

Physical model tests to determine the roughness of stair shaped revetments

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Abstract

Stair shaped revetments are considered as an attractive alternative for traditional revetments since the surface roughness reduces wave overtopping resulting in a lower required crest height. The specific shape enables easy access from and to the water surface, enhancing the attractiveness for tourists and residents. To implement stepped revetments in the design of a seawall there is a need to quantify the roughness of a stair shaped revetment to predict wave overtopping rates. This paper describes research in which 2D physical model experiments were conducted in Deltares' Scheldt Flume. Based on the obtained data a method to quantify the roughness coefficient of such structures is suggested.

1 Introduction

1.1 Background

There is an increasing demand to minimize the height and width of coastal structures to meet restrictions with respect to available space, optimize cost, touristic attractiveness and environmental quality of coasts and banks. To meet technical requirements with respect to the amount of wave overtopping during design conditions, solutions can be found by increasing the roughness of the outer slope of the dike.

A way to increase the roughness is to design a stair shaped outer slope which also enhances the attractiveness for tourist and residents since this enables easy access to and from the water surface. To incorporate the roughness in the design there is a need to determine the roughness coefficient that is used in wave overtopping formulas.

As part of a dike reinforcement project in Den Oever, located in the north-western part of the Netherlands, the Dutch Water Board Hoogheemraadschap Hollands Noorderkwartier initiated the design of a sea dike that incorporates a stair shaped outer slope to meet the demands with respect to the limited space around the dike. To support the design process of this dike, generic tests were done in a wave flume and discussed in

this paper. An impression of the design of the stair shaped revetment in Den Oever is shown in Figure 1.

Figure 1. Artist impression of design of primary flood defence with stair shaped revetment at Den Oever, The Netherlands



1.2 Technical background: wave overtopping

A generally accepted method to determine the wave overtopping discharge is described in TAW (2002). In that approach the dimensionless wave overtopping discharge is defined as:

$$\frac{q}{\sqrt{gH_{m0}^3}} = \frac{0,067}{\sqrt{\tan \alpha}} \cdot \gamma_b \xi_{m-1,0} e^{\left(-a \frac{R_c}{H_{m0}} \cdot \frac{1}{\xi_{m-1,0} \gamma_b \gamma_f \gamma_\beta \gamma_v} \right)} \quad (1)$$

With a maximum of

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0,2 \cdot \exp\left(-b \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f \gamma_\beta}\right) \quad (2)$$

With

$$\xi_{m-1,0} = \frac{\tan \alpha}{\sqrt{s_{m-1,0}}} \quad (3)$$

$$s_{m-1,0} = \frac{H_{m0}}{L_{m-1,0}} = \frac{2\pi H_{m0}}{gT_{m-1,0}^2} \quad (4)$$

Where a and b are empirical coefficients (-); g is the acceleration due to gravity (m/s^2); q is the mean wave overtopping discharge ($\text{m}^3/\text{s}/\text{m}$); H_{m0} is the spectral significant wave height (m); $\xi_{m-1,0}$ is the breaker parameter (-); R_c is the crest height (m), α is the slope angle ($^\circ$), $s_{m-1,0}$ is the wave steepness (-); and γ_β , γ_b , γ_v and γ_f are influence factors (-) for the angle of wave attack, roughness of slope, berms, and crest elements respectively.

The reliability of the formulas is given by empirical coefficients a and b which are normally distributed stochastic functions: $\mu_a = 4.75$, $\mu_b = 2.6$, $\sigma_a = 0.5$, $\sigma_b = 0.35$.

1.3 Technical background: roughness

To incorporate the effect of the roughness of the slope, the influence factor for roughness γ_f is used in Eq. (1) and Eq. (2). A value of $\gamma_f = 1.0$ indicates no roughness, a lower value indicates roughness. The value of this factor is usually empirically derived and is given as a fixed value for several types of revetments. In TAW (2002) (based on DWW, 2002), a list with fixed factors for γ_f is given for several types of placed block revetments ($0.75 \leq \gamma_f \leq 1.0$, depending on specific type of placed blocks), asphalt ($\gamma_f = 1.0$), and rock armour (double layer: $\gamma_f = 0.55$). In some cases the influence factor for roughness is variable. Three different examples are given:

For grass covers a reduction factor for roughness of $\gamma_f = 1.0$ is advised in case the significant wave height H_{m0} is larger than 0.75 m. However, for lower values of H_{m0} , lower influence factors of grass covers can be applied as described in EurOtop (2016), Van Steeg (2014) and TAW (1997).

For channel shaped placed block revetments such as Hillblocks, a theory based on the accommodation of water volume in the channels is reported in Van Steeg et al. (2016). Based on the theory and supported by data obtained with large-scale physical model tests it was concluded that the influence factor of channel shaped block revetments is variable and, amongst other, dependent on the significant wave height H_{m0} and a representative channel height.

Placed block revetments with enhanced roughness, such as rib-patterns and chessboard patterns, are discussed in Capel (2015) who developed a theoretical model that was calibrated in a 2D wave flume. Capel (2015) concluded that the roughness of the revetment was, amongst others, dependent on the total area of protruding elements and the wave conditions.

Based on the above studies it is stated that the influence factor for roughness of stair-shaped slopes is likely not a single value but dependent on other parameters such as the dimensions of the stairs, the slope angle and the wave conditions.

1.4 Technical background: roughness of stair shaped revetments

In Kerpen and Schlurmann (2016), a sound overview is given of studies performed to wave run-up, wave overtopping, wave loads and scour of stair shaped revetments. 30 studies were mentioned and categorized into the studied phenomena (run-up, overtopping, scour), the type of waves (regular, irregular) and the type of research (data collection, discussion). Run-up and regular waves are outside the scope of this paper and therefore not discussed. Data with irregular waves is reported in Heimbach (1988) and extended by Ward and Ahrens (1992), Suzuki et al. (2003) and Ward (2003).

The data by Heimbach (1988) is influenced by the presence of a curved seawall and seiche effects in the flume. Ward and Ahrens (1992) concluded that the effect of the stair-shaped revetment was limited but used relatively small step heights in their model ($9 < H/h_{\text{stair}} < 11$, with h_{stair} is the step height and H is wave height) and the presence of a large parapet influenced the results.

Suzuki et al. (2003) present results for both smooth and stepped structures but the step height was very small (1cm, which probably led to scaling issues) and the ratio between the wave height and step height was relatively high ($7 < H_{1/3}/h_{\text{stair}} < 11$).

The data of Ward (2003) was influenced by re-reflected waves at the wave board and the test set-up was designed for a specific case (with, amongst others, a large parapet) and not in a generic way.

Based on the above described analysis, there is almost no data with good quality available on the topic addressed here, since all available data-sets are either based on regular wave fields, influenced by re-reflection from the wave board, a range outside the present scope (relatively small step heights), or the overtopping is significantly influenced by the presence of a parapet. Therefore, new data is required which is presented in this paper.

2 Test set-up

2.1 Model facility and scaling

All tests were carried out in the Scheldt Flume of Deltares. This flume has a length of 55 m (and can be extended to 110 m), a width of 1.0 m and a height of 1.25 m. The flume is equipped with a Piston type wave board that can generate both regular and irregular waves. The wave board is equipped with an Active Reflection Compensation system; this system prevents reflection from the wave board into the flume. During the tests use is made of second order steering to compensate for disturbance waves.

The research is performed on a geometric scale of 1:10 and is based on Froude scaling to obtain the same ratio between inertia and gravity.

2.2 Tested structures

Seven different structures were tested. Structural variations were (1) slope angle: 1:2 and 1:3, (2) step height of the stairs: 0.23 m, 0.46 m and 0.00 m (smooth slope serving as reference section), and (3) shape of stairs: ‘perpendicular’ and ‘inclined’. An overview is given in Table 1 and figures 2-5. In each test set-up use is made

of a splitting screen which divided the structure into two parts with a width of 0.49 m. This splitting screen is applied from the toe of the structure until the crest of the structure. In this way it was possible to perform two tests simultaneously. The toe of the structure was at a distance of 34.4 m (Test Series 1-3) or 35.5 m (Test Series 4-7) of the wave board. At the back of each structure an overtopping box was placed where the overtopping water was collected.

Figure 2. Impression of test series with 1:3 slope (dimension in mm prototype)

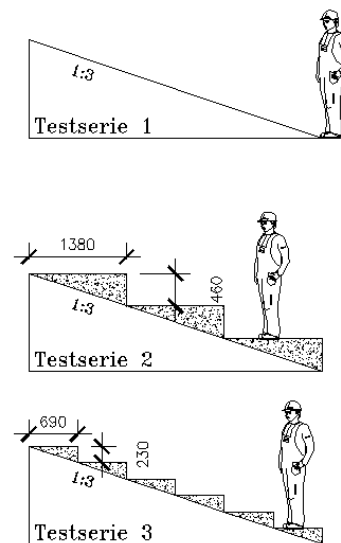


Figure 3. Impression of test series with 1:2 slope

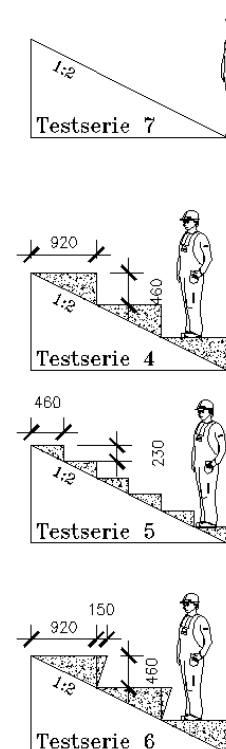


Table 1. Overview of test set-up

Test Series	cota	step height h_{stair} (m)	shape of stairs
1	3	0 (smooth)	no stairs (reference)
2	3	0.46	perpendicular
3	3	0.23	perpendicular
4	2	0.46	perpendicular
5	2	0.23	perpendicular
6	2	0.46	inclined
7	2	0 (smooth)	no stairs (reference)

Figure 4. Impression of test series with 1:3 smooth slope



Figure 5. Impression of test series with 1:3 slope



2.3 Measurements

Waves were measured using three resistance type wave gauges which were placed at a distance of 28.49 m, 29.23 m and 29.5 m of the wave board. The incidence wave was determined using the method as described in Mansard and Funke (1980). By combining this measuring method and a wave generation system with Active Reflection Compensation system it is estimated that er-

rors due to wave generation and wave measurements are minimal. The wave overtopping discharge was measured by measuring the water level in the overtopping box with a wave gauge.

3 Results and interpretation

3.1 Calibration of coefficients a and b

The corresponding values of a and b in Eq. (1) and Eq. (2) for the specific tests with smooth slopes (Test Series 1 and Test Series 7) are determined by analysing the results of the tests with the smooth slopes. The corresponding values of a and b in Eq. (1) and Eq. (2) are applied to the other test results to obtain the value of the influence factor of roughness γ_f . Example: the coefficient a that was found by analysing the results at Test 1.1 (smooth 1:3 slope) was also applied to Test 2.1 (stair shaped 1:3 slope with step height of 0.46 m) and Test 3.1 (stair shaped 1:3 slope with step height of 0.23 m). An overview of all applied factor is given in Table 2.

Table 2. Overview determined values of a and b

Calibration test	a, b	Applied to
1.1	$a = 5.16$	T2.1, T3.1
1.2	$b = 2.55$	T2.2, T3.2
1.3	$b = 2.15$	T2.3, T3.3
7.1	$b = 2.24$	T4.1, T5.1, T6.1
7.2	$b = 2.13$	T4.2, T5.2, T6.2
7.3	$b = 2.21$	T4.3, T5.3, T6.3
μ_{TAW}	$a = 4.75$ $b = 2.60$	

3.2 Measured and determined values

Now all the parameters of Eq. (1) to Eq. (4) are given; a and b are given in Table 2; H_{m0} , $T_{m-1,0}$ and q are measured values; the influence factors for berms (none), crest elements (none) and angle of wave incidence (perpendicular) are equal to $\gamma_v = \gamma_b = \gamma_\beta = 1.0$; crest height R_c and acceleration due to gravity $g (= 9.81 \text{ m/s}^2)$ are given values. The influence factor for roughness γ_f can be determined for each single test by using Eq. (1) to Eq. (4). An overview of all measured and determined values is given in Table 3 and Table 4.

Table 3. Overview of test set-up (prototype values) for $\text{cot}\alpha = 3$ ($N_{\text{waves}} \approx 1000$)

Test	h_{stair} (m)	R_c (m)	H_{m0} (m)	$T_{m-1,0}$ (s)	h (m)	$\zeta_{m-1,0}$ (-)	q (l/s/m)	γ_f (-)
1.1	0.00	3.80	1.55	5.2	7.20	1.7	0.85	1.00
1.2		2.86	1.18	5.1	8.14	2.0	1.68	1.00
1.3		1.73	0.75	5.1	9.27	2.5	2.86	1.00
2.1	0.46	2.60	1.55	5.2	7.20	1.7	0.11	0.53
2.2		2.00	1.17	5.1	7.80	2.0	0.07	0.47
2.3		1.30	0.77	5.1	8.50	2.4	0.07	0.42
3.1	0.23	2.60	1.55	5.2	7.20	1.7	0.25	0.59
3.2		2.00	1.17	5.1	7.80	2.0	0.40	0.58
3.3		1.30	0.77	5.1	8.50	2.4	0.21	0.43

 Table 4. Overview of test set-up (prototype values) for $\text{cot}\alpha = 2$ ($N_{\text{waves}} \approx 1000$)

Test	h_{stair} (m)	R_c (m)	H_{m0} (m)	$T_{m-1,0}$ (s)	h (m)	$\zeta_{m-1,0}$ (-)	q (l/s/m)	γ_f (-)
4.1	0.46	2.60	1.54	5.2	7.20	2.6	1.25	0.55
4.2		1.89	1.17	5.1	7.91	2.9	1.09	0.52
4.3		1.20	0.75	5.1	8.60	3.7	0.45	0.52
5.1	0.23	2.60	1.54	5.2	7.20	2.6	4.20	0.67
5.2		1.89	1.17	5.1	7.91	2.9	4.34	0.66
5.3		1.20	0.75	5.1	8.60	3.7	3.15	0.73
6.1	0.46 *	2.60	1.52	5.2	7.20	2.7	0.90	0.54
6.2		1.89	1.15	5.1	7.91	3.0	0.89	0.52
6.3		1.20	0.76	5.1	8.60	3.7	0.28	0.48
7.1	0.00	4.00	1.54	5.3	7.20	2.7	3.52	1.00
7.2		2.88	1.16	5.2	8.32	3.0	3.92	1.00
7.3		1.73	0.74	5.1	9.47	3.7	2.28	1.00

* with inclined shape of stairs

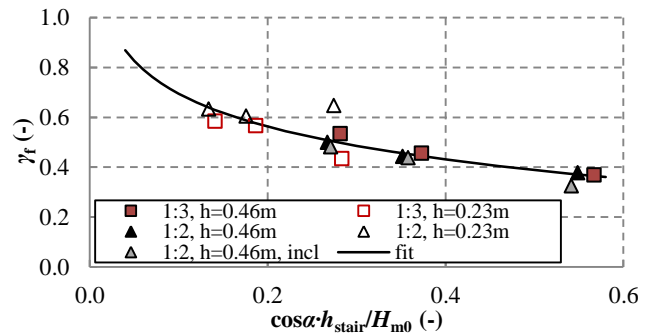
4 Analysis

According to TAW (2002) the influence factors for roughness in TAW (2002) are valid for $\gamma_b \zeta_{m-1,0} < 1.8$ where γ_b is the influence factor for the presence of a berm and $\zeta_{m-1,0}$ is the breaker parameter. From $\gamma_b \zeta_{m-1,0} = 1.8$, the influence factor for roughness increases linearly up to 1 for $\gamma_b \zeta_{m-1,0} = 10$. Since some tests were performed with values of $\gamma_b \zeta_{m-1,0}$ larger than 1.8 the derived values for the influence factor for roughness (γ_f) should therefore be corrected to a situation with $\gamma_b \zeta_{m-1,0} = 1.8$. The corrected values are presented in Table 5.

 Table 5. Corrected values of influence factor for roughness (corrected to a value corresponding with $\gamma_b \zeta_{m-1,0} = 1.8$)

Test	$\zeta_{m-1,0}$ (-)	$\gamma_{f,m}$ (-)	$\gamma_{f,corr}$ $\zeta_{m-1,0}=1.8$ (-)
2.1	1.7	0.53	0.54
2.2	2.0	0.47	0.46
2.3	2.4	0.42	0.37
3.1	1.7	0.59	0.59
3.2	2.0	0.58	0.57
3.3	2.4	0.43	0.43
4.1	2.6	0.55	0.50
4.2	2.9	0.52	0.44
4.3	3.7	0.52	0.38
5.1	2.6	0.67	0.63
5.2	2.9	0.66	0.60
5.3	3.7	0.73	0.65
6.1	2.7	0.54	0.48
6.2	3.0	0.52	0.44
6.3	3.7	0.48	0.33

The remainder of this analysis uses the corrected influence factor for roughness ($\gamma_{f,corr}$). In Figure 6 the corrected influence factor $\gamma_{f,corr}$ is presented as function of the ratio of the effective height of each step ($\text{cot}\alpha \cdot h_{\text{stair}}$) and the significant wave height (H_{m0}).

 Figure 6. Influence factor for roughness γ_f as function of the height of stairs and wave height $\text{cot}\alpha \cdot h_{\text{stair}}/H_{m0}$


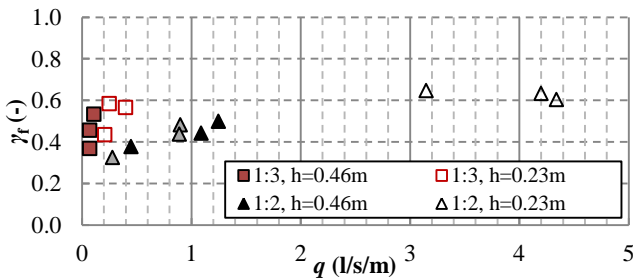
As can be seen in Figure 6 there is a relatively good correlation ($R^2 = 0.77$ based on a logarithmic fit). It can be seen that with increasing effective step height ($\text{cot}\alpha \cdot h_{\text{stair}}$), or with lower significant wave height (H_{m0}), the influence factor for roughness γ_f decreases, indicating more roughness. The fit is described with

$$\gamma_f = -0.190 \cdot \ln \left(\frac{\cos \alpha \cdot h_{\text{stair}}}{H_{m0}} \right) + 0.257 \quad (5)$$

With α is the slope angle ($^\circ$), h_{stair} is the height of a single step (m), and H_{m0} is the significant wave height (m).

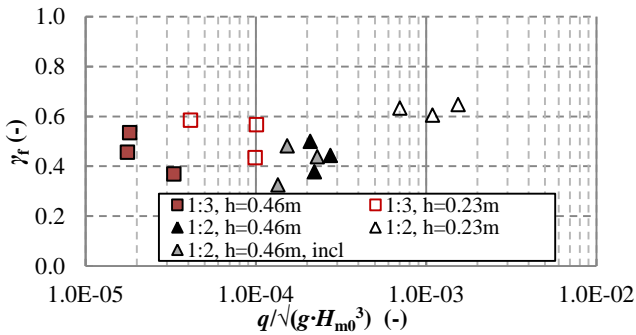
It is noted that one test with a 1:2 slope and a step height of $h_{\text{stair}} = 0.23$ m (open triangles) seems to deviate. This is probably due to the relatively large amount of wave overtopping (q) in these tests, as can be seen in Figure 7.

Figure 7. Influence factor for roughness γ_f as function of overtopping rate q (prototype values)



A common way to present the overtopping rate is to make the overtopping discharge (q) dimensionless with $\sqrt{(g \cdot H_{m0}^3)}$ as shown in Figure 8.

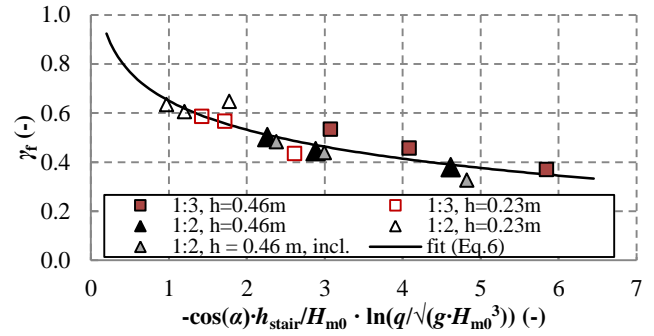
Figure 8. Influence factor for roughness γ_f as function of dimensionless overtopping rate $q/\sqrt{(g \cdot H_{m0}^3)}$



It can be seen in Figure 8 that with a higher overtopping rate the influence factor for roughness increases slightly.

A combined use of the parameters $\cos \alpha \cdot h_{\text{stair}}/H_{m0}$ and $\ln(q/\sqrt{g \cdot H_{m0}^3})$ is given in Figure 9.

Figure 9. Influence factor for roughness γ_f as function of dimensionless parameter $\cos \alpha \cdot h_{\text{stair}}/H_{m0} \cdot \ln[q/\sqrt{(g \cdot H_{m0}^3)}]$.



The fit through the data as given in Figure 9 is described by

$$\gamma_f = -0.170 \cdot \ln \left(\frac{-\cos \alpha \cdot h_{\text{stair}}}{H_{m0}} \cdot \ln \left(\frac{q}{\sqrt{g \cdot H_{m0}^3}} \right) \right) + 0.650 \quad (6)$$

With α is the slope angle ($^\circ$), h_{stair} is the height of a single step (m), H_{m0} is the significant wave height (m), q is the wave overtopping discharge ($\text{m}^3/\text{s}/\text{m}$) and g is acceleration due to gravity (m/s^2). Since q is not known a-priori some iteration is required. This can however be avoided to use Eq. 5 first and use the determined value of q as input for Eq. 6.

The fit as described in Eq. 6 is slightly improved compared to the fit as described in Eq. 5 ($R^2 = 0.81$ vs. $R^2 = 0.77$). Both fits go nearly through the point $(x,y) = (0,1)$ indicating a physical sound relation since a step height of $h_{\text{stair}} = 0.0$ m indicates a smooth slope and should have by definition a roughness coefficient of $\gamma_f = 1.0$.

Additional analysis that considered the influence of the slope angle has been performed. Since this did not lead to improved correlation and the procedure became more complicated, it was chosen not to include additional consideration to the slope angle.

5 Discussion

In the previous section two methods to determine the influence factor of roughness are described.

The first method is to apply Eq. (5). The basic idea of this method is that the influence factor for roughness (γ_f) is dependent on the ratio between the effective step height (vertical distance h_{stair} corrected with the slope angle $\cos \alpha$) and the significant wave height (H_{m0}).

The second method is to apply Eq. (6) which gives a slightly better correlation than the first method. This method is based on the same idea as the first method but accounts for the influence of large overtopping discharges on the (reduced) roughness; the stairs are less effective for large overtopping discharges. The advantage of this method is that it slightly better resembles the obtained data. This method requires the wave overtopping discharge q as input. This overtopping discharge is not known a priori but can be determined by using Eq. (5) in combination with Eq. (1) and Eq. (2).

Despite the relatively good correlation there is still some spread around the predicted value. This is also the case for research that was performed for other types of revetments which are presented as fixed values in TAW (2002). According to the description in TAW (2002b), on which the influence factors for roughness in TAW (2002) are based, the mean value can however be used in the TAW (2002) method since the spreading is assumed to be included in the total spreading around the overtopping formulas.

The suggested method can be used for preliminary design of stair shaped revetments. One should however realise that the data is obtained based on test conditions as given in Table 6. For situations that deviate from these conditions, such as the presence of berms, inclined wave attack et cetera, it is recommended to perform additional tests.

The influence factors of roughness should be used as described in TAW (2002); Eq. (5) and Eq. (6) are valid for $\gamma_b \zeta_{m-1,0} < 1.8$ where γ_b is the influence factor for the presence of a berm and $\zeta_{m-1,0}$ is the breaker parameter. From $\gamma_b \zeta_{m-1,0} = 1.8$, the influence factor for roughness increases linearly up to 1 for $\gamma_b \zeta_{m-1,0} = 10$.

Table 6. Overview characteristics of tests with stair shaped geometry

slope angle	$\cot\alpha$	2 – 3
stair height	$(\cos\alpha \cdot h_{\text{stair}})/H_{m0}$	0.13 – 0.57
overtopping rate	$q/\sqrt{gH_{m0}^3}$	$1.8 \cdot 10^{-5} - 1.5 \cdot 10^{-3}$
crest height	R_c/H_{m0}	1.58 – 1.71
breaker parameter	$\zeta_{m-1,0}$	1.7 – 3.7
wave steepness	$s_{m-1,0}$	0.018 – 0.037
Influence factor for berms	γ_b	1
Influence factor for angle of incidence	γ_β	1

The influence factor for roughness of stair shaped revetments is dependent on several parameters and is certainly not a fixed value. This is in line with the findings of research on channel shaped block revetments (Van Steeg et al, 2016), rib-patterns and chessboard patterns (Capel, 2015) and grass revetments (TAW, 1997).

An important aspect of a stair shaped revetment, but outside the scope of this paper, is the stability of the revetment under wave loads. This will be discussed in a future paper (Steendam et al, 2018).

6 Conclusions

Based on data obtained in a physical model, the influence factor for roughness γ_r of a stair shaped revetment is determined. This influence factor can be determined for preliminary design using Eq. (6). That equation requires the wave overtopping discharge as an input parameter which can be obtained with Eq. (5). The given method is based on a dataset as summarized in Table 5 and can be used in the wave overtopping formulas in TAW (2002). For cases outside the tested range additional research is recommended.

Based on the findings in this research and other research it is concluded that the influence factor for roughness is not a fixed value but dependent on other parameters such as the wave height, overtopping discharge and height of the protruding elements. It is therefore likely that optimization of the design is possible for other revetments types for which a fixed value for the influence factor of roughness is used (such as rock armour, concrete blocks with angled corners or holes, et cetera). Therefore, it is recommended to perform additional research to the influence factor of roughness of these types of revetments.

7 Acknowledgements

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