CIRCULAR SHAPED ROUGHNESS ELEMENTS TO MITIGATE OVERTOPPING OF COASTAL REVETMENTS

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This paper presents preliminary design guidelines for wave overtopping when circular-shaped roughness elements (ring-type revetment) are placed on the upper slope of a coastal revetment. Such a type of revetment was designed during the tendering phase of the Afsluitdijk reinforcement in 2017 as an innovative and highly effective way of reducing overtopping rates along coastal revetments. The design combines a relatively smooth lower slope (~1 in 2.5), wide storm berm (~1.5x wave height) and the roughened upper slope (~1 in 3) with a specific pattern of circular elements, resulting in a roughness comparable to that of a double layer rubble mound slope with an impermeable core. To effectively reduce overtopping rates, the circular elements require an average height of ~1/10 of the wave height and diameter of ~1/3 of the wave height, as well as a specific placement pattern (staggered pattern and spacing ~1/10 of the wave height).

Keywords: innovative dike revetment; coastal defense, wave overtopping, hydraulic roughness; pattern placed revetments;

INTRODUCTION

The Afsluitdijk is a dike along the Dutch Waddensea connecting the provinces of North-Holland and Friesland. This dike required an upgrade to withstand far more severe wave attack than originally designed for due to higher flood protection standards. For the subsequent Afsluitdijk reinforcement tender in 2017 an innovative design was developed by Royal HaskoningDHV, in cooperation with ZJA architects, Vista landscape architects, and led by the joint venture Royal Boskalis Westminster and Royal VolkerWessels.

Propositions were evaluated based on lowest price and major quality components, which included a strong focus on innovative design for the dike revision. The most significant evaluation criteria were to maintain the iconic status of the Afsluitdijk and to ensure sufficient flood protection with an attractive and innovative aesthetical design. High and breaking design wave conditions (H_{m0}= 4.27 m, T_p = 7.7s, 4.5% steepness), strict overtopping requirements (<10 l/s/m), combined with a maximum crest height limit and several other geometrical (narrow allowed profile, limited horizontal space) and aesthetic constraints (no rubble mound at upper slope), added to the complexity of the design.

Against this technically challenging background and owing to the strong focus on innovation in the award criteria, two new types of revetments were developed for the major part of the 32 km dike. The chosen design principle was basically a typical Dutch sea dike, including a storm berm. The final design was developed based on an extensive physical model test campaign. On the lower slope a new type of pattern-placed block revetment (accessible by foot) was designed to absorb future wave impacts (Mooyaart et al. 2019), as well as a storm berm (providing a bicycle and foot path), together with a new type of upper slope revetment to maximally limit wave overtopping (Figure 1 and Figure 2), whilst still allowing access to the slope.

The stability of the innovative elements on the lower slope was discussed in (Mooyaart et al 2019). This present paper discusses the overtopping performance and design of the innovative upper slope revetment, which consists of a specific arrangement of circular shaped roughness elements (patent pending).

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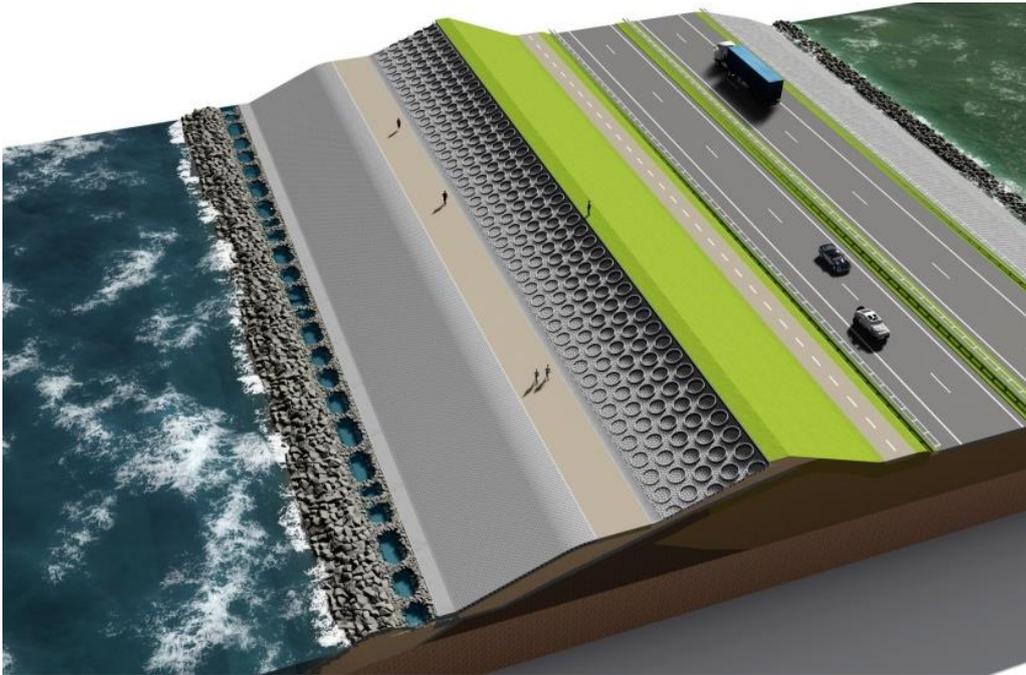
Figure 1. Artist impression of final design - bird's eye view

Figure 2. Artist impression - final design from the horizontal berm

CROSS SECTIONAL DESIGN

The preferred design for the dike geometry consisted of a relatively steep (1:2.5) lower slope, a wide storm berm slightly below design water level and an upper slope (1:3) with roughness elements and a wave wall. The design philosophy was to separate the technical functions of the dike revetment: the wave impacts to be absorbed by the smooth lower slope, the wide storm berm to transform the wave and the hydraulic roughness and low non-protruding wave wall on the upper slope to tackle wave runup and reduce overtopping (Figure 3).
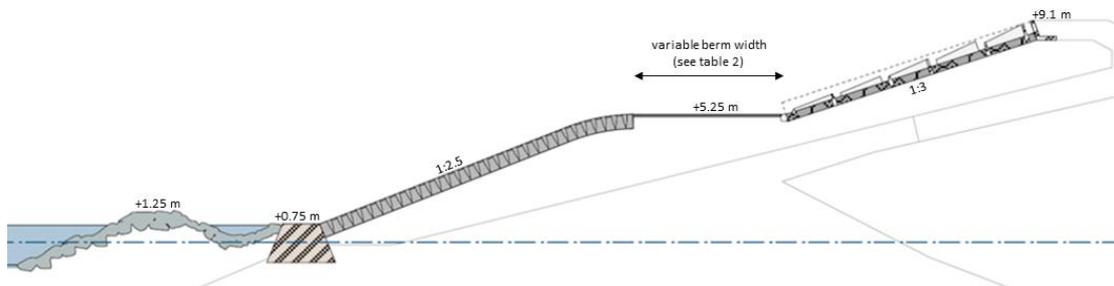
Figure 3. Cross sectional design of the dike

UPPER SLOPE DESIGN

To increase the effective hydraulic roughness of the upper slope and effectively limit wave overtopping, a modular system of circular protruding non-reinforced concrete elements ('rings') was developed. Inside and in-between the rings the slope is protected with a pattern placed revetment (Figure 4). This revetment consists of triangular elements inside the rings with pentagonal elements in between the rings.
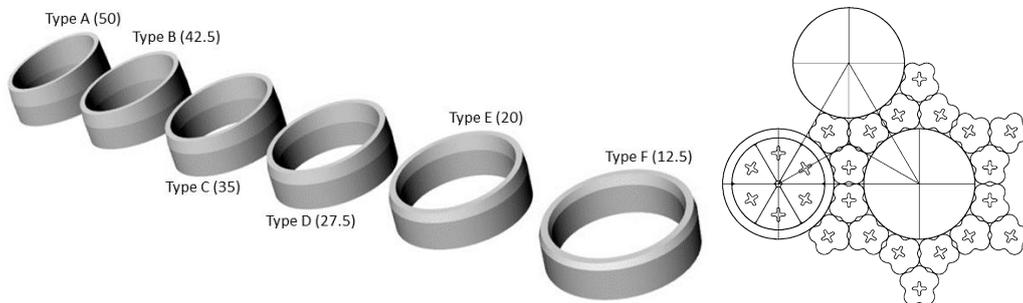
Figure 4. Ring types (left) and pattern placed revetment in between the rings (right)

By altering the height and arrangement of the rings as well as the berm width, the design can be optimized for different locations and situations. The optimum configuration for the Afsluitdijk consists of five rows of rings with a constant inner diameter (ID), outer diameter (OD) and spacing (s), and various ring types with variable front (h_1) and rear heights (h2) for the elements in each row (see Figure 5). The low non-protruding wave wall near the crest is perpendicular to the slope with a height equal to the rear height (h_2) of the highest roughness element.
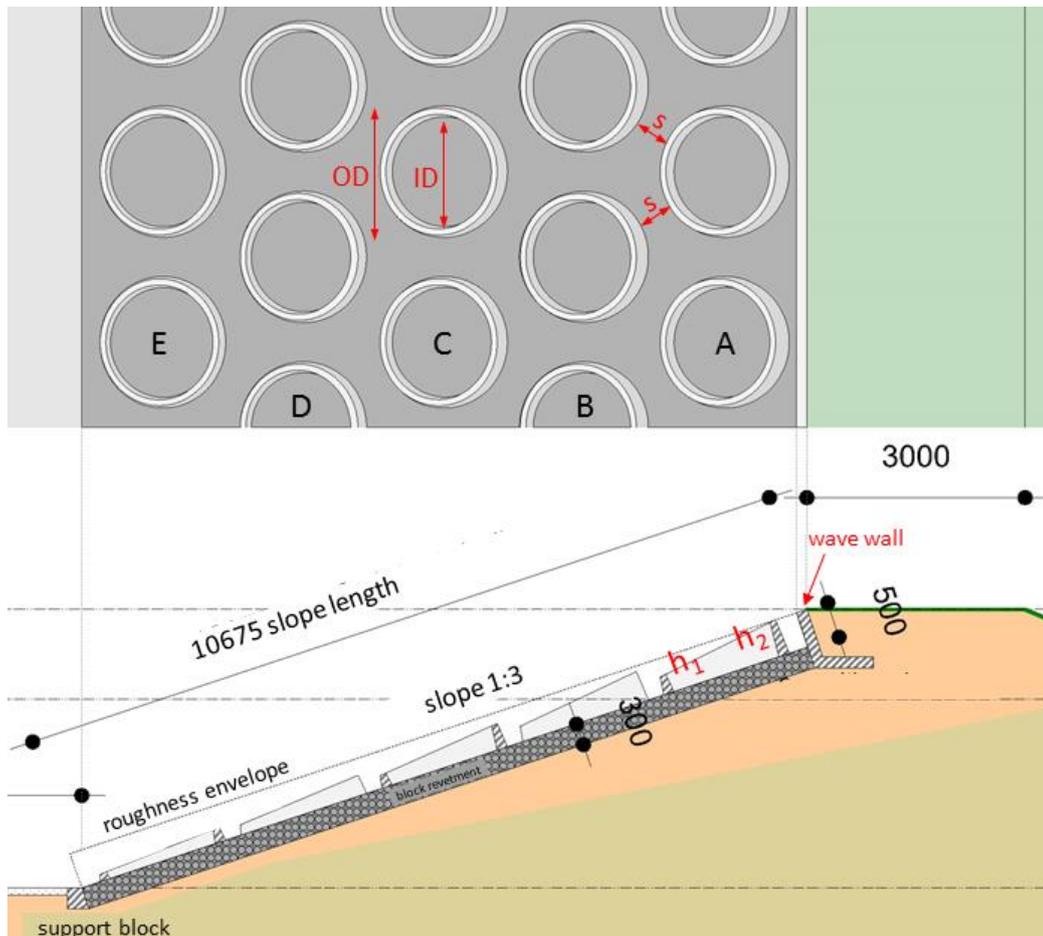
Figure 5. Optimum ring configuration and parameterization with Outer Diameter (OD), Inner Diameter (ID), Front height (h1), Rear height (h2), spacing (s).

Placed in a pattern of 5 rows, the rings had an increasing height from the berm leading up to the crest level. The reason for this is the stability under severe hydraulic loads. The rings closer to the berm were subject to greater forces and therefore lower. Moreover, this gradual growth maintained a high efficiency for reducing wave overtopping by leading the water through a sequence of rings in growing height. The overtopping efficiency was further enhanced by placing the rings in a triangular setting, which contributed to a prolonged wave run-down phase.

For all elements the rear height h_2 was twice the front height h_1. Using six different ring types (Table 1), and by varying the berm width, the optimal design of all dike sections along the Afsluitdijk could be developed.

Table 1. Ring types and heights (h_1 and h_2).						
	A	B	C	D	E	F
Rear height h_2 [cm]	50	42.5	35	27.5	20	12.5
Front height h_1 [cm]	25	21.25	17.5	13.75	10	6.25

For a relatively rough configuration more rows with higher elements (Type 'A') were applied, whereas for a relatively smooth configuration more rows with lower elements (Type 'F') were used. For the Afsluitdijk, this led to several potential design configurations, which are displayed in Table 2. All configurations had rings with the same inner and outer diameters (~$H_{m0}/3$) and spacings (~$H_{m0}/10$) placed in a triangular pattern. Other configurations that featured different ring dimensions (inner, outer diameters and spacing) were tested in an earlier phase of the model test campaign, but proved to be less effective.

Table 2. Design configurations available for the Afsluitdijk							
Configuration	Berm width	Wall height equal to	1st (top) element	2nd element	3rd element	4th element	5th (lowest) element
I	7.5 m	A	A	B	C	D	E
II	7.25 m	B	B	C	D	E	F
III	7.0 m	C	C	D	E	F	F
IV	6.75 m	D	D	E	F	F	F
V	6.5 m	E	E	F	F	F	F
VI	6.25 m	F	F	F	F	F	F
Smooth	6.0 m	-	-	-	-	-	-

Application of configurations I and IV is illustrated in the figures below.
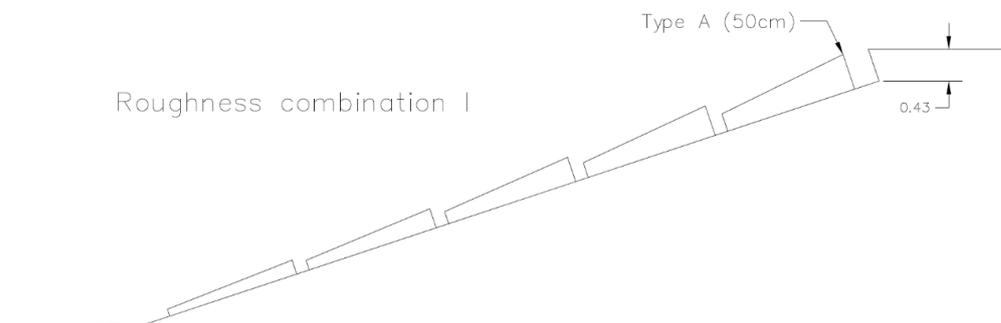
Figure 6. Configuration I
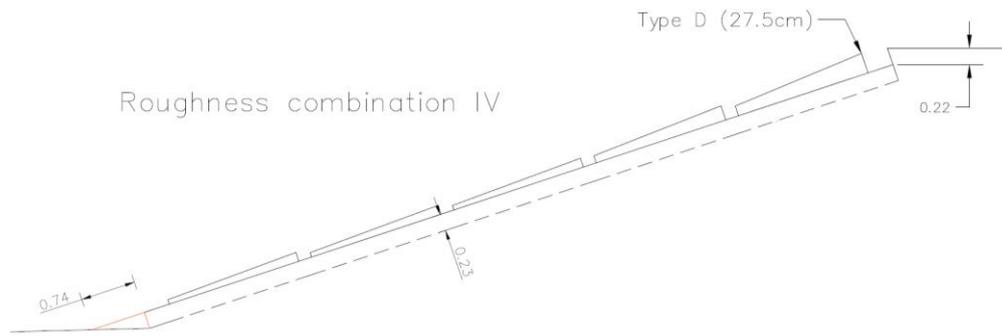
Figure 7. Configuration IV

PHYSICAL MODEL TEST SETUP

About 800 small-scale 2D tests were performed at DHI Denmark to arrive at the final design. The tests were split up in two testing series:

- Tests series with length scale 1 in 18 to develop the cross-sectional design and assess design overtopping rates.
- Tests series with length scale 1 in 30 to investigate various design sensitivities (wider or smaller berm, steeper slope, variations of the toe construction, etc.).

The basic setup for the 1 in 18 tests is displayed in Figure 8 and 9 in which real-size distances (prototype scale) are displayed.
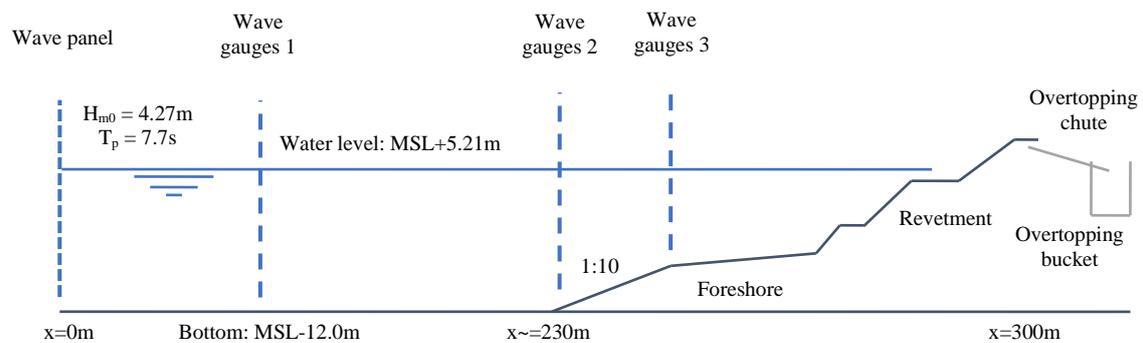
Figure 8. Cross-section of test setup including design conditions (dimensions in real-size)
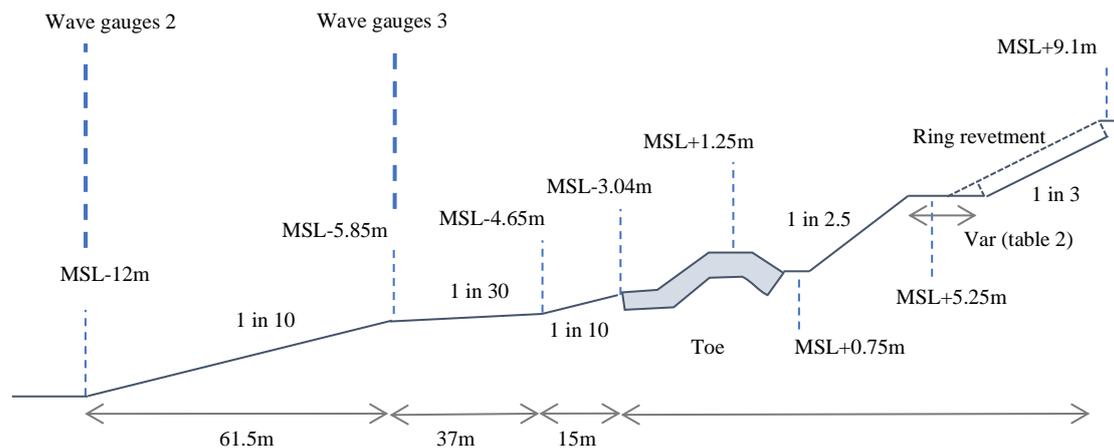
Figure 9. Detailed cross-section of the foreshore and profile (dimensions in real-size)
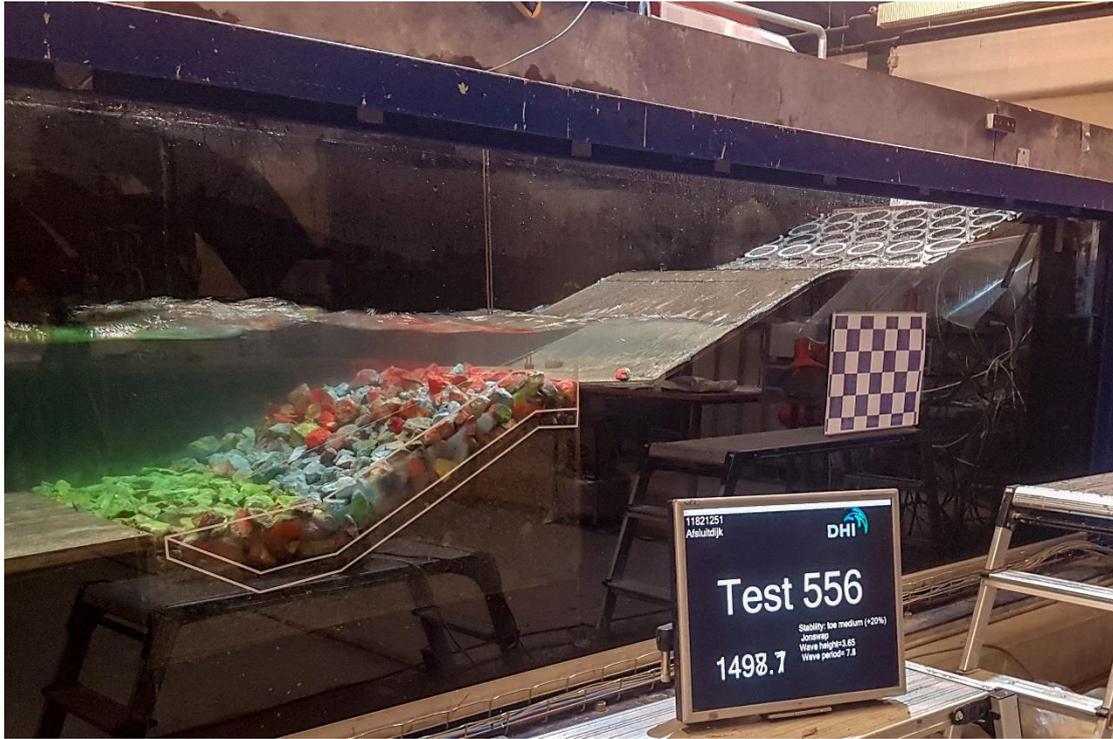
Figure 10. Flume tests at DHI (scale 1 in 18)

Wave gauges were placed at the shortest distance possible from the wave panel, where the waves were fully grown. Wave gauges were also placed at two different places near the foreshore. Test duration equaled 500 waves per test. The spectral period was about 7 seconds, which means that one hour of a real-life storm was simulated. The seed number (for the generated train of waves) was kept constant, but was carefully chosen beforehand, so that it represented an average amount of overtopping. The overtopping rate was measured with an overtopping bucket, which collected water using an overtopping chute. This water was weighed real-time and after each test to derive the overtopping rate.

Most of the 800 tests were convergence tests towards the final design. 23 tests (all at 1:18 length scale) were performed with the final design and these have been considered in this paper. The other tests explored alternative solutions and aided to develop the final design, partly as sensitivity tests. The final design was also tested at a length scale 1:5 in the Large Wave Flume (FZK Facilities in Hannover, Germany) to verify overtopping requirements as well as the stability of the revetments. The results of these tests have not been included in this paper, as the resulting overtopping discharges proved to be somewhat different. These differences might be caused by scale effects and different foreshore geometries and flume lengths. Time has not been available thus far to analyze these differences in detail, but it is recommended to look further into the cause of these differences.

The 23 tests that concerned the final design of the upper slope ring-type revetment, were done for a variety of heights of the roughness elements, i.e. the tested configurations are I, II, IV, VI and smooth (see table 1). For these configurations, several settings have been used at the wave panel, all of which are steep and breaking waves:

- Design waves (H_{m0}= 4.27 m, T_p = 7.7s, 4.5% wave steepness)
- 10% lower than design waves with equal steepness
- 10% higher than design waves with equal steepness
- Design waves with 10% increase in steepness (rough configurations only)
- Design wave with 10% decrease in steepness (rough configurations only)

OVERTOPPING PHYSICS

The physical model scale testing led to detailed insight into the physics of overtopping. By optimization of the complex interaction between the main structural dike elements, the overtopping rate could finally be considerably reduced in order to satisfy the overtopping requirement:

1. Maximum wave breaking on the steep lower slope was promoted by applying a high armour rock toe at some distance from the dike body. The toe basically "trips" the wave.
2. The high wave impacts on the lower slope were absorbed by a pattern placed revetment with physical interlocking, which is fully submerged during storm surge conditions.
3. Optimally increased roughness on the upper slope including a low upper crest wall.
4. Strong counteraction with the next wave was achieved by optimally timed wave run-down along the upper slope and the wide storm berm as it collides with the wave-run up of the next wave.

In the final arrangement the circular elements produced a very strong energy dissipation and delayed wave run-down which was attributed to the following effects:

1. The circular shapes act as a partially reflective wave wall while simultaneously creating a 3D-effect in which the water is concentrated and 'jumps' from ring to ring, thus strongly reducing wave runup and overtopping (Figure 11).
2. The rings delay the wave run-down such that it optimally coincides with the consecutive incident wave and counteracts the uprush of this wave.
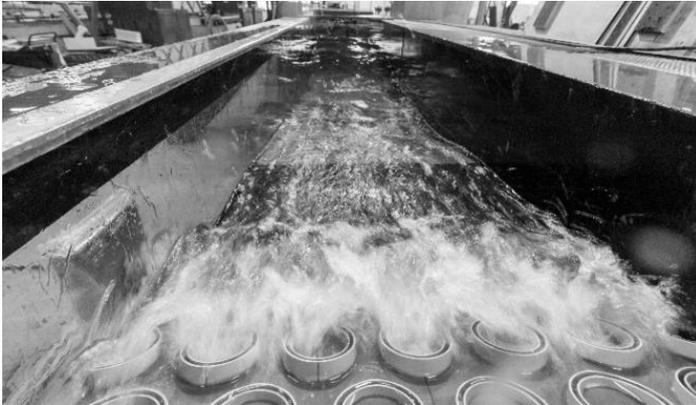
Figure 11. 3D effect, reducing wave runup and overtopping

PRELIMINARY DESIGN GUIDELINES

Test results are analyzed using the current overtopping equations. As basis the mean-value equation from the EurOtop Manual (EurOtop, 2018) is used to derive a best-fit for the measured parameter values (see equation 5.10 and 5.11 from the EurOtop manual).

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

$$\text{with a maximum } \frac{q}{\sqrt{g \cdot H_{m0}^3}} = 0.09 \cdot exp\left(-\left(1.5 \cdot \frac{R_c}{H_{m0}} \cdot \frac{1}{\gamma_f \cdot \gamma_\beta \cdot \gamma^*}\right)^{1.3}\right) \quad (2)$$

In this equation, q is the overtopping rate [m³/s/m], g is the gravitational constant [m/s²], H_{m0} is the significant wave height [m], tan α is the equivalent slope angle [-], $\xi_{m-1,0}$ is the breaker parameter [-], R_c is the freeboard [m] and all γ factors are influence parameters [-], for which γ_b is the berm, γ_f is the friction/roughness, γ_β is the oblique angle of attack and γ_v/γ^* encompasses the influence of several other types of elements such as wave wall or promenade.

The EurOtop equations require the wave height at the toe of the revetment. However, measuring the wave height at the toe of the revetment proved to be impossible due to extreme turbulence and white-washing. Therefore, wave gauges were placed as close as possible to the toe of the revetment (location 3 in Figure 8) and these gauges were used to analyze the tests. To exclude the influence of the toe and remaining foreshore, first a smooth plate was placed on the upper slope as smooth slopes are well described in the EurOtop manual ($\gamma_f = 1$). The resulting overtopping rates for the smooth plate were fitted with the overtopping equation (1) by an additional coefficient γ_{fs} to account for the influence of the toe and remaining foreshore. The value of this additional coefficient was found to be $\gamma_{fs} = 0.87$. This leads to a fit of the smooth data with the mean value equation, as displayed in Figure 12. All other values in equation (1), such as the influence of the berm, are derived using the procedures described in the EurOtop manual.
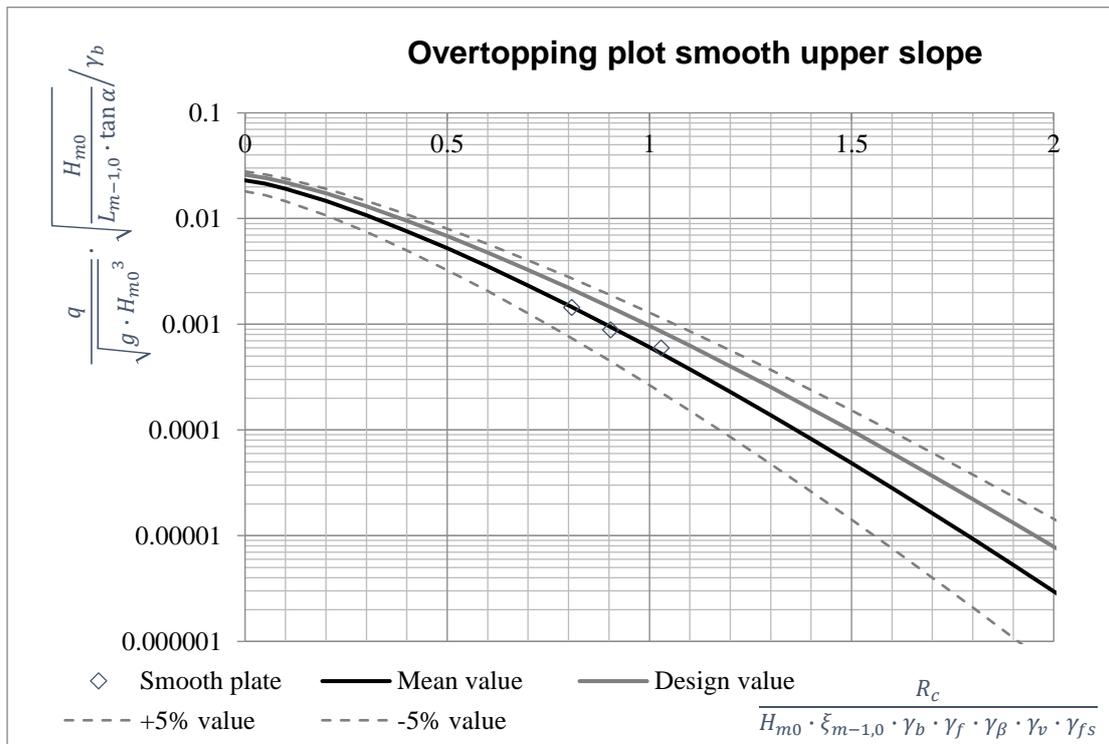
Figure 12. Overtopping plot for a smooth upper slope

The EurOtop describes equation (3) to estimate the slope-averaged roughness for composite slopes, in which the indices correspond to the placement of the roughness: upper slope (no 1), berm (no 2) and lower slope (no 3). In this equation the roughness is considered equally effective on the upper slope, berm and lower slope.

$$\gamma_f = \frac{\gamma_{f,1}L_1 + \gamma_{f,2}L_2 + \gamma_{f,3}L_3}{L_1 + L_2 + L_3} \tag{3}$$

If equation (3) is used, the upper slope roughness for configuration I (see table 2) corresponds to an upper slope roughness of approximately $\gamma_{f,1} = 0.55$, which is similar to the roughness of a rock revetment (2 layers, impermeable core). This is elaborated in 'Calculation example'.

However, other tests in the testing series have shown that rings placed on the upper slope are considerably more effective in comparison to rings placed on the berm or the lower slope. This is confirmed by (Chen & Van Gent, 2020), who proposed equation (4) to estimate the slope-averaged roughness for composite slopes, considering the location of the roughness elements

$$\gamma_f = \frac{\alpha_1 \gamma_{f,1} L_1 + \alpha_2 \gamma_{f,2} L_2 + \alpha_3 \gamma_{f,3} L_3}{\alpha_1 L_1 + \alpha_2 L_2 + \alpha_3 L_3} \tag{4}$$

The location-weighting coefficients α_1 (upper slope), α_2 (berm) and α_3 (lower slope) describe the effect of the locations of roughness elements on the overall roughness influence factors.

Upper slope:	$\alpha_1 = 0.65$
Berm:	$\alpha_2 = 0.22$
lower slope:	$\alpha_3 = 0.13$

This equation is applied for fitting the effect of the circular elements. The lower slope and the berm are smooth ($\gamma_{f,2} = 1$ and $\gamma_{f,3} = 1$). It may be that the roughness of the elements is dependent on the wave run-up tongue thickness and that elements placed higher on the slope are more effective, just as Chen & Van Ghent state that general placement on the upper slope is more effective than placement on the berm. However, no tests have been performed to confirm this. Here it is assumed there is independence between each row of elements (i.e. a row of elements responds the same on every location on the upper slope), meaning that the product for all rows of elements leads to the friction coefficient of the upper slope:

$$\gamma_{f,1} = \prod_{i=1}^{n} \gamma_{f,element,i} \tag{5}$$

Fitting the available overtopping data for each configuration, the best fit is derived using the following equation for the coefficient of each i-th row of elements.

$$\gamma_{f,element,i} = 0.77^{\left[\left(\frac{h_{element,i}}{H_{m0}}\right)^{0.75}\right]} \tag{6}$$

In which $h_{element,i}$ is the rear height (h_2, see table 1) of the i-th row of elements. The power of 0.75 in this equation shows that elements that are twice as high, are not twice as effective. The base of 0.77 characterizes the effectiveness for this specific combination of spacing and ring size.

In this equation, it has been assumed that the wall is twice as effective as a row of circular elements (all configurations include a wave wall as '6th element', see table 2). Accordingly, in equation (6) the wall coefficient can be determined by making $h_{element,i}$ equal to the wall height and then squaring the resulting coefficient. This is an educated guess as no literature was found on these types of wave walls. Previous research by (Van Doorslaer, 2017) and (Harlingen, 1998) describe wave walls that are much higher, so that all horizontal kinetic energy is converted into vertical kinetic energy (Schoemaker, 2019). This means that a wave wall can be summarized in one coefficient, regardless of its actual height. The wave wall in this design is much smaller (1/10th of the wave height), meaning that only a part of the horizontal kinetic energy is converted into vertical kinetic energy. Therefore, its effectiveness depends on the height of the wave wall.

The equations described above are applied to all measurements. The resulting fit is displayed in Figure 13. As can be seen, all measurements are fitted well around the mean-value equation 5.10 from the EurOtop, equation (1). All of the measurements are also below the design-value equation (equation 5.12 in the EurOtop manual), which is one standard equation above the mean-value equation in the EurOtop manual. This means that equation (6) is well-suited for design purposes with comparable geometries.

Overtopping plot all tests

$$\frac{q}{\sqrt{g \cdot H_{m0}^3}} \cdot \sqrt{\frac{H_{m0}}{L_{m-1,0} \cdot \tan \alpha}} / \gamma_b$$

$$\frac{R_c}{H_{m0} \cdot \xi_{m-1,0} \cdot \gamma_b \cdot \gamma_f \cdot \gamma_\beta \cdot \gamma_v \cdot \gamma_{fs}}$$

◇	Smooth plate	✕	Circular I (A-B-C-D-E)
☐	Circular II (B-C-D-E-F)	○	Circular IV (D-E-F-F-F)
△	Circular VI (F-F-F-F-F)	——	Mean value
——	Design value	- - - -	+5% value
- - - -	-5% value		
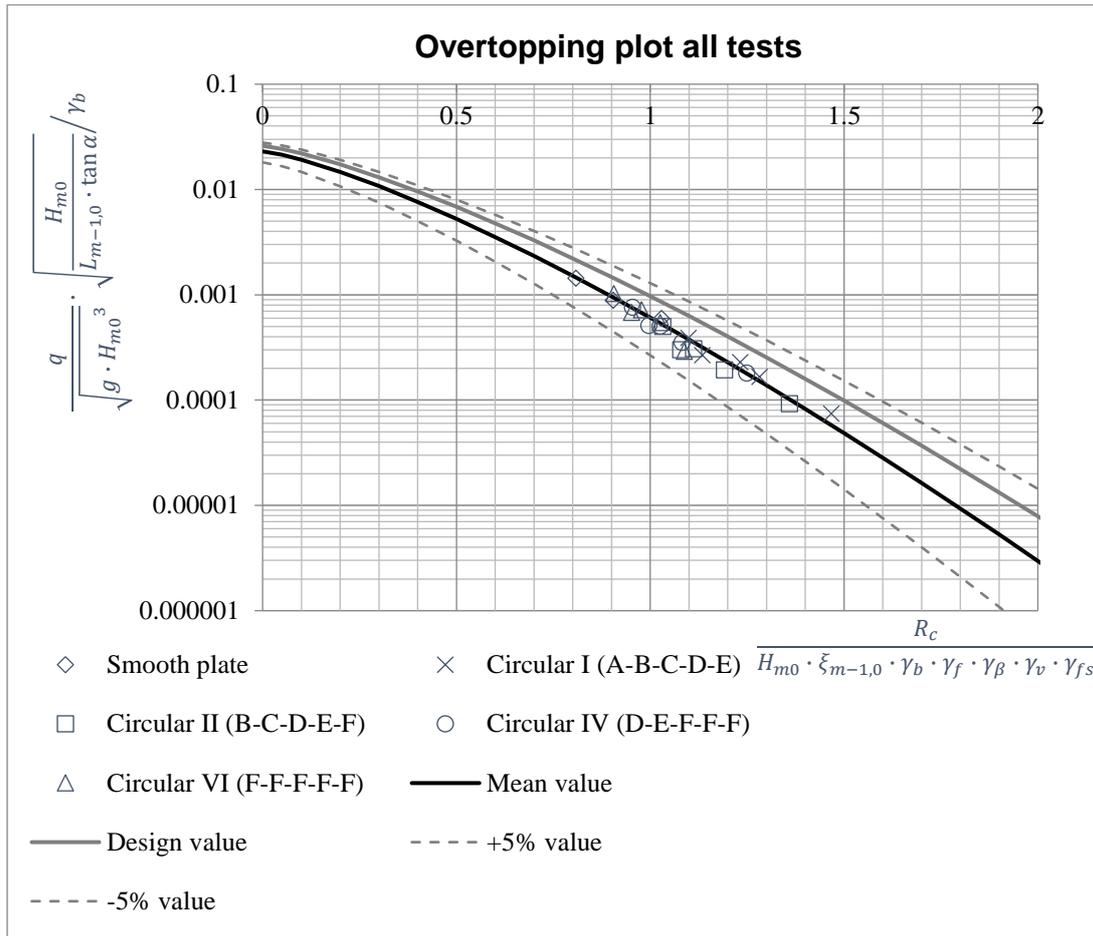
Figure 13. Overtopping plot for all 23 tests

CALCULATION EXAMPLE

In this section, a calculation example is provided for rings configuration I and the measured design waves. Table 3 shows the parameters specific for this cross-section and measurement.

Table 3. Relevant parameters for calculation example.			
Parameter	Symbol	Value	Remarks
Water level	h	MSL + 5.21 m	Measured
Significant wave height	H_{m0}	3.51 m	Measured at wave gauge 3 (fig 8)
Spectral period	$T_{m-1,0}$	7.29 s	Measured at wave gauge 3 (fig 8)
Overtopping rate	q	7.23 l/s/m	Measured
Berm width	B_b	7.5 m	From drawings
Berm level	z_b	MSL + 5.25 m	From drawings
Berm coefficient	γ_b	0.720	Computed using EurOtop section 5.4.6
Lower slope	$\tan \alpha_2$	1 in 2.5	From drawings
Berm slope	$\tan \alpha_b$	1 in 40	From drawings
Upper slope	$\tan \alpha_1$	1 in 3	From drawings
Average slope	$\tan \alpha$	0.369	Computed using EurOtop section 5.4.6
Coefficient for foreshore/toe	γ_{fs}	0.87	See preliminary design guidelines
Breaker parameter	$\xi_{m-1,0}$	1.794	Computed using measurements and average slope from the EurOtop
Freeboard	R_c	3.89 m	From drawings
Upper slope length	L_1	11.89 m	From drawings
Berm length	L_2	7.50 m	From drawings
Lower slope length	L_3	4.48 m	From drawings, 0.25*$R_{u2\%,smooth}$ below the still water line (EurOtop)
Berm roughness	$\gamma_{f,2}$	1	Smooth berm
Lower slope roughness	$\gamma_{f,3}$	1	Smooth lower slope

Configuration I consists of rings as displayed in table 2, repeated below in table 4. Here, also the coefficients for each row of elements are calculated using equation (6).

Table 4. Design configuration I and associated roughness coefficients						
	Wall height equal to	1st (top) element	2nd element	3rd element	4th element	5th (lowest) element
Config I	A	A	B	C	D	E
Height	50cm	50cm	42.5cm	35cm	27.5cm	20cm
Coefficient using eq (6)	0.886	0.941	0.948	0.955	0.962	0.970

Equation (5) states that the upper slope roughness coefficient can be determined by taking the product of all these coefficients, yielding $\gamma_{f,1} = 0.704$. Using equation (4) the slope-averaged roughness for the composite slope is determined. This yields $\gamma_f = 0.770$.

With all parameters now known, equation (1) is used to compute the predicted overtopping rate, which is 6.6 l/s/m. The measured overtopping rate is 7.2 l/s/m, as such the predicted overtopping rate is very close to this value and well within the standard confidence intervals of the equation. If the design-value is used from the EurOtop manual (equation 5.12 in the manual), an overtopping rate of 12.1 l/s/m is predicted.

For comparison, an additional calculation is made with equation (3), following the traditional method for slope-averaged roughness for composite slopes from the EurOtop manual. For an upper slope roughness of $\gamma_{f,1} = 0.55$, a slope-averaged roughness for the composite slope $\gamma_f = 0.776$ is found. This results in a predicted overtopping rate of 7.0 l/s/m with equation (1). An upper slope roughness coefficient of $\gamma_{f,1} = 0.55$ is similar to rocks (2 layers, impermeable core) from the EurOtop manual, proving the effectiveness of the circular elements and this type of ring revetment.

This proves that the ring-type revetment has a comparable effectiveness and demonstrates the enormous potential for this innovative revetment.

CONCLUSIONS AND RECOMMENDATIONS

Against the technically challenging background of the Afsluitdijk reinforcement tender a new type of upper slope revetment was developed to maximally limit wave overtopping. The innovative ring-type upper slope revetment consists of circular shaped roughness elements, which are placed in a triangular pattern and in multiple rows on the slope, with an ascending height from the water level to the crest. Near the crest a low wave wall was placed perpendicular to the slope with a height equal to the rear height (h_2) of the highest roughness element.

The design of the rings was based on extensive physical model research. Exploration and examination of the actual physics of overtopping and wave impact during the tests, provided considerable gains in time as well as in quality for the design of the revetments. The interaction of the rings and the wide storm berm resulted in a very high hydraulic roughness (even comparable to a double layered rock protection on an impermeable core), which provided a substantial wave run-up reduction. The optimum configuration for the Afsluitdijk consisted of five rows of rings with a constant inner diameter (ID), outer diameter (OD) and spacing (s), and varying ring heights. By altering the heights and arrangements of the rings, the design could be optimized for different cross section locations.

A preliminary design guideline is presented to estimate the influence coefficient for roughness of a ring configuration for a specific dike geometry and boundary conditions. In other comparable situations this coefficient can be calculated with equations (3), (4) and (5). 'Comparable situations' implies that the following conditions should be similar:

- Dike geometry with a wide storm berm, 1:2.5 smooth lower slope and 1:3 rough upper slope (small deviations may possibly be allowed)
- Breaking wave conditions (steepness ~4-5%, $\xi_{m-1,0}$ ~< 2)
- Similar ring parameterization in comparison to the wave height

- o Outer diameter (OD) ~ $H_{m0}/3$; Inner diameter (ID) ~80% of OD
- o Upper height h_2 ~ $H_{m0}/10$; Lower height $h_1 = 0.5\ h_2$
- o Spacing (s) ~ $H_{m0}/10$;

For broader application, the performance of the ring-type revetments should be investigated for a larger variety of slopes, storm berm levels and widths and hydraulic boundary conditions. Other ring parameterizations may also be explored to examine the influence of spacing, ring diameters, wall thickness in specific situations. Furthermore, dedicated tests are required to quantify the influence of the upper wave wall more accurately. Finally, it is recommended to further examine the effectiveness of the ring depending on its location on the upper slope as well as the influence of the storm berm. The expectation is that the ring-type revetment without a storm berm will be somewhat less effective, but that the overtopping performance is still favorable.

The ring-type revetment for the Afsluitdijk has proven to be very effective in reducing overtopping and thus in reducing dike crest elevation. In their final arrangement the rings on the upper slope had a hydraulic roughness comparable to rock (2 layers, impermeable core). This demonstrates the enormous potential for this innovative revetment, especially with rising sea levels and increasingly harsh hydraulic conditions. The system is suitable for application on coastal defenses with low crest heights, especially if there is little space for dike widening (the latter associated with crest elevation). Given the influence of local conditions and the fact that local boundary conditions will vary for each project, conducting (scale) model research is essential to develop and validate the detailed design of the ring-type revetment and optimal dike geometry, providing for the most cost-effective solution.

With the ring-type revetments, a solution can be offered that reduces costs by limiting or even preventing crest elevation and associated widening of the dike. Note that the ring-type revetment and associated pattern-placed protection elements can be considered as an add-on for many sea defenses, thus avoiding extensive dike reconstruction works, whilst maintaining accessibility over the outer dike slope towards the water in front of the dike. Alternative applications may include using the system as a full add-on solution (leaving the present dike body largely intact) or by modular implementation, where additional ring elements are placed over time when the requirements or boundary conditions become more severe during the lifetime.

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