1 *Article*

2 Wave Overtopping of Stepped Revetments

3 **Nils B. Kerpen [1],*, Talia Schoonees [1] and Torsten Schlurmann [1]**

4 [1] Leibniz University Hannover, Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal
5   Engineering; kerpen@lufi.uni-hannover.de
6 * Correspondence: kerpen@lufi.uni-hannover.de; Tel.: +49-511-762-3740

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

26 **Keywords:** Stepped revetment, wave overtopping, surface roughness, physical model test.
27

28 1. Introduction and Motivation

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

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

42   To the authors' best available knowledge this is the paper embraces the first systematic
43 comparison of the influence of stepped revetments to reduce wave overtopping. The study considers
44 a broad range of hydraulic and structure-related parameters, i.e. breaking and non-breaking wave
45 conditions, slopes between 1:1 to 1:6 and step heights much smaller and much larger than the spectral
46 significant wave height. In addition to the data sets collected in physical modelling studies in

47 Ludwig-Franzius-Institute, data sets from two other laboratories are included in the analysis and
48 results. These data sets are based on comparable experimental setups, which ensure consistency in
49 the conclusions and may exclude biases from model effects from individual studies.
50   The aim of the present paper is the empirical derivation of a roughness reduction coefficient for
51 wave overtopping on stepped revetments in relation to a smooth slope with coherent application to
52 breaking and non-breaking wave conditions to the wave overtopping prediction according to [13].
53   The present paper is structured as follows: First the technical background with focus on data
54 harmonization, wave overtopping prediction and the influence and determination of the roughness
55 of a revetment with special focus to stepped slopes is presented and discussed. In section 2 the
56 experimental set-up, test procedure and conditions of the conducted model tests are described.
57 Section 3 follows with the documentation of the gained results an analysis of the overtopping
58 performance of stepped revetments in comparison to smooth slopes follows. The principle processes
59 of the energy dissipation over stepped slopes are discussed in section 5 in the context of findings from
60 existing literature. Model and scale-effects are discussed. In conclusion, section 6 summarizes the
61 main findings and gives an outlook of future research.

62 *1.1. Technical background*

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

66 Harmonization of data sets

67 Studies with different decade of origin and from diverse laboratories demand for a sound processing
68 and harmonization of certain values that are applied in the present design assessment. The Iribarren
69 number $\xi_{m-1,0} = tan\alpha/\sqrt{s_{f-1,0}}$ applied in wave run-up and overtopping predictions is based on the
70 fictitious wave steepness s_f [14]. This fictitious wave steepness is a function of the spectral
71 significant wave height $H_{m0} = 4\sqrt{m_0}$ and the mean energy wave period $T_{m-1,0}$, both measured at
72 the toe of the structure as follows:

$$s_{f-1,0} = \frac{2\pi H_{m0}}{g T_{m-1.0}^2} \tag{1}$$

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

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

75 and the mean spectral wave period $T_{m-1,0}$ is correlated to the peak wave period T_p according to
76 [16] by

$$T_{m-1,0} = T_p/1.17 \tag{3}$$

77 Wave overtopping prediction

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

$$\frac{q}{\sqrt{g H_{m0}^3}} = \frac{a}{\sqrt{tan\alpha}} \cdot \gamma_b \cdot \xi_{m-1,0} \cdot \exp\left[-\left(b \frac{R_c}{H_{m0} \cdot \xi_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v}\right)^{1.3}\right] \tag{4}$$

with $a = 0.023$ and b = 2.7

with q $[m^3 s^{-1} m^{-1}]$ 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 γ_f the reduction coefficient for friction. The influence factors for the presence of a berm (γ_b), oblique wave attack (γ_β) and a vertical wall on the crest of the structure (γ_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

$$\frac{q}{\sqrt{g H_{m0}^3}} = \text{a} \cdot \exp\left[-\left(b\frac{R_c}{H_{m0} \cdot \gamma_f}\right)^{1.3}\right] \text{ with a = 0.09 and } b = 1.5 \tag{5}$$

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

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

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

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 γ_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

$$\gamma_f = \frac{R_{u,2\%, \text{ rough slope}}}{R_{u,2\%, \text{ smooth slope}}} \tag{7}$$

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

$$\gamma_f = \frac{ln(q_{\text{ smooth slope}})}{ln(q_{\text{ rough slope}})} \tag{8}$$

As mentioned by [9], the roughness reduction coefficient γ_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 $\gamma_f = 1$

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

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 $\gamma_{f,surging}$. Hence, an adjusted roughness factor has to be determined by a rearrangement of Equation (9) to

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

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

114   literature review on hydraulic model tests related to stepped revetments with focus on wave run-up,
115   wave overtopping and scour development at the toe of such revetments is provided by [20]. The
116   review includes the main findings from [3–7,21] and others. For regular waves, a prediction of the
117   mean overtopping discharges on stepped revetments is given by [22]. Literature, focusing
118   particularly on physical model tests on the wave run-up or wave overtopping by irregular waves at
119   stepped revetments (without influence of parapets as data sets provided [7,11,23]) are summarized
120   in the following.
121   [6] provide overtopping data for a stepped revetment ($cot\alpha = 2$) with two different sloped
122   foreshores (1:10 and 1:30). The *SWL* of the set-up is located at the toe of the stepped revetment and
123   the end of the inclined foreshore with smooth surface. Hence, only broken waves reach the stepped
124   revetment and cause overtopping. But for the reason that this study provides data for relatively large
125   dimensionless step heights H_{m0}/S_h {19.4; 29.1} it is included for comparison and corrected against
126   the effect of broken waves in the analysis. [6] provide a roughness influence factor of $0.93 < \gamma_f <$
127   0.98 for very large dimensionless step heights H_{m0}/S_h {19.4; 29.1} and broken waves with a narrow
128   band of deep water Iribarren number in the range of $2.48 < \xi < 2.55$. As the step heights S_h {0.006 m,
129   0.009 m} in the model tests were relatively small induced by the Froude scale of 1:33.3 these data are
130   likely influenced by scale effects. As [6] provide data for the mean wave period $T_{1/3}$ these are
131   converted according to Equation (2) and (3) to ensure that this data set is comparable. The wave data
132   was the further processed with Equation (1).
133   A data set of wave overtopping at stepped revetment ($cot\alpha = 3$) with smaller dimensionless
134   step heights ($5 < H_{m0}/S_h < 8$) is provided by [24]. Below the *SWL* ($z = 0$) the stepped revetment
135   is continued up to a distance of $0.375 < z/H_{m0} < 0.6$. Below this value the slope is modelled as
136   smooth slope. [24] gradually increased the freeboard height in the tests by adding additional steps
137   on the crest, until an overtopping volume less than a certain target was measured. The corresponding
138   roughness reduction coefficient of this study is $\gamma_f = 0.6$.
139   A comprehensive study and comparison of different data sets of wave run-up and wave
140   overtopping in regular and irregular waves is provided by [8]. This data set covers a wide range of
141   application ($0.5 < H_{m0}/S_h < 2.5$; $1.5 < \xi_{m-1,0} < 8.5$; $cot\alpha$ {1; 2; 3}). However, because of slightly
142   better coefficients of determination the roughness influence factors γ_f for the wave run-up was
143   calculated against the smooth slope prediction by [25]. To enable a standardized implementation of
144   the roughness influence factor in the [13] formulae the present paper will incorporate the measured
145   overtopping values accordingly.
146   [9] is based on an internal project report [21] and provides data for stepped revetments with
147   $cot\alpha$ {2; 3}. Compared to [6] and [24] the analyzed dimensionless step heights are smaller
148   ($1.6 < H_{m0}/S_h < 6.7$) and plunging and surging wave breaking is covered ($1.7 < \xi_{m-1,0} < 3.7$). The
149   provided roughness reduction coefficients are in a range of $0.8 < \gamma_f < 0.9$ for small steps ($S_h =$
150   $0.023\ m$) and reduced values in a range of $0.6 < \gamma_f < 0.7$ for steps with a doubled height ($S_h =$
151   $0.046\ m$). They derived a correlation between the roughness reduction coefficient and the step height
152   and the slope, related to the wave height and weighted by the dimensionless overtopping discharge
153   which follows the form

$$\gamma_f = a - b\left[-\frac{cos\alpha \cdot S_h}{H_{m0}} ln\left(q/\sqrt{gH_{m0}^3}\right)\right] \tag{11}$$

154   [10] discusses overtopping data for stepped revetments for steep slopes ($cot\alpha$ {0.58; 1}) and the
155   impact of surging waves ($3.9 < \xi_{m-1,0} < 14.7$). He provides a formula to predict the roughness
156   reduction coefficient which is for tested configurations in a range of $0.5 < \gamma_f < 0.91$. The author
157   compares his findings with [8] and found lower γ_f – values for equal Iribarren numbers.
158   [12] provide overtopping data for stepped revetments over gentle slopes ($cot\alpha = 6$). The tests
159   were conducted in the same wave flume as the present study. They cover dimensionless step heights
160   in a range of ($3.1 < H_{m0}/S_h < 4.6$) for plunging waves ($0.8 < \xi_{m-1,0} < 1.1$). The derived roughness
161   reduction coefficient for gentle slopes – compared to the other studies – is $\gamma_f = 0.74$ with a
162   corresponding goodness of fit of $R^2 = 0.94$ and a root mean square error of $RMSE = 3.09e^{-5}$.

163   **Table 1** gives a summary of the γ_f – values for wave run-up and overtopping on plain stepped
164   revetments as reported by various authors. The dimensionless step heights, Iribarren number and
165   slopes indicate the ranges for which the roughness factors are applicable. Only studies with irregular
166   wave conditions are included in the table. Reliable data for further analysis in this paper can be
167   extracted from [6,8,9,12].

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

Author	Step height S_h [m]	Dimensionless step height H_{m0}/S_h [–]	Iribarren number $\xi_{m-1,0}$ [–]	Slope $cot\alpha$ [–]	Roughness factor γ_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	$0.35 - 0.9 \, (R_{u,2\%})$
					$0.5 - 0.95 \, (q)$
[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

169
170   From **Table 1** it is evident that individual studies mostly considered stepped revetments with
171   limited parameter ranges. In order to draw universal conclusions regarding the overtopping
172   performance of stepped revetments, this paper considers data sets of a number of studies and by this
173   means covers a wider range of dimensionless step heights, slopes and wave breaking conditions in
174   order to achieve a greater understanding of the reduction of wave overtopping on stepped
175   revetments. According to [19], the influence factor for roughness was derived for breaking wave
176   condition and should therefore be adapted the friction reduction for non-breaking waves or surging
177   ($\xi_{m-1,0} > 1.8$). Currently, only [9] considered this adaptation, and thus data from [6,8] have to be
178   recalculated according to Equation (10). [12] provides solely breaking wave conditions and thus no
179   adaptation is required.

180   **2. Experimental set-up, procedure and test conditions**

181   *2.1. Model set-up and procedure*

182   Hydraulic model tests were conducted in a wave flume with a length of 110 m, a width of 2.2 m and
183   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
184   with a hydraulic driven piston type wave maker (wet-back). Waves can be generated with a total
185   stroke of 0.6 m and a maximum velocity of 1.2 m/s. Hence, dependent on the water depth h_s,
186   significant wave heights up to $H_s = 0.32 \, m$ and wave periods larger than $T \geq 0.9 \, s$ can be
187   generated. A 1:10 inclined rubble mound slope is located at the end of the flume to serve as a passive
188   wave absorber. The models, constructed from composite timber sheets, are placed on the horizontal
189   flume bed at a distance of 85 m from the wave board with respect to the model's crest. Further details
190   of the model set-up are provided by [8,26]. An impression of the model set-ups is given in **Figure 1**.
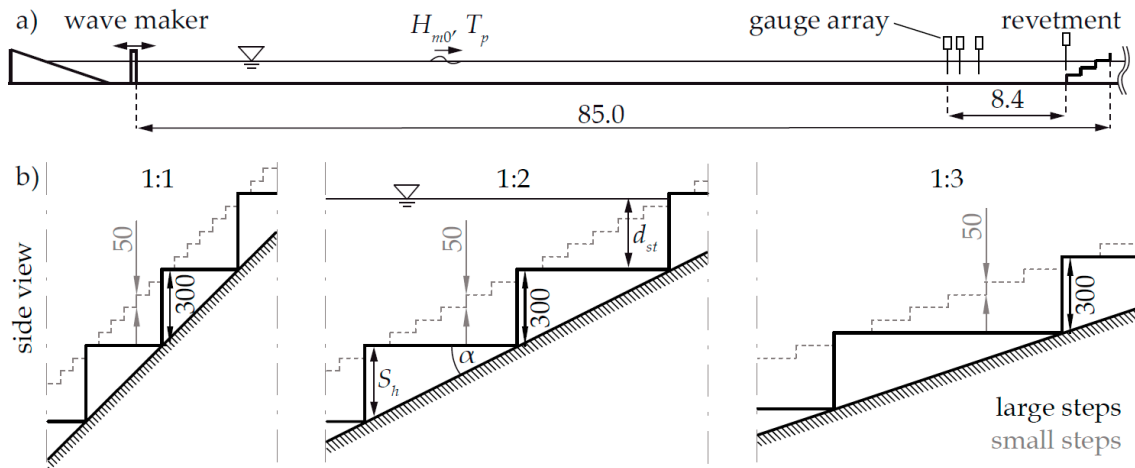
Figure 1. a) Side view of the model set-up with wave gauge positions. b) Side view of the tested step geometries.

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 $0.4 L_p$ 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 ($S_h = 0.0\,m$), tests for small ($S_h = 0.05\,m$) and large step heights ($S_h = 0.3\,m$) are conducted. The wave overtopping was analyzed for three different slopes ($cot\alpha\{1; 2; 3\}$) and three freeboard heights ($R_c\{0.121\,m; 0.211\,m; 0.3\,m\}$). 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:

$$F\left(\frac{h_s}{L_{m-1,0}};\ \xi_{m-1,0};\ cos\alpha;\ \frac{R_c}{H_{m0}};\ \frac{q}{\sqrt{gH_{m0}^3}};\ \frac{S_h}{H_{m0}}\right) = 0 \tag{12}$$

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_{m0}. 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 ($1.5 < \xi_{m-1,0} < 9.4$, $1 \leq cos\alpha \leq 3$, $0.85 < R_c/H_{m0} < 4.5$, $1.6E^{-6} < q/\sqrt{gH_{m0}^3} < 1.0E^{-2}$). 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 γ_f which is interpreted as a roughness coefficient is calculated in relation to the wave overtopping on a smooth slope following

223 Equation (8). The overtopping volume measured for a rough slope ($q_{\text{rough slope}}$) is to be correlated with
224 the corresponding value from a regressions best fit through the smooth slope data ($q_{\text{smooth slope}}$) [13].
225 The fitted curves for the smooth slopes of the present study (Equation (4) and (5) with regression
226 coefficients a and b according to **Table 2**) are plotted in **Figure 2**.

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

233   **Figure 2** (a) provides steep slope conditions ($cot\alpha = 1$) for non-breaking waves. The measured
234 dimensionless overtopping discharge for the smooth slope is larger than the prediction with Equation
235 (5) but the deviations are covered with the corresponding 90% confidence band representing a
236 5%–exceedance from the prediction. The dimensionless overtopping discharge decreases only
237 slightly with increasing step height. For the largest tested step height ($S_h = 0.3m$) data scatters
238 significantly.

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

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

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

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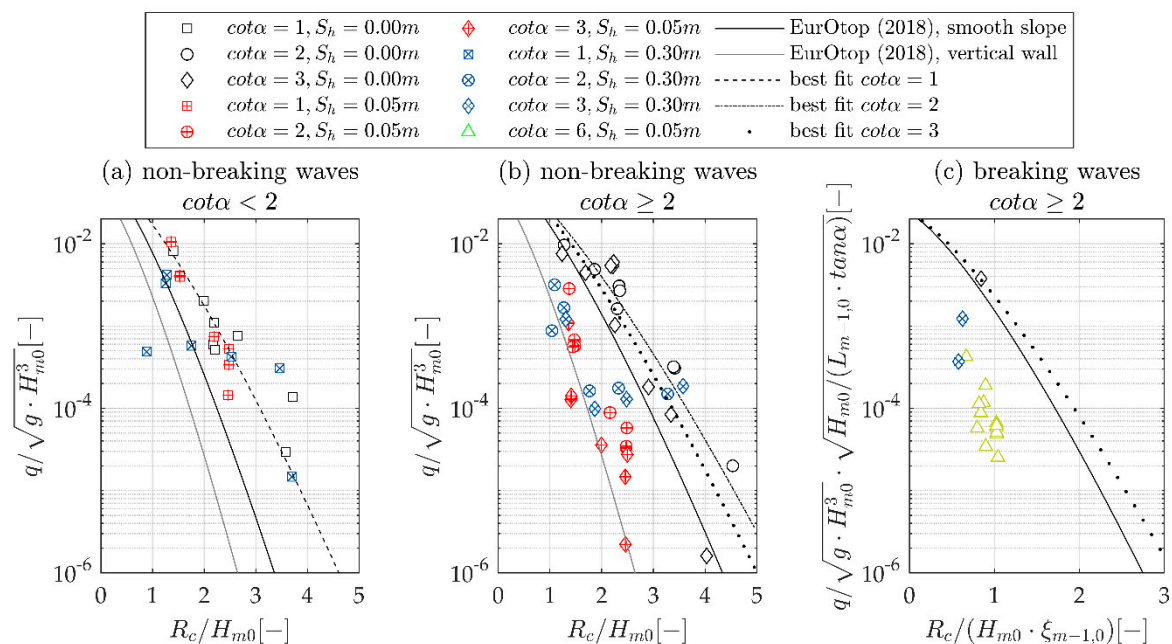252 **Figure 2.** Dimensionless overtopping discharge over the dimensionless freeboard height for smooth
253   and stepped surfaces with different slope angles. Overtopping prediction formulae according to [13]
254   for smooth slopes and vertical walls are given as reference. Determined best fits for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

256 milder slopes with $cot\alpha \geq 2$ and non-breaking wave conditions and (c) mild slopes with $cot\alpha \geq 2$
257 and breaking wave conditions.

258 **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

259 *3.2. Measured and determined values*

260 The regression coefficients listed in **Table 2** are empirically derived and applied to the prediction
261 formulae (Equation (4) or (5)) and set in proportion with the mean overtopping volumes obtained
262 from the stepped surface tests. The influence factor for roughness γ_f is calculated by applying Eq.
263 (8). The derived values for γ_f for non-breaking waves are corrected according to Equation (10). **Table**
264 **3** provides an overview of the measured parameters of the conducted model tests. The mean
265 overtopping volume q, the calculated (γ_f) and corrected ($\gamma_{f,corr}$) friction reduction coefficients for
266 stepped revetments are also given.

267 **Table 3.** Overview of model test parameter, including calculated (γ_f) and corrected ($\gamma_{f,corr}$) roughness
268 reduction coefficients for stepped revetments.

$cot\alpha$ [-]	S_h [m]	h_s [m]	R_c [m]	H_{m0} [m]	$T_{m-1,0}$ [s]	$\xi_{m-1,0}$ [-]	q [l/(sm)]	γ_f [-]	$\gamma_{f,corr}$ [-]
1	0.0	0.921	0.300	0.081	1.43	6.27	0.010	1.0	1.0
		1.01	0.059	0.059	1.46	7.52	0.001	1.0	1.0
				0.080	1.41	6.25	0.053	1.0	1.0
				0.096	2.13	8.61	0.048	1.0	1.0
				0.096	2.13	8.58	0.103	1.0	1.0
				0.097	2.13	8.55	0.056	1.0	1.0
		1.10	0.121	0.061	1.46	7.42	0.095	1.0	1.0
				0.086	1.39	5.93	0.654	1.0	1.0
	0.05	1.01	0.211	0.085	2.18	9.36	0.041	0.76	0.54
				0.085	2.14	9.18	0.026	0.73	0.48
				0.086	2.15	9.16	0.011	0.67	0.37
		1.10	0.121	0.055	1.46	7.79	0.030	0.69	0.46
				0.079	1.40	6.23	0.276	0.65	0.47
				0.079	1.40	6.20	0.284	0.65	0.47
				0.079	1.39	6.18	0.286	0.65	0.47
				0.089	2.18	9.12	0.877	0.70	0.42
	0.3	0.921	0.300	0.081	1.38	6.07	0.001	0.81	0.71
				0.171	2.18	6.59	0.127	0.61	0.39
		1.01	0.211	0.061	1.31	6.64	0.014	0.95	0.92
				0.084	1.30	5.63	0.032	0.75	0.64
				0.168	2.13	6.48	0.715	0.60	0.37
		1.10	0.121	0.095	1.38	5.58	0.383	0.60	0.41
				0.137	1.40	4.72	0.077	0.39	0.17
2	0.0	0.921	0.300	0.066	1.45	3.52	0.001	1.0	1.0
				0.088	1.41	2.97	0.025	1.0	1.0
		1.01	0.211	0.062	1.46	3.65	0.016	1.0	1.0
				0.090	2.13	4.45	0.226	1.0	1.0
				0.090	2.12	4.42	0.261	1.0	1.0
				0.090	2.13	4.42	0.260	1.0	1.0
				0.092	1.41	2.91	0.141	1.0	1.0
		1.10	0.121	0.065	1.46	3.58	0.252	1.0	1.0
				0.095	1.41	2.85	0.884	1.0	1.0
	0.05	1.01	0.211	0.085	2.07	4.45	0.004	0.54	0.39
				0.085	2.08	4.45	0.003	0.52	0.36
2	0.05	1.10	0.121	0.056	1.43	3.77	0.004	0.49	0.37
				0.082	1.38	3.01	0.042	0.46	0.38
				0.082	1.38	3.00	0.050	0.47	0.39
				0.084	1.38	2.97	0.042	0.45	0.37
				0.088	2.11	4.45	0.234	0.53	0.37
	0.3	0.921	0.300	0.170	2.11	3.19	0.036	0.47	0.38
		1.01	0.211	0.064	1.36	3.34	0.008	0.73	0.68
				0.091	1.34	2.79	0.015	0.56	0.51
				0.166	2.01	3.08	0.354	0.49	0.41
		1.10	0.121	0.111	1.37	2.57	0.367	0.48	0.43
				0.116	1.38	2.53	0.109	0.40	0.35
3	0.0	0.921	0.300	0.074	1.42	2.17	0.000	1.0	1.0
				0.090	1.38	1.92	0.007	1.0	1.0
		1.01	0.211	0.073	1.44	2.22	0.011	1.0	1.0
				0.094	1.39	1.89	0.092	1.0	1.0
				0.095	2.09	2.83	0.540	1.0	1.0
				0.095	2.08	2.82	0.493	1.0	1.0
				0.097	2.10	2.81	0.514	1.0	1.0
		1.10	0.121	0.072	1.48	2.30	0.266	1.0	1.0
				0.098	1.40	1.87	0.723	1.0	1.0
	0.05	1.01	0.211	0.085	2.11	3.02	0.002	0.54	0.48
				0.086	2.10	2.98	0.000	0.45	0.37
				0.086	2.07	2.94	0.001	0.51	0.45
		1.10	0.121	0.061	1.40	2.37	0.002	0.46	0.42
				0.086	1.36	1.93	0.010	0.41	0.40
				0.086	1.36	1.93	0.011	0.41	0.40
				0.086	1.36	1.93	0.010	0.41	0.40
				0.089	2.07	2.89	0.090	0.49	0.42
	0.3	0.921	0.300	0.161	2.09	2.17	0.020	0.49	0.47
		1.01	0.211	0.059	1.35	2.32	0.008	0.86	0.85
				0.085	1.35	1.94	0.010	0.62	0.61
				0.161	2.05	2.12	0.245	0.50	0.48
		1.10	0.121	0.116	1.36	1.67	0.441	0.55	0.55
				0.134	1.38	1.57	0.154	0.46	0.46

0.085   2.09   4.48   0.003   0.51   0.35

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 $cos\alpha$:

$$k_h = \cos\alpha \cdot S_h \tag{13}$$

Figure 3 gives the calculated correlation between the reduction coefficients for roughness of a stepped revetment γ_f against the corresponding step ratio k_h/H_{m0}. The given values for γ_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 ($cot\alpha\{1; 2; 3; 6\}$) and a wide range of step ratios ($0.03 < k_h/H_{m0} < 5.0$) 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:

$$\gamma_f = 1.55 - 0.55 \, \text{atan}\left[12\left(\frac{k_h}{H_{m0}} + 0.07\right)^{1.4}\right] + 0.35 \cdot \text{atan}\left[0.6\left(\frac{k_h}{H_{m0}} - 3.5\right)\right] \tag{14}$$

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 $k_h/H_{m0} = 0$ the derived prediction for γ_f decreases up to a minimum value of 0.38 for $k_h/H_{m0} = 1$ and increases again for $k_h/H_{m0} > 1$. The minimum γ_f represents the maximum efficiency of wave overtopping reduction and is in a range of $0.5 < k_h/H_{m0} < 1.5$.
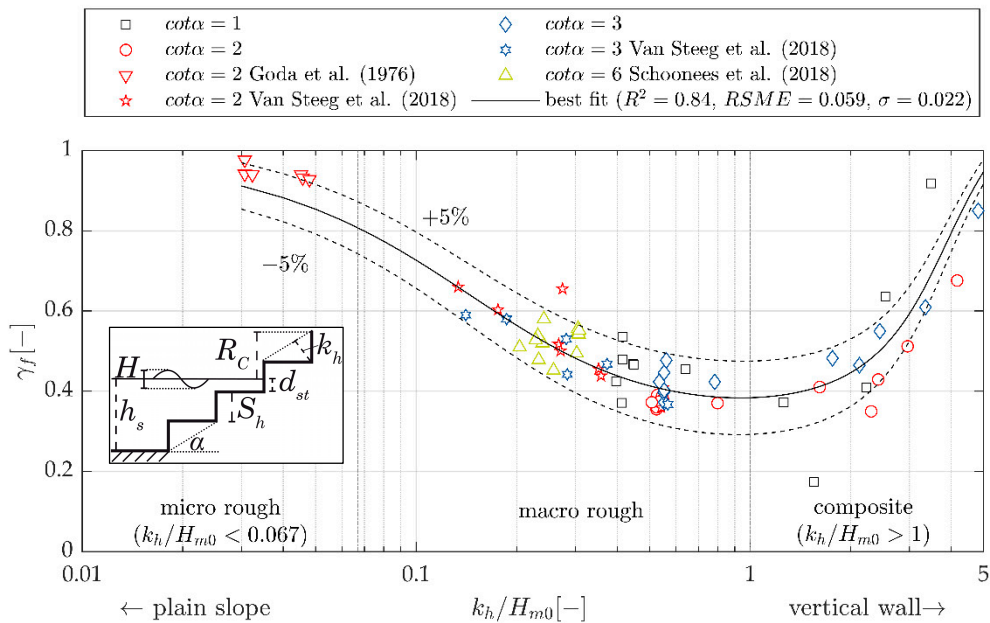
Figure 3. Reduction coefficient γ_f versus the step ratio (k_h/H_{m0}) for varying slopes $(1 \leq cot\alpha \leq 6)$ including a best fit regression line and the 90% confidence band.

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 $(R_c/H_{m0} = 3.5)$ 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 γ_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 (σ) for data given in **Figure 3** according to Equation (14).

cot α	Study	R^2	$RMSE$	σ
1	present	0.75	0.041	0.034
2	present	0.91	0.038	0.051
2	[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 γ_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

318 to **Table 2** ($b_{corr} = b_{measured}/b_{predicted}$). [9] provides similar regression coefficients for which the
319 presented results are corrected. For [6] the effect of broken waves over the shallow foreshore ($cot\alpha = $
320 i) is simplified calculated by Equation (5) and corresponding regression coefficients $b = 4$ (for $i = $
321 10) and $b = 8$ (for $i = 30$). The mean overtopping discharge for breaking and non-breaking
322 waves at steep and gentle sloped stepped revetments can be predicted within the 90% confidence
323 bands given by [13]. Consequently, it is recommended, to increase the average discharge by about
324 one standard deviation for a design or assessment approach. Limits for an application are steep slopes
325 ($cot\alpha < 2$) in combination with large step ratios ($k_h/H_{m0} > 2$). For these composite-like boundary
326 conditions the position of the SWL relative to the step edge becomes important and a prediction in
327 analogy to a composite wall should be considered.

328
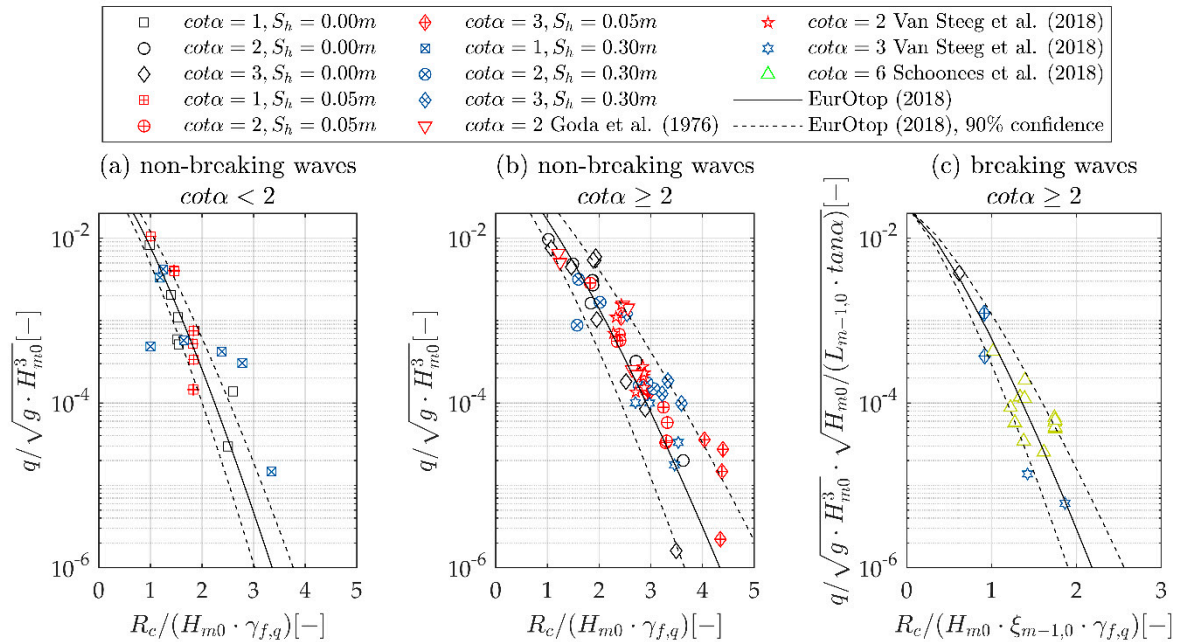
329 **Figure 4.** Dimensionless overtopping discharge against the dimensionless freeboard height including
330 a roughness coefficient for stepped revetments. Overtopping prediction formulae according to [13]
331 are given for smooth slopes and 90 % confidence bands. Data for (a) steep slopes with $cot\alpha < 2$ and
332 non-breaking wave conditions, (b) milder slopes with $cot\alpha \geq 2$ and non-breaking wave conditions
333 and (c) mild slopes with $cot\alpha \geq 2$ and breaking wave conditions.

334 **5. Discussion**

335 In the analysis, data sets from different studies are gathered and combined to determine the
336 overtopping reduction performance of stepped revetments with varying slopes and step ratio in
337 order to attempt formulating a homogeneous basis for comprehensive analysis on the mitigation of
338 overtopping of stepped revetments. As the different authors draw their own conclusions based on
339 their original experimental set-up and data analysis, both consistencies and contradictions in the
340 findings and interpretation exist.
341 Data displayed in the present study are based on hydraulic model tests conducted in [8]. This
342 data analysis did not account for the correction of the roughness reduction coefficient for $\xi_{m-1,0} > $
343 1.8 as required by [19], which serves as basis for the present wave run-up and overtopping prediction
344 in [13]. Hence, the roughness reduction coefficient γ_f derived in [8] was a function of the Iribarren
345 number. [9] already accounted for the correction of the roughness reduction coefficient for non-
346 breaking waves. Besides the dependency of γ_f on the step ratio, [9] refined the correlation by
347 introducing an additional dependency on the dimensionless overtopping discharge. This approach
348 was not followed in the present study as no significant improvement was observed for the extended

349 parameter range. Conveniently, the iteration of q is avoided and for clarity the dependencies of γ_f
350 should be based only on the key variable step ratio.
351   In **Figure 3** data from [6] show comparably low values for the reduction coefficient ($\gamma_f > 0.9$).
352 Evidently, the corresponding low step ratios ($0.03 < k_h/H_{m0} < 0.05$) have only a minor influence on
353 the wave overtopping reduction due to only small energy dissipation rates. This phenomena is
354 already known from dikes covered with grass meadows. [19] recommends to neglect the roughness
355 of grass cover of sloping coastal protecting structures for wave heights larger than $H_{m0} > 0.75\ m$ in
356 the calculation of wave run-up in consequence of the underlying hydraulic insignifance. Assuming
357 that the mean grass height is about $h_{grass} = 0.05\ m$ and that this roughness value is comparable with
358 the step diameter k_h a limit of

$$k_h/H_{m0} \approx h_{grass}/H_{m0} = 0.067 \qquad (15)$$

359 can be derived. The space in the step niches (porosity) is relatively low compared to the water volume
360 in the wave run-up and run-down. Below this value, the roughness can be defined as micro-rough
361 with negligible influence on the wave run-up and overtopping reduction due to only marginal energy
362 dissipation rates.
363   For $k_h/H_{m0} > 1$ the step geometry becomes the governing parameter and scatter increases
364 between the prediction of Equation (14) and the achieved reduction coefficient. The position of the
365 *SWL* relative to the step edge d_{st} becomes important (**Figure 3**). For step ratios $k_h/H_{m0} > 1$ it is
366 therefore advisable to take the overtopping prediction according for composite walls given in [13]
367 into account.
368   Nonetheless, there is still an uncertainty in the prediction of the reduction coefficient for
369 roughness of stepped revetments, but it could be shown that this uncertainty is covered by the
370 already established 90% confidence band given in [13].
371

5.1. Principle process description

373 The number of steps as well as the step ratio influence the energy dissipation at stepped revetments
374 significantly. The intensity of the wave-induced turbulence due to presence of the steps is dependent
375 on the roughness elements (shape and dimensions) and the flow velocity [33]. The dependence
376 between the geometrical parameters of the stepped revetment and the hydraulic boundary conditions
377 are derived in section 4. The following process description is based on these findings and graphically
378 summarized in **Figure 5**.
379   A step ratio equal to zero ($S_h = 0$) represent a smooth slope. The highest overtopping volumes
380 are measured for smooth slopes due to relatively low energy dissipation on their surfaces in
381 comparison to the macro roughness surfaces of stepped revetments. As a consequence, the shear
382 stresses on the smooth slope are also low and, thus, induce relatively low shear stresses on the
383 structure. Most of the kinetic wave energy converts into potential energy in the run-up process. With
384 increasing step height, the roughness and turbulence increase continuously, and in consequence lead
385 to decreasing overtopping volumes. A minor part of the kinetic energy of the incident waves is
386 converted to potential energy as some energy is dissipated by increasing turbulence.
387   As already discussed it is found that the step geometry has little influence on the energy
388 dissipation for very small step heights ($S_h \ll H$). The flow direction of the wave run-up is still slope-
389 parallel. Consequently, these small steps can be considered as micro roughness and are therefore
390 comparable in terms of run-up reduction effectiveness to any other impermeable micro-rough
391 surface.
392   With increasing step height ($S_h < H$) the slope-parallel wave run-up is disturbed by means of
393 the step edges effectively. The flow processes on a single step become more important and induced
394 vorticity to diminish kinetic energy. Likewise, vortex shedding occurs at the step edges in
395 dependence of the relative step to wave height and period of the run-up process. In relation to smooth
396 slopes smaller amounts of kinetic energy of the incident wave are converted into potential energy as
397 wave-induced energy is dissipated by production of step-induced vortices, stronger turbulence and

398 non-linear wave transformation processes over the steps. A detailed discussion about the vortex
399 shedding on stepped revetments is provided by [34]. In effect, a maximum in total energy dissipation
400 leads to the lowest overtopping volumes at stepped revetments that is identified for step ratios in the
401 range of $0.5 < k_h/H_{m0} < 2$. Step ratios $k_h/H_{m0} > 2$ appear to mimic conditions for vertical walls.
402 For a low step ratio, the influence of the offshore located steps decreases due to less energy dissipation
403 in increasing water depth. With increasing step ratio the revetment becomes more reflective and the
404 wave breaking is effected by the step geometry itself. Therefore, also the water depth over the step
405 (d_{st}) influences the wave overtopping. This system performance is comparable to composite walls
406 ($k_h/H_{m0} > 1$). If the step height is much larger than the wave height ($S_h \gg H$) the wave overtopping
407 tends to mimic the physical conditions of vertical walls. The kinetic energy of the incident wave is
408 converted to potential energy. Most of the incoming wave energy is reflected at the wall.
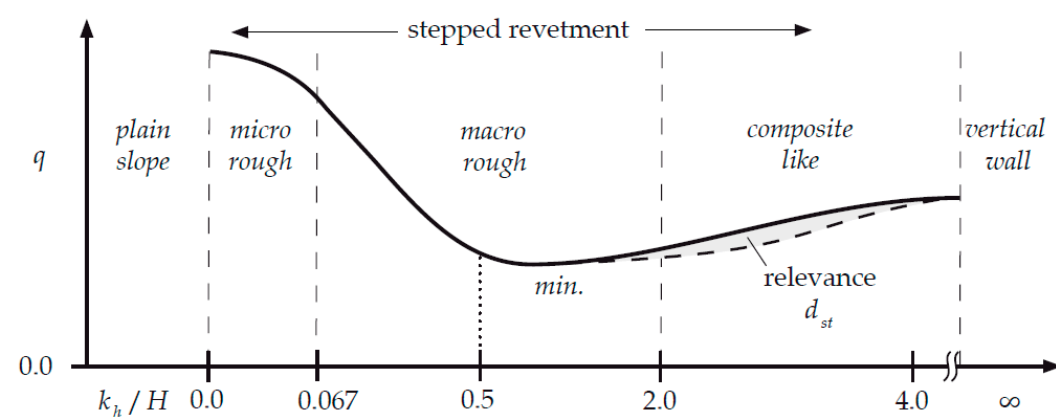

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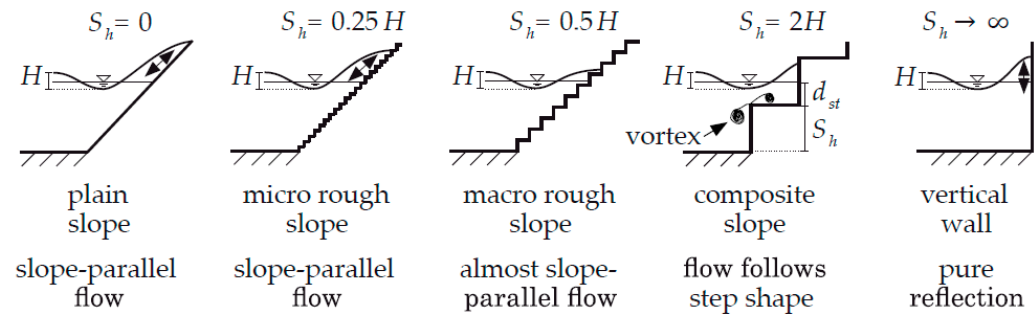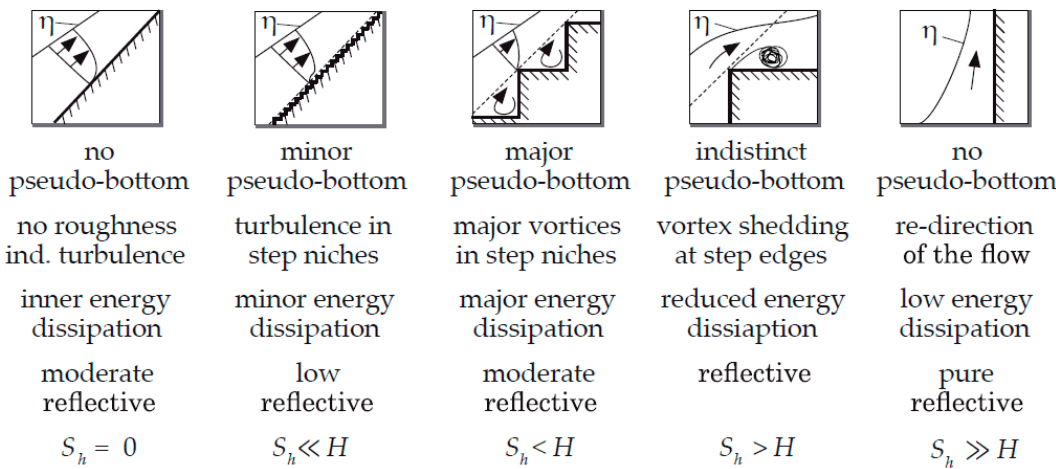
410 **Figure 5.** Dependence of the step ratio on the wave run-up and wave overtopping.

411 *5.2. Model and scale effects*

412 In most coastal engineering applications, the Froude scaling law is applied when tests are not
413 conducted under prototype conditions. The presented parameter study has no particular scale but
414 wave conditions are certainly lower than in prototype. Therefore, predominantly inertial forces and
415 gravity are considered whereas viscosity, elasticity, and surface tension are incorrectly represented.
416 In the EC Mast III Opticrest research project results from scaled model tests were compared to
417 prototype tests to identify scale effects. [35] found about 50% higher run-up heights for a rubble
418 mound breakwater in prototype conditions than predicted by empirical formulae.

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

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

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

441 **6. Conclusion**

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

447 The present study adapted and combined available data sets for the wave overtopping on
448 stepped revetments. A new set of hydraulic model tests extended the range of parameters to cover
449 the full range of step ratios between the two defined extreme conditions, a plain slope and a vertical
450 wall. The tests included 69 individual tests with irregular waves covering steep and gentle slopes
451 ($1 \leq cos\alpha \leq 3$), breaking and non-breaking wave conditions ($1.5 < \xi_{m-1,0} < 9.4$), and
452 dimensionless freeboard heights of $0.85 < R_c/H_{m0} < 4.5$. The corresponding mean overtopping
453 discharge was in the range of $1.6E^{-6} < q/\sqrt{gH_{m0}^3} < 1.0E^{-2}$.

454 Processes that govern the energy dissipation of a stepped revetment are discussed in relation to
455 the step ratio. Three different zones of energy dissipation are identified, namely micro rough, macro
456 rough and composite-like roughness. An optimum in the reduction of the mean overtopping
457 discharge (by about 60% for breaking waves compared to a smooth slopes) is identified for step
458 ratios in the range of $0.5 < k_h/H_{m0} < 2$. For non-breaking waves the influence of γ_f decreases for
459 increasing Iribarren numbers as the step niches are filled water from the previous wave run-up and
460 the macro roughness of the revetment is thereby reduced. In analogy to grass slopes it is shown that
461 the wave overtopping reduction for step ratios smaller than $k_h/H_{m0} > 0.067$ is negligible. An

462 application of the derived prediction formula for the roughness coefficient of a stepped revetment to
463 the design approach according to [13] results in accordance with the given 90% confidence band.
464 The new formula comprises only the step ratio. Influences in the wave breaking on the slope are
465 considered by the standard design approach according to [13].

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

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

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

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