Wave Overtopping of Stepped Revetments

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Abstract: Wave overtopping, i.e., excess of water over the crest of a coastal protection infrastructure due to wave run-up, of a smooth slope can be reduced by introducing slope roughness. A stepped revetment ideally constitutes a slope with uniform roughness. Apart from reducing overtopping, a stepped revetment provides safer access to a beach compared to conventional rubble. In recent years, research studies on stepped revetments have provided valuable findings regarding the performance and design optimization of stepped revetments as a typical mean of coastal protection. A stepped revetment can reduce overtopping volumes of breaking waves up to 60% compared to a smooth slope. The effectiveness of the overtopping reduction decreases with increasing Iribarren number. However, up to date a unique approach applicable for a wide range of boundary conditions is still missing. The present paper critically reviews previous findings, gathers and analyzes data from previous studies and proposes a new formula for robust prediction of overtopping of stepped revetments. By means of this approach a critical assessment based on beforehand disclosed parameter ranges between a smooth slope on the one hand and a plain vertical wall on the other are contrasted. By analysis of a new data set compounded from different original studies a novel empirical formulation is derived to predict the roughness reduction coefficient of a stepped revetment for breaking and non-breaking waves. This coefficient is developed and adjusted for a direct incorporation into the present design guidelines. Underlying uncertainties are clearly addressed and quantified. Scale effects are highlighted.

Keywords: Stepped revetment, wave overtopping, surface roughness, physical model test.

1. Introduction and Motivation

Traditionally the main purpose of a coastal structure is to provide coastal safety, taking into account constraints from urban development, environmental compatibility and costs. However, lately increasing emphasis is placed on the secondary purposes of coastal structures, e.g. tourism and recreation [1,2]. As a result, a coastal protection system ideally combines secondary purposes without affecting its main purpose of providing protection against storm surges. A stepped revetment can be built with steep slopes and thus could have a relatively small footprint. These steep slopes can be easily and safely accessed, thus shaping the concept and realization of stepped revetments an appealing multi-functional coastal structure.

A number of scientific studies has proven the ability of a stepped revetment to reduce wave run-up and wave overtopping [3–11]. The results of these studies are partly inconclusive, mainly due to the variable hydraulic- and geometric boundary conditions from which conclusions on reduction were determined. The present paper is mainly based on findings from [8] incorporating findings from latest studies [9,12].

To the authors’ best available knowledge this is the paper embraces the first systematic comparison of the influence of stepped revetments to reduce wave overtopping. The study considers a broad range of hydraulic and structure-related parameters, i.e. breaking and non-breaking wave conditions, slopes between 1:1 to 1:6 and step heights much smaller and much larger than the spectral significant wave height. In addition to the data sets collected in physical modelling studies in
Ludwig-Franzius-Institute, data sets from two other laboratories are included in the analysis and results. These data sets are based on comparable experimental setups, which ensure consistency in the conclusions and may exclude biases from model effects from individual studies.

The aim of the present paper is the empirical derivation of a roughness reduction coefficient for wave overtopping on stepped revetments in relation to a smooth slope with coherent application to breaking and non-breaking wave conditions to the wave overtopping prediction according to [13].

The present paper is structured as follows: First the technical background with focus on data harmonization, wave overtopping prediction and the influence and determination of the roughness of a revetment with special focus to stepped slopes is presented and discussed. In section 2 the experimental set-up, test procedure and conditions of the conducted model tests are described. Section 3 follows with the documentation of the gained results an analysis of the overtopping performance of stepped revetments in comparison to smooth slopes follows. The principle processes of the energy dissipation over stepped slopes are discussed in section 5 in the context of findings from existing literature. Model and scale-effects are discussed. In conclusion, section 6 summarizes the main findings and gives an outlook of future research.

1.1. Technical background

In the following, fundamentals and definitions for the processing related to wave overtopping are summarized. The described methods are applied to data from different authors in the results and analysis section.

Harmonization of data sets

Studies with different decade of origin and from diverse laboratories demand for a sound processing and harmonization of certain values that are applied in the present design assessment. The Iribarren number $\xi_{m-1,0} = \tan \alpha / \sqrt{g T_{m-1,0}}$ applied in wave run-up and overtopping predictions is based on the fictitious wave steepness $s_f$ [14]. This fictitious wave steepness is a function of the spectral significant wave height $H_{m0} = 4\sqrt{n_m}$ and the mean energy wave period $T_{m-1,0}$ both measured at the toe of the structure as follows:

$$s_{f-1,0} = \frac{2\pi H_{m0}}{g T_{m-1,0}^2} \quad (1)$$

According to [15] the peak wave period $T_p$ for a wave spectrum following Bretschneider’s distribution ($\gamma = 1$) is correlated to the mean wave period $T_{1/3}$ by

$$T_p \cong T_{1/3} / [1 - 0.132 \cdot (\gamma + 0.2)^{-0.559}] \quad (2)$$

and the mean spectral wave period $T_{m-1,0}$ is correlated to the peak wave period $T_p$ according to [16] by

$$T_{m-1,0} = T_p / 1.17 \quad (3)$$

Wave overtopping prediction

Wave overtopping is caused by waves running up the face of a dike or seawall [13]. If the wave run-up is higher than the freeboard height of the structure water will reach and pass over the crest. Also splash and spray induced from waves breaking on the face of the structure cause overtopping. The general equations for the relative overtopping discharge prediction under breaking waves for relatively gentle slopes ($\cot \alpha \geq 2$) is given by the mean value approach

$$q = \frac{a}{\sqrt{g H_{m0}^3}} = \frac{a}{\sqrt{\tan \alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot \exp \left[ - \left( \frac{b}{H_{m0} \cdot \xi_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\theta \cdot \gamma_\eta} \right)^{1.3} \right]$$

with $a = 0.023$ and $b = 2.7$. 

Preprints | www.preprints.org  | NOT PEER-REVIEWED  | Posted: 19 April 2019
Peer-reviewed version available at Water 2019, 11, 1035; doi:10.3390/w11051035
with \( q \text{ [m}^3\text{s}^{-1}\text{m}^{-1}] \) depicting the mean overtopping volume per meter crest width and second, \( a \) and \( b \) represent regression coefficients, \( R_c \) is the freeboard height defined as the crest height of a structure relative to the still water line (SWL) and \( \gamma_f \) the reduction coefficient for friction. The influence factors for the presence of a berm (\( \gamma_b \)), oblique wave attack (\( \gamma_o \)) and a vertical wall on the crest of the structure (\( \gamma_v \)) are not relevant for the present study and therefore set to 1.0 in subsequent equations. For non-breaking waves under the same boundary conditions by

\[
\frac{q}{\sqrt{g H^3}} = a \cdot \exp \left[- \left( b \frac{R_c}{H_\text{mo} \cdot \gamma_f} \right)^{1.3} \right] \text{ with } a = 0.09 \text{ and } b = 1.5
\]  
(5)

For very steep slopes (\( \cot \alpha < 2 \)) and non-breaking waves [13] is referring to the work by [17] who provides the coefficients

\[
a = 0.09 - 0.01(2 - \cot \alpha)^{2.1} \text{ for } \cot \alpha < 2 \text{ and } a = 0.09 \text{ for } \cot \alpha \geq 2
\]

\[
b = 1.5 + 0.42(2 - \cot \alpha)^{1.5}, \text{ with a maximum of } b = 2.35 \text{ and } b = 1.5 \text{ for } \cot \alpha \geq 2
\]  
(6)

for Equation (5). But, this formula is valid only for smooth slopes, hence, the friction reduction coefficient has to be set to \( \gamma_f = 1 \). For breaking waves, Equation (4) shall be used.

The slope roughness is represented in the empirical formulae by the roughness influence factor \( \gamma_f \), representing the permeability and roughness of or on the slope. The mean value approach provided in [13] to predict the mean wave overtopping discharge on coastal dikes and embankments is derived originally by [18].

The influence of roughness

The influence factor for the permeability or roughness of or on the slope is defined for the wave run-up as

\[
\gamma_f = \frac{R_{u,2\%}, \text{rough slope}}{R_{u,2\%}, \text{smooth slope}}
\]  
(7)

with \( R_{u,2\%} \) defined as the wave run-up level, measured vertically from the SWL which is exceeded by 2% of the number of incident waves. For wave overtopping, the roughness reduction factor is defined as

\[
\gamma_f = \frac{\ln(q \text{ smooth slope})}{\ln(q \text{ rough slope})}
\]  
(8)

As mentioned by [9], the roughness reduction coefficient \( \gamma_f \) is derived for a method described in [19] and is valid only for breaking waves (\( \xi_{m-1,0} < 1.8 \)). For Iribarren numbers larger than \( \gamma_b \cdot \xi_{m-1,0} = 1.8 \) (with \( \gamma_b = 1 \) in the present study) the roughness reduction coefficient has to be corrected by linear extrapolation between its value at 1.8 along \( 1.8 < \xi_{m-1,0} < 10 \) to \( \gamma_f = 1 \)

\[
\gamma_{f,\text{surling}} = \gamma_f + \frac{\left[ (\xi_{m-1,0} - 1.8)(1 - \gamma_f) \right]}{(8.2)} \text{ for } \xi_{m-1,0} > 1.8
\]  
(9)

Although this approach is based on findings from tests with impermeable rock slopes, [19] advises to also apply Equation (9) for cases with roughness elements. Results of hydraulic model tests already incorporate the reduced influence of friction for surging waves \( \gamma_{f,\text{surling}} \). Hence, an adjusted roughness factor has to be determined by a rearrangement of Equation (9) to

\[
\gamma_{f,\text{corr}} = \gamma_{f,\text{surling}} - \frac{\left[ (\xi_{m-1,0} - 1.8)(1 - \gamma_f) \right]}{(8.2)} \text{ for } \xi_{m-1,0} > 1.8
\]  
(10)

1.2. Roughness of stepped revetments

Drivers and processes of wave-induced responses of stepped revetments have been a major focus of research in the discipline of Coastal Engineering have studied within last 100 years. A comprehensive
literature review on hydraulic model tests related to stepped revetments with focus on wave run-up, wave overtopping and scour development at the toe of such revetments is provided by [20]. The review includes the main findings from [3–7,21] and others. For regular waves, a prediction of the mean overtopping discharges on stepped revetments is given by [22]. Literature, focusing particularly on physical model tests on the wave run-up or wave overtopping by irregular waves at stepped revetments (without influence of parapets as data sets provided [7,11,23]) are summarized in the following.

[6] provide overtopping data for a stepped revetment (cota = 2) with two different sloped foreshores (1:10 and 1:30). The SWL of the set-up is located at the toe of the stepped revetment and the end of the inclined foreshore with smooth surface. Hence, only broken waves reach the stepped revetment and cause overtopping. But for the reason that this study provides data for relatively large dimensionless step heights $H_{mo}/S_h (19.4; 29.1)$ it is included for comparison and corrected against the effect of broken waves in the analysis. [6] provide a roughness influence factor of $0.93 < \gamma_f < 0.98$ for very large dimensionless step heights $H_{mo}/S_h (19.4; 29.1)$ and broken waves with a narrow band of deep water Iribarren number in the range of $2.48 < \xi < 2.55$. As the step heights $S_h (0.006 \text{ m}, 0.009 \text{ m})$ in the model tests were relatively small induced by the Froude scale of 1:33:3 these data are likely influenced by scale effects. As [6] provide data for the mean wave period $T_{1/4}$ these are converted according to Equation (2) and (3) to ensure that this data set is comparable. The wave data was the further processed with Equation (1).

A data set of wave overtopping at stepped revetment (cota = 3) with smaller dimensionless step heights ($5 < H_{mo}/S_h < 8$) is provided by [24]. Below the SWL ($z = 0$) the stepped revetment is continued up to a distance of $0.375 < z/H_{mo} < 0.6$. Below this value the slope is modelled as smooth slope. [24] gradually increased the freeboard height in the tests by adding additional steps on the crest, until an overtopping volume less than a certain target was measured. The corresponding roughness reduction coefficient of this study is $\gamma_f = 0.6$.

A comprehensive study and comparison of different data sets of wave run-up and wave overtopping in regular and irregular waves is provided by [8]. This data set covers a wide range of application ($0.5 < H_{mo}/S_h < 2.5; 1.5 < \xi_{m-1.0} < 8.5; \text{cota} (1; 2; 3)$). However, because of slightly better coefficients of determination the roughness influence factors $\gamma_f$ for the wave run-up was calculated against the smooth slope prediction by [25]. To enable a standardized implementation of the roughness influence factor in the [13] formulæ the present paper will incorporate the measured overtopping values accordingly.

[9] is based on an internal project report [21] and provides data for stepped revetments with cota(2;3). Compared to [6] and [24] the analyzed dimensionless step heights are smaller ($1.6 < H_{mo}/S_h < 6.7$) and plunging and surging wave breaking is covered ($1.7 < \xi_{m-1.0} < 3.7$). The provided roughness reduction coefficients are in a range of $0.8 < \gamma_f < 0.9$ for small steps ($S_h = 0.023 \text{ m}$) and reduced values in a range of $0.6 < \gamma_f < 0.7$ for steps with a doubled height ($S_h = 0.046 \text{ m}$). They derived a correlation between the roughness reduction coefficient and the step height and the slope, related to the wave height and weighted by the dimensionless overtopping discharge which follows the form

$$\gamma_f = a - b \left[ \frac{\cos \alpha \cdot S_e}{H_{mo}} \ln \left( \frac{q}{\sqrt{gH_{mo}^2}} \right) \right]$$

(11)

[10] discusses overtopping data for stepped revetments for steep slopes ($\text{cota} (0.58; 1)$) and the impact of surging waves ($3.9 < \xi_{m-1.0} < 14.7$). He provides a formula to predict the roughness reduction coefficient which is for tested configurations in a range of $0.5 < \gamma_f < 0.91$. The author compares his findings with [8] and found lower $\gamma_f$ – values for equal Iribarren numbers.

[12] provide overtopping data for stepped revetments over gentle slopes ($\text{cota} = 6$). The tests were conducted in the same wave flume as the present study. They cover dimensionless step heights in a range of $(3.1 < H_{mo}/S_h < 4.6)$ for plunging waves ($0.8 < \xi_{m-1.0} < 1.1$). The derived roughness reduction coefficient for gentle slopes – compared to the other studies – is $\gamma_f = 0.74$ with a corresponding goodness of fit of $R^2 = 0.94$ and a root mean square error of $\text{RMSE} = 3.09 \times 10^{-5}$.
Table 1 gives a summary of the \( \gamma_f \) - values for wave run-up and overtopping on plain stepped revetments as reported by various authors. The dimensionless step heights, Iribarren number and slopes indicate the ranges for which the roughness factors are applicable. Only studies with irregular wave conditions are included in the table. Reliable data for further analysis in this paper can be extracted from [6,8,9,12].

Table 1. Influence factors for roughness for plain stepped revetments by various authors.

| Author | Step height \( S_h \) [m] | Dimensionless step height \( H_{mo}/S_h \) [-] | Iribarren number \( \xi_{m-1,0} \) [-] | Slope \( \cot \alpha \) [-] | Roughness factor \( \gamma_f \) [-] |
|--------|-----------------|-----------------|-----------------|-------------|-----------------|
| [6]    | 0.006; 0.009    | 19.4; 29.1      | 0.9 – 2.67      | 2           | 0.8 – 0.9       |
| [24]   | 0.015           | 5.0 – 8.0       |                 | 3           | 0.6             |
| [8]    | 0.05; 0.3       | 0.5 – 2.5       | 1.5 – 8.5       | 1; 2; 3     | 0.35 – 0.9 \( R_{n,20\%} \) |
|        |                 |                 |                 |             | 0.5 – 0.95 \( q \) |
| [9]    | 0.023; 0.046    | 1.6 – 6.7       | 1.7 – 3.7       | 2; 3        | 0.8 – 0.9 \( S_h = 0.023 \) |
|        |                 |                 |                 |             | 0.6 – 0.7 \( S_h = 0.046 \) |
| [10]   | 0.053, 0.106    | 0.7 – 2.45      | 3.9 – 14.7      | 0.58; 1     | 0.5 – 0.91      |
|        |                 |                 |                 |             | 0.91 \( n = 0.58 \) |
| [12]   | 0.05            | 3.1 – 4.6       | 0.8 – 1.1       | 6           | 0.74            |

From Table 1 it is evident that individual studies mostly considered stepped revetments with limited parameter ranges. In order to draw universal conclusions regarding the overtopping performance of stepped revetments, this paper considers data sets of a number of studies and by this means covers a wider range of dimensionless step heights, slopes and wave breaking conditions in order to achieve a greater understanding of the reduction of wave overtopping on stepped revetments. According to [19], the influence factor for roughness was derived for breaking wave condition and should therefore be adapted the friction reduction for non-breaking waves or surging \( (\xi_{m-1,0} > 1.8) \). Currently, only [9] considered this adaptation, and thus data from [6,8] have to be recalculated according to Equation (10). [12] provides solely breaking wave conditions and thus no adaptation is required.

### 2. Experimental set-up, procedure and test conditions

#### 2.1. Model set-up and procedure

Hydraulic model tests were conducted in a wave flume with a length of 110 m, a width of 2.2 m and an overall depth of 2.0 m. The water depth can be varied from 0.0 m to 1.2 m. The flume is equipped with a hydraulic driven piston type wave maker (wet-back). Waves can be generated with a total stroke of 0.6 m and a maximum velocity of 1.2 m/s. Hence, dependent on the water depth \( h_s \), significant wave heights up to \( H_s = 0.32 \) m and wave periods larger than \( T \geq 0.9 \) s can be generated. A 1:10 inclined rubble mound slope is located at the end of the flume to serve as a passive wave absorber. The models, constructed from composite timber sheets, are placed on the horizontal flume bed at a distance of 85 m from the wave board with respect to the model’s crest. Further details of the model set-up are provided by [8,26]. An impression of the model set-ups is given in Figure 1.
Figure 1. a) Side view of the model set-up with wave gauge positions. b) Side view of the tested step geometries.

For each test, standard JONSWAP spectra were generated with a peak enhancement factor of 3.3 and a relative peak width of 0.07 and 0.09 for frequencies below and above the peak frequency respectively. The wave overtopping volume was collected in a reservoir behind the crest of the structure equipped with weighting cells enabling the calculation of the mean overtopping volume. For statistical validity, long test durations with more than 1,000 waves were simulated [27]. Wave conditions in front of the model have been analyzed by a set of 3 gauges placed according to [28]. The gauge array had a minimum distance of $0.4L_p$ from the structure, where $L_p$ is defined as the peak wave length, to avoid influencing effects of evanescent modes [29]. Wave data are analyzed with the Matlab toolbox WAFO [30]. Wave parameters are calculated according to section 1.1 for further analysis. After initial reference tests with a plain slope ($S_\text{ref} = 0.0 \text{ m}$), tests for small ($S_\text{ref} = 0.05 \text{ m}$) and large step heights ($S_\text{ref} = 0.3 \text{ m}$) are conducted. The wave overtopping was analyzed for three different slopes ($\cot \alpha \in \{1; 2; 3\}$) and three freeboard heights ($R_e \in \{0.121 \text{ m}; 0.211 \text{ m}; 0.3 \text{ m}\}$). Additional measurements of horizontal and vertical pressures on the step face were taken, but these results and further details are reported elsewhere [26]. To allow visual interpretation of the results, all tests were documented by video.

2.2. Test conditions

The test conditions are based on the findings of a thorough dimensional analysis following [31] which results in the dimensionless notation for the wave overtopping analysis of stepped revetments:

$$F \left( \frac{h_s}{L_m^{-1.0}}; \xi_m^{-1.0}; \cos \alpha; \frac{R_c}{H_m^0}; \frac{q}{gH_m^0}; \frac{S_h}{H_m^0} \right) = 0$$

with $L_m^{-1.0}$ defined as spectral wave length. As most dimensionless values are already covered by Equation (4) and (5) the roughness reduction coefficient to be derived for stepped revetments should be based only on the remaining dimensionless step height $S_h/H_m^0$. To extend the present understanding and cover the boundary conditions of data stemming from comparable literature [6,8,9,12] a wide parameter range is covered by the present test program ($1.5 < \xi_m^{-1.0} < 9.4$, $1 \leq \cos \alpha \leq 3$, $0.85 < R_c/H_m^0 < 4.5$, $1.6E^{-6} < q/\sqrt{gH_m^3} < 1.0E^{-2}$). An overview of the boundary conditions is given together with the results for each test in Table 3.

3. Results

3.1. Calibration

The overtopping reduction coefficient for the stepped revetments $\gamma_f$ which is interpreted as a roughness coefficient is calculated in relation to the wave overtopping on a smooth slope following
Equation (8). The overtopping volume measured for a rough slope \( q_{ \text{rough slope} } \) is to be correlated with the corresponding value from a regressions best fit through the smooth slope data \( q_{ \text{smooth slope} } \) [13].

The fitted curves for the smooth slopes of the present study (Equation (4) and (5) with regression coefficients \( a \) and \( b \) according to Table 2) are plotted in Figure 2.

**Figure 2** provides an overview of measured dimensionless overtopping volumes versus the dimensionless freeboard height for smooth and stepped slope conditions. The results are separated into breaking and non-breaking wave conditions. For reference, predictions for smooth slopes (Equation (5) with (6)) and vertical wall conditions are given. The mean wave overtopping at a vertical wall – a hypothetical adopted single vertical step face – is predicted by Equation (5) and corresponding regression coefficients \( a = 0.047 \) and \( b = 2.35 \).

**Figure 2** (a) provides steep slope conditions \((\cot\alpha = 1)\) for non-breaking waves. The measured dimensionless overtopping discharge for the smooth slope is larger than the prediction with Equation (5) but the deviations are covered with the corresponding 90% confidence band representing a 5%–exceedance from the prediction. The dimensionless overtopping discharge decreases only slightly with increasing step height. For the largest tested step height \((S_n = 0.3m)\) data scatters significantly.

For milder slopes \((\cot\alpha \geq 2)\) and non-breaking wave conditions (Figure 2 (b)) the mean overtopping discharge for smooth slope conditions is also larger than the prediction with Equation (5). The mean overtopping discharge decreases for an increased surface roughness but is mostly larger than the predicted overtopping for a plain vertical wall.

For breaking wave conditions and mild slopes \((\cot\alpha \geq 2)\) (Figure 2 (c)) only a single tests for smooth slopes is available. Nevertheless, also this mean overtopping discharge is larger than predicted according to Equation (4).

The values \( a \) and \( b \) in Equation (4) and (5) as derived from the regression of the smooth slope data given in Figure 2, are given in Table 2. For a 1:6 slope no data for a smooth slope is available, but the tests were conducted in the same wave flume as the present study. A comparable larger mean overtopping rate relative to the prediction is assumed and therefore applied in further calculations.

![Figure 2](image_url)

**Figure 2.** Dimensionless overtopping discharge over the dimensionless freeboard height for smooth and stepped surfaces with different slope angles. Overtopping prediction formulae according to [13] for smooth slopes and vertical walls are given as reference. Determined best fits for smooth slopes of the present study are given for (a) steep slopes with \( \cot\alpha < 2 \) and non-breaking wave conditions, (b)
milder slopes with \( \cot \alpha \geq 2 \) and non-breaking wave conditions and (c) mild slopes with \( \cot \alpha \geq 2 \) and breaking wave conditions.

### Table 2. Regression coefficients \( a \) and \( b \) according to Equation (8) for corresponding smooth slopes.

| \( \cot \alpha \) | \( \xi_{m-1,0} [-] \) | \( a [-] \) | \( b [-] \) |
|------------------|-----------------|--------|--------|
| 1                | > 1.8           | 0.08   | 1.4    |
| 2                | > 1.8           | 0.09   | 1.2    |
| 3                | > 1.8           | 0.09   | 1.3    |
| 3                | < 1.8           | 0.023  | 2.3    |
| 6                | < 1.8           | 0.023  | 2.3    |

### 3.2. Measured and determined values

The regression coefficients listed in Table 2 are empirically derived and applied to the prediction formulae (Equation (4) or (5)) and set in proportion with the mean overtopping volumes obtained from the stepped surface tests. The influence factor for roughness \( \gamma_f \) is calculated by applying Eq. (8). The derived values for \( \gamma_f \) for non-breaking waves are corrected according to Equation (10). Table 3 provides an overview of the measured parameters of the conducted model tests. The mean overtopping volume \( q \), the calculated (\( \gamma_f \)) and corrected (\( \gamma_{f,corr} \)) friction reduction coefficients for stepped revetments are also given.

### Table 3. Overview of model test parameter, including calculated (\( \gamma_f \)) and corrected (\( \gamma_{f,corr} \)) roughness reduction coefficients for stepped revetments.

| \( \cot \alpha \) | \( S_h \) | \( h_s \) | \( R_e \) | \( H_{mo} \) | \( T_{m-1,0} \) | \( \xi_{m-1,0} \) | \( q \) | \( \gamma_f \) | \( \gamma_{f,corr} \) | \( \cot \alpha \) | \( S_h \) | \( h_s \) | \( R_e \) | \( H_{mo} \) | \( T_{m-1,0} \) | \( \xi_{m-1,0} \) | \( q \) | \( \gamma_f \) | \( \gamma_{f,corr} \) |
|------------------|--------|--------|--------|-------------|-------------|-------------|--------|--------|-------------|-------------|--------|--------|--------|-------------|-------------|-------------|--------|--------|-------------|-------------|
| 1                | 0.3    | 0.25   | 0.08   | 1.0         | 1.0         | 1.0         | 1.0    | 1.0    | 1.0         | 1.0         | 1.0    | 1.0    | 1.0    | 1.0         | 1.0         | 1.0         | 1.0    | 1.0    | 1.0         | 1.0         |
| 2                | 0.25   | 0.15   | 0.08   | 1.0         | 1.0         | 1.0         | 1.0    | 1.0    | 1.0         | 1.0         | 1.0    | 1.0    | 1.0    | 1.0         | 1.0         | 1.0         | 1.0    | 1.0    | 1.0         | 1.0         |

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Peer-reviewed version available at *Water* 2019, 11, 1035; doi:10.3390/w11051035
4. Analysis

Figure 2 indicates that at a stepped revetment the wave overtopping volume is lower than at a smooth slope and larger than at a vertical wall. The reduction is caused by the geometry of the stepped revetment by means of effectively mitigating run-up and overtopping by waves induced by dissipation and reflection of the incoming wave. In analogy to stepped spillways the step diameter $k_h$ is introduced to describe the surface roughness of a stepped revetment [32]. It is defined as the perpendicular distance between the step niche and the straight connection between the two adjacent step edges (Figure 3). The step diameter can be calculated with the step height $S_h$ and the slope angle of the revetment $\cos \alpha$:

$$k_h = \cos \alpha \cdot S_h$$ (13)

Figure 3 gives the calculated correlation between the reduction coefficients for roughness of a stepped revetment $\gamma_f$ against the corresponding step ratio $k_h/H_{mo}$. The given values for $\gamma_f$ refer to the corrected values for surging waves according to Equation (10). Data of the present study are combined with findings by [6,9,12] to extend the range of validity as the additional data sets include different slopes and step ratios. Data for four different slopes ($\cot \alpha \in \{1; 2; 3; 6\}$) and a wide range of step ratios ($0.03 < k_h/H_{mo} < 5.0$) are given.

A plain slope has a step ratio of 0.0 and therefore a corresponding reduction coefficient for roughness equal to 1.0. A vertical wall can be interpreted as a single vertical step face and therefore in analogy as a large step ratio. These two extremes define the outer boundary conditions. In between these values the surface roughness of the stepped revetment influences the wave overtopping discharge. The regression analysis of the data results in a double arctangent function:

$$\gamma_f = 1.55 - 0.55 \cdot \arctan \left[ \frac{k_h}{H_{mo}} + 0.07 \right]^{1.48} + 0.35 \cdot \arctan \left[ 0.6 \left( \frac{k_h}{H_{mo}} - 3.5 \right) \right]$$ (14)

The function describes the relation between the reduction coefficient for roughness of a stepped revetment and the corresponding step ratio with a goodness of fit of $R^2 = 0.82$, a root mean square error of $RMSE = 0.059$ and a standard deviation $\sigma = 0.022$. Starting from $k_h/H_{mo} = 0$ the derived prediction for $\gamma_f$ decreases up to a minimum value of 0.38 for $k_h/H_{mo} = 1$ and increases again for $k_h/H_{mo} > 1$. The minimum $\gamma_f$ represents the maximum efficiency of wave overtopping reduction and is in a range of $0.5 < k_h/H_{mo} < 1.5$. 

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0.085 2.09 4.48 0.003 0.51 0.35
Figure 3. Reduction coefficient $\gamma_f$ versus the step ratio ($k_h/H_{m0}$) for varying slopes ($1 \leq \cot \alpha \leq 6$) including a best fit regression line and the 90% confidence band.

The quality of the derived prediction according to Equation (14) is given for the individual test series in Table 4. Data from the present study show an appropriate goodness of fit for milder slopes ($R^2 > 0.9$). The goodness of fit is lower for the steep 1:1 slope ($R^2 = 0.75$) which is mainly caused by two outliers for step ratio large 1.0. The low outlier belongs to a test with a high wave steepness ($s_{m-1,0} = 0.046$), the upper outlier to a large freeboard height ($R_f/H_{m0} = 3.5$) and therefore a low corresponding overtopping volume. Data from [6,12] cover only a narrow range of step ratios which explains the comparable low goodness of fit for the prediction. Furthermore, increased standard deviations are present. Data from [9] follow the trends observed in the present study. According to the authors the outlier corresponding to the 1:2 slope is caused by a relatively large amount of wave overtopping. Equation (14) gives fairly comparable results for $\gamma_f$ compared to the prediction provided by [9] for $0.1 < k_h/H_{m0} < 0.6$. Hence, the new approach incorporates the findings from [9] and provides an extension of its coverage.

Table 4. Goodness of fit ($R^2$), root mean square error ($RMSE$) and standard deviation ($\sigma$) for data given in Figure 3 according to Equation (14).

| $\cot \alpha$ | Study | $R^2$ | $RMSE$ | $\sigma$ |
|--------------|-------|-------|--------|---------|
| 1            | present | 0.75  | 0.041  | 0.034   |
| 2            | present | 0.91  | 0.038  | 0.051   |
| 2; 3         | [6]    | 0.44  | 0.020  | 0.497   |
| 2; 3         | [9]    | 0.73  | 0.045  | 0.063   |
| 3            | present | 0.94  | 0.041  | 0.045   |
| 6            | [12]   | 0.08  | 0.029  | 0.127   |
| 1; 2; 3; 6   | all data | 0.84  | 0.059  | 0.022   |

A validation of the applicability of the presented approach to the prediction according to [13] is given in Figure 4. The reduction coefficients for the roughness of stepped revetment $\gamma_f$ derived by Equation (14) are plied for the available data to Equation (4) and (5). As all studies showed minor deviations in the mean wave overtopping on smooth slopes between measurement and prediction, the presented results are corrected to this deviation by applying the regression coefficients according
to Table 2 (\(b_{\text{corr}} = b_{\text{measured}}/b_{\text{predicted}}\)). [9] provides similar regression coefficients for which the presented results are corrected. For [6] the effect of broken waves over the shallow foreshore (\(cota = i\)) is simplified calculated by Equation (5) and corresponding regression coefficients \(b = 4\) (for \(i = 10\)) and \(b = 8\) (for \(i = 30\)). The mean overtopping discharge for breaking and non-breaking waves at steep and gentle sloped stepped revetments can be predicted within the 90% confidence bands given by [13]. Consequently, it is recommended, to increase the average discharge by about one standard deviation for a design or assessment approach. Limits for an application are steep slopes (\(cota < 2\)) in combination with large step ratios \((k_{h}/H_{m0} > 2\)). For these composite-like boundary conditions the position of the SWL relative to the step edge becomes important and a prediction in analogy to a composite wall should be considered.

\[ \text{Figure 4. Dimensionless overtopping discharge against the dimensionless freeboard height including a roughness coefficient for stepped revetments. Overtopping prediction formulae according to [13] are given for smooth slopes and 90 % confidence bands. Data for (a) steep slopes with } cota < 2 \text{ and non-breaking wave conditions, (b) milder slopes with } cota \geq 2 \text{ and non-breaking wave conditions and (c) mild slopes with } cota \geq 2 \text{ and breaking wave conditions.} \]

5. Discussion

In the analysis, data sets from different studies are gathered and combined to determine the overtopping reduction performance of stepped revetments with varying slopes and step ratio in order to attempt formulating a homogeneous basis for comprehensive analysis on the mitigation of overtopping of stepped revetments. As the different authors draw their own conclusions based on their original experimental set-up and data analysis, both consistencies and contradictions in the findings and interpretation exist.

Data displayed in the present study are based on hydraulic model tests conducted in [8]. This data analysis did not account for the correction of the roughness reduction coefficient for \(\xi_{m-1.0} > 1.8\) as required by [19], which serves as basis for the present wave run-up and overtopping prediction in [13]. Hence, the roughness reduction coefficient \(\gamma_{f}\) derived in [8] was a function of the Iribarren number. [9] already accounted for the correction of the roughness reduction coefficient for non-breaking waves. Besides the dependency of \(\gamma_{f}\) on the step ratio, [9] refined the correlation by introducing an additional dependency on the dimensionless overtopping discharge. This approach was not followed in the present study as no significant improvement was observed for the extended
parameter range. Conveniently, the iteration of $q$ is avoided and for clarity the dependencies of $\gamma_f$ should be based only on the key variable step ratio.

In Figure 3 data from [6] show comparably low values for the reduction coefficient ($\gamma_f > 0.9$). Evidently, the corresponding low step ratios ($0.03 < k_h/H_{m0} < 0.05$) have only a minor influence on the wave overtopping reduction due to only small energy dissipation rates. This phenomena is already known from dikes covered with grass meadows. [19] recommends to neglect the roughness of grass cover of sloping coastal protecting structures for wave heights larger than $H_{m0} > 0.75 \, \text{m}$ in the calculation of wave run-in up in consequence of the underlying hydraulic insignificance. Assuming that the mean grass height is about $h_{grass} = 0.05 \, \text{m}$ and that this roughness value is comparable with the step diameter $k_h$ a limit of

$$k_h/H_{m0} \approx h_{grass}/H_{m0} = 0.067$$

(15)

can be derived. The space in the step niches (porosity) is relatively low compared to the water volume in the wave run-up and run-down. Below this value, the roughness can be defined as micro-rough with negligible influence on the wave run-up and overtopping reduction due to only marginal energy dissipation rates.

For $k_h/H_{m0} > 1$ the step geometry becomes the governing parameter and scatter increases between the prediction of Equation (14) and the achieved reduction coefficient. The position of the SWL relative to the step edge $d_s$ becomes important (Figure 3). For step ratios $k_h/H_{m0} > 1$ it is therefore advisable to take the overtopping prediction according for composite walls given in [13] into account.

Nonetheless, there is still an uncertainty in the prediction of the reduction coefficient for roughness of stepped revetments, but it could be shown that this uncertainty is covered by the already established 90% confidence band given in [13].

5.1. Principle process description

The number of steps as well as the step ratio influence the energy dissipation at stepped revetments significantly. The intensity of the wave-induced turbulence due to presence of the steps is dependent on the roughness elements (shape and dimensions) and the flow velocity [33]. The dependence between the geometrical parameters of the stepped revetment and the hydraulic boundary conditions are derived in section 4. The following process description is based on these findings and graphically summarized in Figure 5.

A step ratio equal to zero ($S_h = 0$) represent a smooth slope. The highest overtopping volumes are measured for smooth slopes due to relatively low energy dissipation on their surfaces in comparison to the macro roughness surfaces of stepped revetments. As a consequence, the shear stresses on the smooth slope are also low and, thus, induce relatively low shear stresses on the structure. Most of the kinetic wave energy converts into potential energy in the run-up process. With increasing step height, the roughness and turbulence increase continuously, and in consequence lead to decreasing overtopping volumes. A minor part of the kinetic energy of the incident waves is converted to potential energy as some energy is dissipated by increasing turbulence.

As already discussed it is found that the step geometry has little influence on the energy dissipation for very small step heights ($S_h \ll H$). The flow direction of the wave run-up is still slope-parallel. Consequently, these small steps can be considered as micro roughness and are therefore comparable in terms of run-up reduction effectiveness to any other impermeable micro-rough surface.

With increasing step height ($S_h < H$) the slope-parallel wave run-up is disturbed by means of the step edges effectively. The flow processes on a single step become more important and induced vorticity to diminish kinetic energy. Likewise, vortex shedding occurs at the step edges in dependence of the relative step to wave height and period of the run-up process. In relation to smooth slopes smaller amounts of kinetic energy of the incident wave are converted into potential energy as wave-induced energy is dissipated by production of step-induced vortices, stronger turbulence and
non-linear wave transformation processes over the steps. A detailed discussion about the vortex
shedding on stepped revetments is provided by [34]. In effect, a maximum in total energy dissipation
leads to the lowest overtopping volumes at stepped revetments that is identified for step ratios in the
range of $0.5 < k_s/H_{m0} < 2$. Step ratios $k_s/H_{m0} > 2$ appear to mimic conditions for vertical walls.
For a low step ratio, the influence of the offshore located steps decreases due to less energy dissipation
in increasing water depth. With increasing step ratio the revetment becomes more reflective and the
wave breaking is effected by the step geometry itself. Therefore, also the water depth over the step
($d_{st}$) influences the wave overtopping. This system performance is comparable to composite walls
($k_s/H_{m0} > 1$). If the step height is much larger than the wave height ($S_h > H$) the wave overtopping
tends to mimic the physical conditions of vertical walls. The kinetic energy of the incident wave is
converted to potential energy. Most of the incoming wave energy is reflected at the wall.

Figure 5. Dependence of the step ratio on the wave run-up and wave overtopping.
5.2. Model and scale effects

In most coastal engineering applications, the Froude scaling law is applied when tests are not conducted under prototype conditions. The presented parameter study has no particular scale but wave conditions are certainly lower than in prototype. Therefore, predominantly inertial forces and gravity are considered whereas viscosity, elasticity, and surface tension are incorrectly represented.

In the EC Mast III Opticrest research project results from scaled model tests were compared to prototype tests to identify scale effects. [35] found about 50% higher run-up heights for a rubble mound breakwater in prototype conditions than predicted by empirical formulae.

For the present study, all friction effects – especially on the boundary layer – are overestimated. For friction, the Reynolds law is better suited since it considers viscosity. With wave breaking the Weber, Reynolds and Cauchy law should be applied. Therefore, by applying the Froude law, the effects of wave breaking are only idealized. Furthermore, to the wave run-up process Reynolds and Webers law are important.

The surface roughness of the tested revetments can be described as very smooth as it is constructed by wooden planks with a special smooth surface comparable to glass. For the smooth slopes – used as a reference – this means that the surface is not ideally smooth and therefore the run-up is slightly reduced due to surface friction. For the stepped slopes a slightly higher run-up is expected in the model tests as the surface is much smoother than e.g. concrete and therefore less friction is expected in the interface of step and water. Nevertheless, calculated reduction coefficients are on the save side, as both boundaries lead to conservative reductions coefficients. Overall, the effect of the surface roughness of the construction material is of minor importance.

It is expected that the inability to scale the air entrainment will have a more significant effect. The importance of the air entrainment for the energy dissipation is discussed by [36]. The influence of scale effects affecting the air entrainment with Froude similitude was derived by [37] for hydraulic jumps. It is assumed that the described principle processes are comparable with the process of the wave run-up over stepped revetments. [37] conclude that the aeration is significantly lower in smaller scales and cannot be achieved under Froude similitude. Obviously, the presented results based on small scale model tests overestimate the effectiveness of stepped revetments with respect to wave run-up heights and wave overtopping volumes [35]. Consequently, full scale tests can contribute to reduce uncertainties.

6. Conclusion

The objective of the present study was to derive a reduction coefficient for the roughness of a stepped revetment for a wide range of application. Previous literature highlight the importance of the dimensionless step height on the energy dissipation in the wave run-up and as a consequence, the reduction of the mean overtopping discharge. Knowledge from previous studies covered different parameter ranges and differences in the post-processing of data were identified.

The present study adapted and combined available data sets for the wave overtopping on stepped revetments. A new set of hydraulic model tests extended the range of parameters to cover the full range of step ratios between the two defined extreme conditions, a plain slope and a vertical wall. The tests included 69 individual tests with irregular waves covering steep and gentle slopes (1 ≤ cosa ≤ 3), breaking and non-breaking wave conditions (1.5 < ξm−1,0 < 9.4), and dimensionless freeboard heights of 0.85 < Rs/R1 < 4.5. The corresponding mean overtopping discharge was in the range of 1.6E−6 < q/√gHm0 < 1.0E−2.

Processes that govern the energy dissipation of a stepped revetment are discussed in relation to the step ratio. Three different zones of energy dissipation are identified, namely micro rough, macro rough and composite-like roughness. An optimum in the reduction of the mean overtopping discharge (by about 60% for breaking waves compared to a smooth slopes) is identified for step ratios in the range of 0.5 < kh/Hm0 < 2. For non-breaking waves the influence of γγ decreases for increasing Iribarren numbers as the step niches are filled water from the previous wave run-up and the macro roughness of the revetment is thereby reduced. In analogy to grass slopes it is shown that the wave overtopping reduction for step ratios smaller than kh/Hm0 > 0.067 is negligible. An
application of the derived prediction formula for the roughness coefficient of a stepped revetment to
the design approach according to [13] results in accordance with the given 90% confidence band.

The new formula comprises only the step ratio. Influences in the wave breaking on the slope are
considered by the standard design approach according to [13].

The derived roughness coefficient for stepped revetments is not based on prototype scale. Hence, it is likely influenced by scale effects. If a correction for scale effects, such as provided by [38],
is applicable for stepped revetments has to be determined by further research.

Funding: The presented findings were developed within the framework of the research project ‘waveSTEPS –
Wave run-up and overtopping at stepped revetments’ (03KIS118) funded by the Federal Ministry of Education
and Research (BMBF) through the German Coastal Engineering Research Council (KFKI).

Acknowledgements: The authors gratefully acknowledge the support of the German Coastal Engineering
Research Council (KFKI) within the project “waveSTEPS” (BMBF: 03KIS118). Valuable discussions with Mr. K.–F. Daemrich throughout the entire project are appreciated.

Author Contributions: T.S. and N.B.K. developed the presented idea and designed the research project
“waveSTEPS”. N.B.K. developed the theory, conducted the hydraulic model tests, analyzed and verified the
results from physical model tests and compared the findings with the literature. Ta.S. provided data and insights
from 1:6 slope tests. All authors discussed the results and contributed to the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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