a load cell placed below the inner shell. In the event that the overtopping container reached its capacity, water was pumped out from the container. A trigger signal recorded the time intervals that the pump was running.

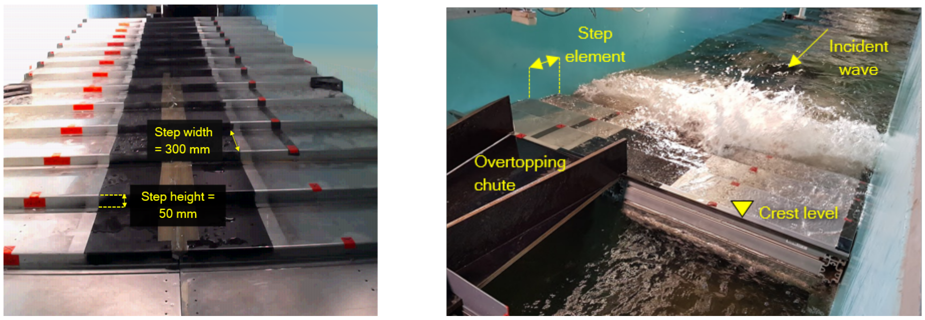
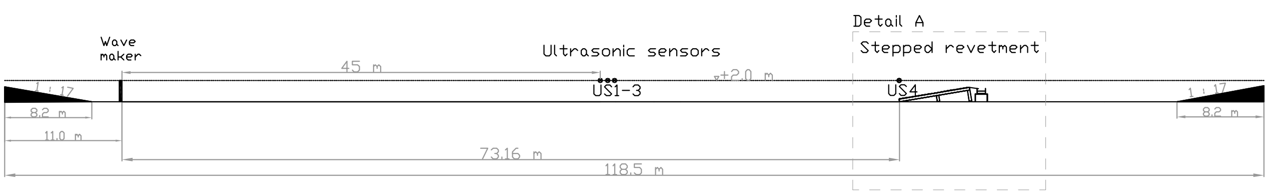
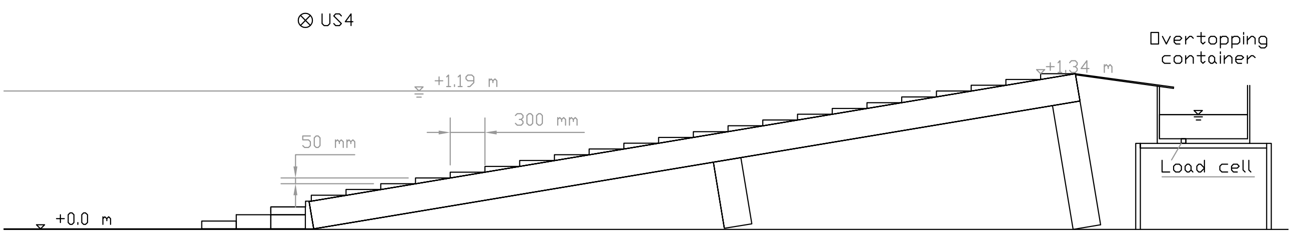



**Figure 1: Model setup of the stepped revetment**




**(a) Side view of the flume**




**(b) Detail A: Side view of model construction**

**Figure 2: Schematic impression of the (a) wave flume and (b) model setup**

### Test conditions

The test campaign included a total of 13 wave overtopping tests. The other tests, not discussed within the paper, focused on measuring wave run-up. For each test a minimum number of 1000 waves with a JONSWAP spectrum ($\gamma$ = 3.3) were generated. Table 1 gives an overview of the test conditions. Significant wave heights ($H_{m0}$) between 0.16 and 0.23 m were generated, while peak wave periods ($T_p$) ranged between 1.9 and 3.0 s. All wave conditions result in plunging waves ($\xi_{m-1,0}$ = 0.79 - 1.08) which are thus classified as breaking waves according to EurOtop (2016).

## ANALYSIS AND RESULTS

A reflection analysis was performed on the three ultrasonic sensors ($US1-3$) by employing the *Wave-Lab 3* software of the Aalborg University, Denmark. With the analysis the reflection coefficient ($C_r$) and wave periods ($T_{m-1,0}$;$T_p$) were calculated. A time series analysis was applied to the measurements of the ultrasonic sensor at the toe of the structure ($US4$) by which the total significant wave height ($H_{m0}$) is deter-

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Step height | $S_h$ | 0.05 | m |
| Slope angle | $\alpha$ | 9.46 | ° |
| Slope | $cot\alpha$ | 6 | - |
| Spectral significant wave height | $H_{m0}$ | 0.16 - 0.23 | m |
| Peak wave period | $T_p$ | 1.86 - 3.03 | s |
| Spectral wave period | $T_{m-1,0}$ | 1.75 - 2.75 | s |
| Water depth | $d$ | 1.14 - 1.19 | m |
| Freeboard | $R_c$ | 0.15 - 0.20 | m |
| Wave steepness | $s_{m-1,0}$ | 0.023 - 0.044 | - |
| Surf similarity parameter | $\xi_{m-1,0}$ | 0.79 - 1.08 | - |
| Step ratio | $H_{m0}/S_h$ | 3.10 - 4.62 | - |
| Relative feeboard | $R_c/H_{m0}$ | 0.73 - 1.04 | - |

**Table 1: Test conditions**

mined. The reflection coefficient is then applied to the total significant wave height to obtain the incident wave conditions at the toe of the structure as used in the results.

The load cell measured a time series of the weight of the overtopped water from which the total volume of water entering the container across a 0.7 m crest length was determined. The average wave overtopping discharge in $m^3/s$ per $m$ over the duration of the test was calculated.

Fig. 3 presents the results ($\cot\alpha = 6$) as relative overtopping rate versus relative freeboard. Following EurOtop (2016), Equation 1 applies since test conditions included breaking waves only ($\xi_{m-1,0} < 2$). The line $\gamma_f = 1$ represents the wave overtopping prediction for a smooth slope. Reference tests for a smooth slope were not included in the test campaign, which means that an influence factor for roughness ($\gamma_f$) cannot be derived for single tests. Hence an overall $\gamma_f$ is determined by fitting Equation 1 through the data points with $\gamma_f$ as the only unknown variable. An influence factor for roughness of 0.74 was determined with a coefficient of determination ($r^2$) of 0.94 and a root mean squared error ($RMSE$) of $3.09e^{-5}$.

As a qualitative comparison, Fig. 3 shows additional data points of Kerpen (2017) based on tests on a stepped revetment with $\cot\alpha = 3$ and $S_h = 0.05$ m under breaking wave conditions. It becomes evident that for the reduction in wave overtopping for the steeper stepped revetment is significantly higher than for the $\cot\alpha = 6$ revetment.

## DISCUSSION

The test results indicate that the stepped revetment significantly reduces the wave overtopping when compared to a smooth slope. This reduction is induced by the steps of the revetment that act as roughness elements, presented as the influence factor for roughness ($\gamma_f$). A $\gamma_f$ of 0.74 is proposed for stepped revetments with slopes of $\cot\alpha = 6$ to be applied in combination with the prediction formula of EurOtop (2016).

The qualitative comparison with data points from Kerpen (2017) for a stepped revetment with $\cot\alpha = 3$ (Fig. 3) indicate a strong slope dependency since the $\gamma_f$ for the two slopes differs considerably. The results show a significant lower influence factor for roughness for the steeper sloped stepped revetment. This implies that under breaking wave conditions, stepped revetments with steeper slopes are more effective in reducing wave overtopping when compared to smooth slopes. A reason for this could be the effect of a longer run-down time for gentler slopes. In the run-up process the roughness of the steps is reduced when a residual layer of water from a previous wave remains on the steps as the next wave approaches. During the model tests such a residual layer of water was observed which could explain the higher $\gamma_f$.

Furthermore, Kerpen (2017) found that the influence factor for roughness strongly depends on the step ratio for the revetment ($H_{m0}/S_h$). He identified a minimum $\gamma_f$ for a step ratio of 2. Tests in the present study have been conducted with step ratios between 3.10 and 4.62, while the data points of Kerpen (2017) are

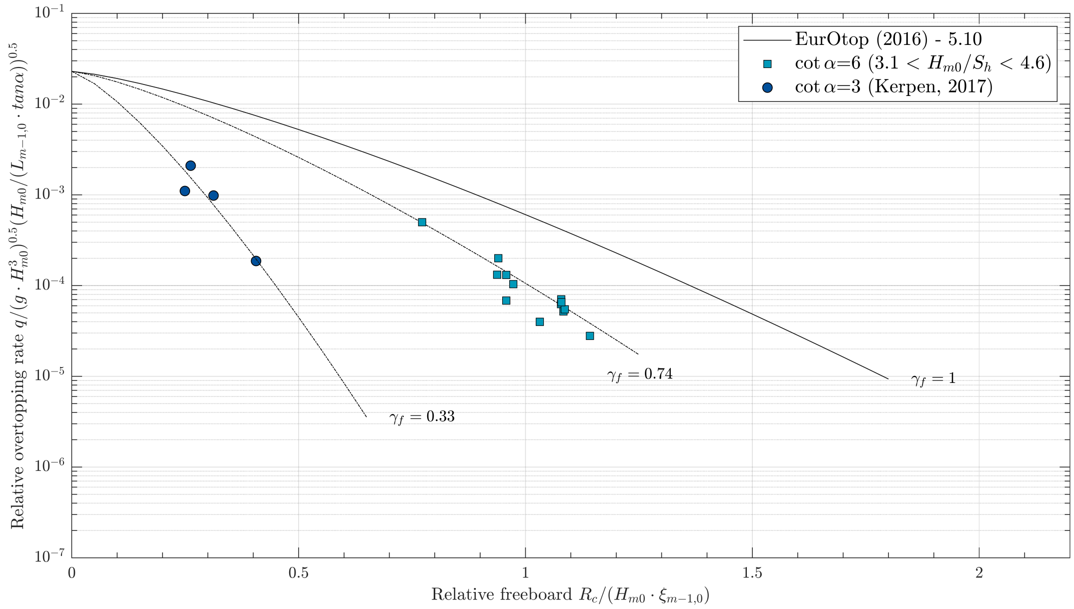



**Figure 3: Wave overtopping results for stepped revetment**

based on tests with step ratios close to the optimum value of 2. Consequently, the results of the two studies should not be compared directly due to the different step ratios. Another point to consider is that the surf similarity parameter of the Kerpen (2017) data is between 1.8 and 2.0 which is in the transition between breaking and non-breaking waves. To compare the roughness of the two slopes for the same step ratios and boundary conditions, Equation 3 is applied to determine $\gamma_f$. The prediction yields $\gamma_f$ values between 0.55 and 0.60 for a stepped revetment with $\cot\alpha = 3$. It should be noted that the prediction formula has mainly been derived from non-breaking wave conditions. Nevertheless, through the results for $\cot\alpha = 3$ and the prediction formula it can be concluded that the influence factor for roughness for a 1:6 sloped revetment is higher than for a 1:3 sloped stepped revetment and is thus less effective in reducing wave overtopping.

## CONCLUSION

The study investigated the overtopping performance of a stepped revetment with a slope of $\cot\alpha = 6$ and step heights ($S_h$) of 0.05 m. It was found that in comparison to a smooth slope, a significant reduction in wave overtopping can be achieved. This reduction can be ascribed to the influence factor for roughness ($\gamma_{m-1,0}$) which can be applied in the wave overtopping prediction of EurOtop (2016). By means of physical model tests an influence factor for roughness of 0.74 was determined ($r^2 = 0.94$; $RMSE = 3.09e^{-5}$) which is applicable for: $3.10 < H_{m0}/S_h < 4.62$ ; $0.79 < \xi_{m-1,0} < 1.08$ and $0.73 < R_c/H_{m0} < 1.04$.

Based on a comparison with results from a previous study (Kerpen, 2017), the reductive effect of the steps on wave overtopping for breaking waves becomes lower for gentler sloped stepped revetments. For a gentler slope revetment the wave overtopping with plunging waves, significant energy dissipation already occur during the wave breaking process. A higher $\gamma_f$ for a milder revetment could be explained by a longer wave run-down time, which lead to a residual layer of water on the revetment for the next approaching wave thus reducing the roughness.

To study the wave overtopping performance of gentler sloped stepped revetments in greater detail, it is recommended to systematically investigate a wide range of step ratios. For establishing an empirical prediction for influence factors for roughness under breaking wave conditions, additional tests for stepped revetments with steeper slopes ($\cot\alpha < 6$) are required.

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