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# Design Verification of Afsluitdijk Renovation with Large Scale Tests

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# Design Verification of Afsluitdijk Renovation with Large Scale Tests

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**Abstract:** In the north of the Netherlands a 32 km long dam divides the Wadden Sea from the Lake IJssel: the 'Afsluitdijk'. Currently this dam is being rehabilitated by increasing the crest level to reduce the wave overtopping and reinforce the armour layers on the seaward and lake side of the dam. The Dutch Ministry of infrastructure and Water Management (Rijkswaterstaat division) has commissioned Levvel, a consortium of BAM, Van Oord and Rebel, to carry out this renovation as a design, built, finance and maintenance contract. Rijkswaterstaat gave the opportunity to the contractor to offer an innovative design. New techniques and or armour units were allowed to use, but design verification with large scale physical model tests was prescribed. The verification of the design has been carried out in the Delta Flume of Deltares. Levvel proposed two new armour materials to protect the dam against wave action: Quattroblocks® a product of Holcim Coastal and Levvel-blocs, internationally known as Xblocplus® by BAM. This paper describes the large-scale tests and results with regard to armour stability and wave overtopping. The results of the large-scale tests show a high stability of the Levvel-blocs ($H_{m0}/\Delta D_n > 3$) and very high stability of the Quattroblocks ($H_{m0}/\Delta D > 8$) in the wave impact zone. The stability of the Quattroblocks with ribs in the wave run-up zone was $H_{m0}/\Delta D = 15$.

*Keywords: Afsluitdijk, Block revetment, Levvel-bloc, XblocPlus, Quattroblock, slope protection, large-scale tests, wave overtopping measurement*

## 1 Introduction

In the north of the Netherlands a large dam divides the Wadden Sea from the Lake IJssel, see Figure 1. This dam was built around 1932. After 90 years this dam undergoes a largescale renovation. The Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat division) has commissioned Levvel, a consortium of the contractors Van Oord, BAM, and Rebel, to carry out this renovation as a design, built, finance and maintenance contract.


Fig. 1. Afsluitdijk in the north of the Netherlands.

Ample room for innovation was given in the tender procedure, stimulating the use of new materials and building methods, but large-scale verification tests to prove the stability and limited wave overtopping were obligatory. The verification of the design has been carried out in the Delta Flume of Deltares. This large-scale facility is 300 m long, 9.5 m deep and 5 m wide, see Figure 2. Waves can be generated up to a maximum significant wave height of 2 m, while the record wave height of an individual wave is 4.7 m. The design verification tests in the Delta Flume focused on the stability of the slope, the rock toe structure and the wave overtopping discharge.


Fig. 2. Delta Flume of Deltares (left: wave board; middle: breaking wave; right: wave attack on Afsluitdijk).

The contractual requirements are based on an adaptive approach, which means that the dike design can be easily adapted for wave overtopping following the actual sea level rise. The contract also motivates contractors to come up with dedicated designs which minimize the material use, minimize the use of protected N2000 Wadden Sea area and maximise material reuse. These contractual requirements led to an innovative dike design.

The new armour layer will be built on top of the existing Afsluitdijk, giving it a higher crest and stronger slopes. The 32 km long dam has been subdivided into several sections. All tested sections have a berm at a level near to the design water level. Above this berm a gentle slope of 1:3.5 to 1:4 is used with Quattroblocks® of Holcim Coastal (see Figure 3). These blocks have been put on the slope in a special pattern, with high blocks and low blocks, forming a rough slope with protruding elements, ribs. For most of the sections the slope below the berm is protected with newly developed Levvel-blocs (see Figure 4) with a rock toe, except for Dike section 17 which also has Quattroblocks on the slope below the berm. Dike sections 8 and 17 have been tested in the Delta Flume.

## 2 Quattroblocks and Levvel-blocs

### *2.1 Quattroblocks*

Holcim Coastal recently developed a new type of block revetment in the Netherlands: the Quattroblock®. The design of this block type has been based on the Basalton column, which has been successfully applied on many dikes in the Netherlands. The stability under wave loading of Quattroblock® has significantly increased compared to the Basalton column by connecting four individual blocks with a concrete bridge, see Figure 3. The stability in waves has increased by combining the high friction between the blocks and increased weight by connecting individual blocks, but at the same time ensuring the open space (10.5%) in the blocks to drain water overpressures under the blocks.

Earlier Large-scale tests in the Delta Flume of Deltares have demonstrated that the stability of this type of revetment is very high compared to other types of placed block revetments. The Quattroblocks® did not fail at a wave attack on a slope of 1:3.6 with the following conditions:

$$\frac{H_{mo}}{\Delta D} = 7.6 \qquad s_{op} = 0.038 \qquad (1)$$

with: $H_{m0}$ = significant spectral wave height at the toe of the dike (m); $\Delta = (\rho_c - \rho)/\rho$ = relative density of the concrete of the blocks (-); $\rho_c$ = density of the concrete of the blocks (kg/m$^3$); $\rho$ = density of water (kg/m$^3$); D = layer thickness of the revetment (typically between 20 and 50 cm); $s_{op}$ =

$H_{m0}/(gT_p^2/(2\pi))$ = deep water wave steepness (-); g = acceleration of gravity ($m/s^2$); $T_p$ = wave period at the peak of the spectrum (s).

The block revetment is applied on a thin gravel layer on a geotextile on clay (or sand in the wave run-up zone). The blocks are placed adjacent to each other on the slope, without any interconnection or interlocking. The interaction between adjacent blocks is achieved by filling the joints with small gravel, which increases the friction between the blocks and reduces the possibility of lifting a single block out of the slope.

This excellent hydraulic performance was one of the reasons for Levvel to choose this innovative block revetment for the Afsluitdijk design.

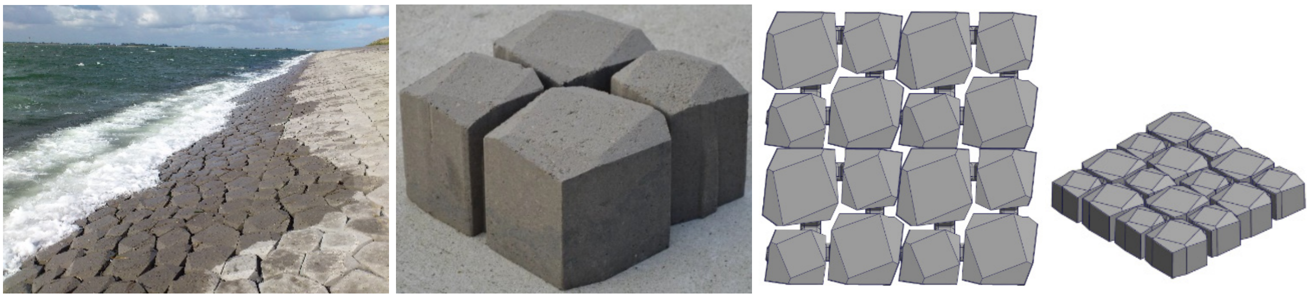

Fig. 3. Basalton (left) and Quattroblock® of Holcim Coastal.

A disadvantage of this system is the rather smooth surface, leading to a higher wave run-up levels giving larger wave overtopping amounts. Artificial ribs have been applied on the upper slope to increase the roughness, as can be seen in Figure 9 and 10. These ribs are constructed by applying higher Quattroblocks.

## *2.2 Levvel-blocs*

The Levvel-bloc (Figure 4) has been developed as further development of the widely used single layer armour unit called Xbloc and will be applied worldwide under the name XblocPlus. The main advantages of the Levvel-bloc are the reduced material quantities and $CO_2$ emissions and the regular placement grid, which simplifies block placement and makes verification of installation of the units much easier. The new block combines these advantages with an aesthetic appearance which is suitable for the renovation of this historic dam.

The Levvel-bloc is a concrete element which has large interlocking capacity. This results in a design stability number of $H_s/\Delta D_n = 2.5$ (Delta Marine Consultants, 2018), although small scale model tests indicate a significantly higher stability, withstanding waves up to 250% of the design conditions. For the Afsluitdijk the units will be installed on a 1:2 slope. The Levvel-blocs are installed on a granular underlayer.

The Levvel-blocs have large open spaces resulting in a large influence factor for roughness ($\gamma_f$). The roughness factor for Levvel-bloc on a permeable core is $\gamma_f = 0.45$ (Delta Marine Consultants, 2018).

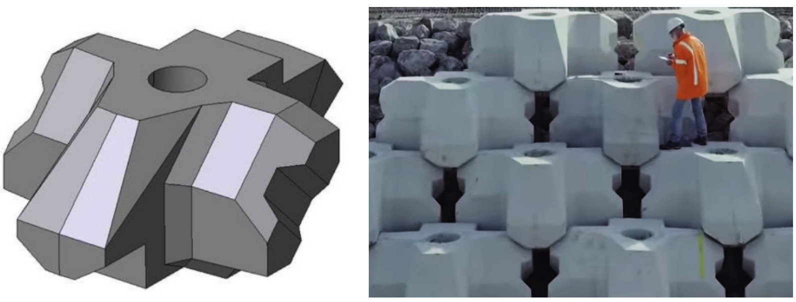

Fig. 4. Levvel-bloc.

## 3 Theory

### *3.1 Stability of pitched block revetment*

The stability of pitched block revetments, like Quattroblock®, is governed by the hydraulic load (pressure difference across the cover layer), the weight of the blocks and the interaction between the blocks. The pressure difference across the cover layer is dependent on the wave conditions and the permeability of the structure. The stability of a normal block revetment is not susceptible for the fast-flowing water during wave run-up and wave rundown because of its rather smooth surface. The stability is especially jeopardized by pressure gradients on the slope. For practical reasons we focus on the pressure potential (piezometric head) $\phi$:

$$\phi = \frac{p}{\rho g} + z \tag{2}$$

with $\phi$ = pressure potential (m); p = pressure (Pa) and z = vertical coordinate (m)

The pressure potential in the filter underneath the cover layer is a damped representation of the pressure distribution on the slope. This is shown in Figure 5 at the moment of a wave impact.

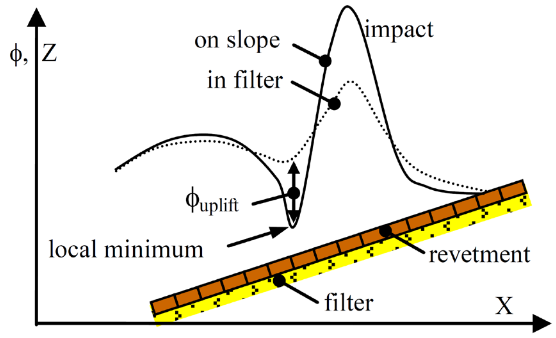


Fig. 5. Pressure potential distribution on the slope.

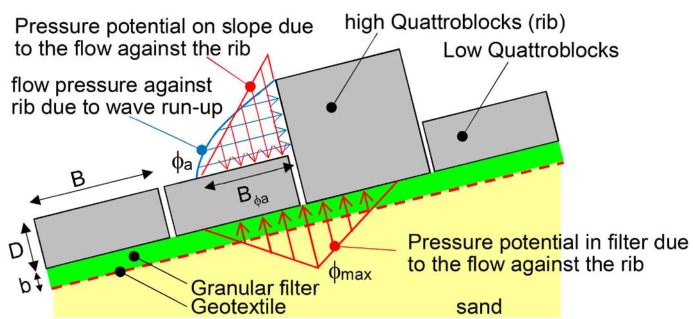


Fig. 6. Hydraulic load on the ribs on the upper slope and in the filter during wave impact (schematised).

A formula for the pressure potential in the filter can be derived on the basis of the mass balance in a infinitely small section of the revetment and filter (Bezuijen et al 1996). The pressure transmission through the filter is governed by the leakage length ($\Lambda$):

$$\Lambda = \sqrt{\frac{kDb}{k'}} \tag{3}$$

where k and k' are the permeability of the filter and top layer respectively (m/s) and b and D the thickness of these layers (m). A long leakage length means quite some damping of the pressures in the filter layer compared to the wave pressure on the slope and therefore potentially high uplift pressures.

The above theory is applicable for revetments with a rather smooth surface. However, the present structure has ribs in the revetment on the upper slope. The wave run-up hitting the ribs is an important contribution to the hydraulic load of the upper slope. This hydraulic load results in high pressure against the rib, which is transmitted into the filter layer underneath the block revetment, see Figure 6. This leads to uplift pressures, combined with the forces parallel to the revetment, which eventually could lead to unacceptable deformations. The magnitude of the uplift pressure can be estimated with the Laplace equation:

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{\phi - \phi'}{\Lambda^2} \tag{4}$$

with x = coordinate along the slope under the block revetment (m); $\phi'$ = pressure potential on top of the block revetment; $\phi$ = pressure potential in the filter layer (m)

This can be solved with the following boundary conditions, schematised with a constant pressure potential on top of the block in front of the rib over a length $B_\phi = B_{\phi a}/2$:

$x = -\infty$ => $\phi = 0$

$x \leq -B_\phi$ => $\phi' = 0$

$-B_\phi < x < 0$ => $\phi' = \phi_a$

$x \geq 0$ => $\phi' = 0$

$x = \infty$ => $\phi = 0$

with $\phi_a$ = maximum pressure potential of the wave run-up flow against the rib (m); $B_\phi$ = width of the zone with high pressure potential in front of the rib (m)

This equation yields with these boundary conditions the following for the maximum uplift pressure:

$$\phi_{max} = \frac{1}{2}\phi_a\left(1 - e^{-B_\phi/\Lambda}\right) \quad (5)$$

with: $\phi_{max}$ = maximum pressure potential in the filter underneath the revetment (m)

An interesting conclusion from this theory is that the contribution of this uplift force will be lower if the leakage length is longer, which is opposite to smooth revetments in the wave impact zone.

Unfortunately, there was no opportunity in the project to check this theory experimentally.

Note that this uplift pressure is not the only force on the rib that can cause instability. There is a large force from the flow in the run-up against the rib and also the high turbulence of the overflowing water over the ribs could contribute to uplift forces.

The deformation of the ribs that occurred during some of the tests was a gradual upward motion and a rotation backwards.

### *3.2 Wave overtopping*

The average wave overtopping discharge can be predicted with the formulas from the EurOtop 2018 (Van der Meer et al, 2018) using the mean value approach:

$$\frac{q}{\sqrt{gH_{m0}^3}} = \min\left\{\frac{0.023\cdot\gamma_b\xi_{m-1,0}}{\sqrt{\tan\alpha}}\exp\left(-\left(\frac{2.7R_c}{\xi_{m-1,0}H_{m0}\gamma_b\gamma_f\gamma_\beta\gamma_v}\right)^{1.3}\right); 0.09\cdot\exp\left(-\left(\frac{1.5R_c}{H_{m0}\gamma_f\gamma_\beta\gamma^*}\right)^{1.3}\right)\right\} \quad (6)$$

with: q = average overtopping discharge ($m^3/s/m$); $R_c$ = freeboard = crest level relative to the water level (m); $\alpha$ = slope angle (°); $\xi_{m-1,0} = \tan\alpha/\sqrt{H_{m0}/(gT_{m-1,0}^2/(2\pi))}$ = breaker parameter (-); $\gamma_b$ = the influence factor for a berm (-); $\gamma_f$ = the influence factor for the roughness of the slope (-); $\gamma_\beta$ = the influence factor for oblique wave attack (-), $\gamma_v$ and $\gamma_*$ = influence factor for a wall on top of the slope (not applicable here).

For the composite slope of the Afsluitdijk it is difficult to predict the value of $\gamma_f$. The roughness strongly depends on the amount of wave overtopping and wave steepness. Capel (2015) has recognized a dependency of the roughness of rib patterns on the amount of wave overtopping. However, the combined effect of the berm and different roughness factors from the lower slope (Levvel-blocs) and upper slopes (Quattroblocks) is difficult to estimate. Therefore, we have used the formula in combination with the test results to find a measured value of $\gamma_f$, see chapter 5.3.

## 4 Test set-up in the Delta Flume

### *4.1 Introduction*

The proposed structure was built in the Delta Flume on scale 1:2.95 and was tested with the design conditions. This large scale was used because the scale effects for tests on the stability of block revetments are negligible up to a scale of approximately 3 (Bezuijen 1990). Otherwise there will be a conflict between the Reynolds scaling law for the flow in the filter and the Froude scaling of the waves. All dimensions in this paper are given on model scale, unless otherwise specified.

The density of the concrete used for the Levvel-blocs and Quattroblocks was reduced to account for the density difference between the fresh flume water (1000 kg/m³) and the salt seawater (1025 kg/m$^3$). The asphalt berm has been represented by low quality concrete with a tensile strength of 50 year old asphalt, on scale 1:2.95.

Fig. 7. Placement of Levvel-blocs (left), placement of Quattroblocks (middle) and finished structure of section 8 (right).

The leakage length theory was used to calculate the dimensions of the filter layer under the Quattroblocks in the Delta Flume. The leakage length was scaled on the length scale. The 8 cm thick filter layer with grain size $D_{15}$ = 18 mm was represented in the Delta Flume by a 3 cm thick filter layer with a grain size of $D_{15}$ = 6.3 mm.

Behind the crest an overtopping collection reservoir was constructed with two wave probes to measure the water level during the tests.

### *4.2 Dike section 17*

Section 17 is located in the north-east of the Afsluitdijk, connecting to the mainland. It is sheltered by shallow areas in front of the dike which makes that the design wave conditions are milder than for other sections.

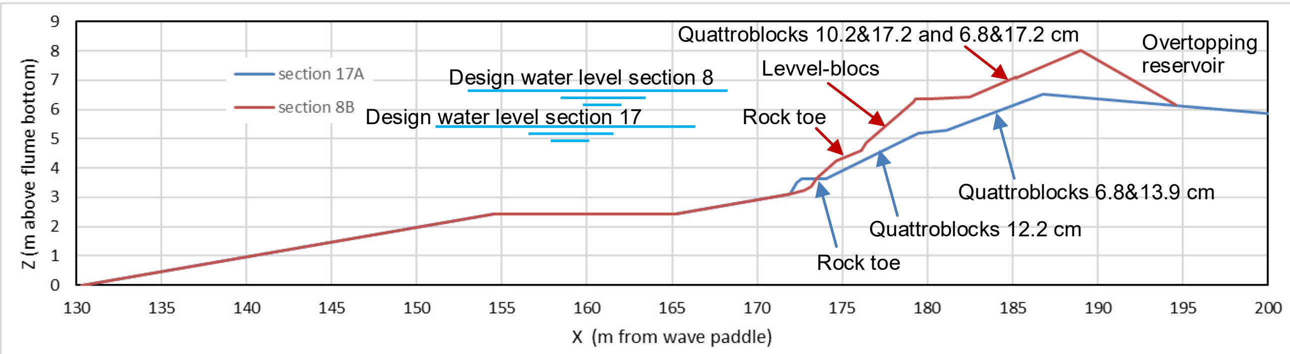


Fig. 8. Cross section of foreshore and dike (model dimensions).

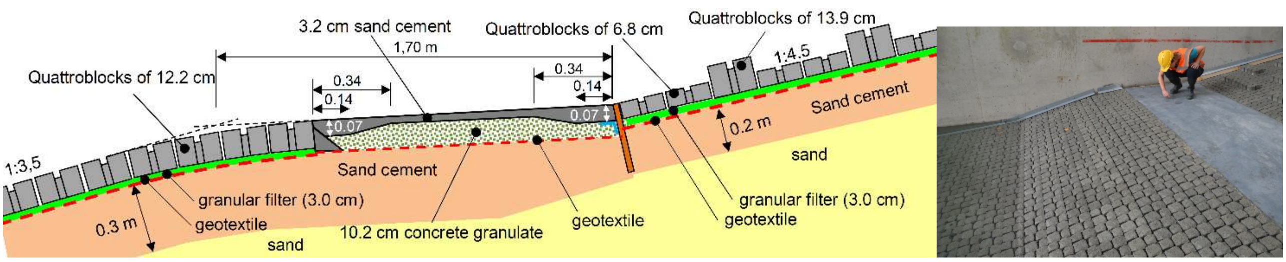


Fig. 9. Cross section of dike at the berm of section 17 (model dimensions) (left) and berm in Delta Flume (right).

The designed structure has a rock toe (2-11 kg, on scale 1:2.95), block revetment of Quattroblocks with thickness of 12.2 cm on a slope of 1:3.5, a 1.7 m wide berm of sand cement (representing old asphalt on scale) with thickness of 3.2 cm and an upper slope of Quattroblocks with thickness of 6.8 cm on a slope of 1:4.5 with ribs of 7.1 cm made of 13.9 cm Quattroblocks. The filter layer under the block revetment was 3 cm thick with a grain size of $D_{15}$ = 6.3 mm (model dimensions).

Details of the structure and the foreshore are given in Figure 8 and 9. Note that also alternative revetments on the upper slope have been tested with a different revetment thickness and rib height.

## 4.3 *Dike Section 8*

Dike section 8 is located in the middle of the Afsluitdijk, exposed to the most severe wave conditions.

The designed structure has a rock toe (15-60 kg), Levvel-blocs of 216 kg on a slope of 1:2 with a 27 cm filter of 3-15 kg rock, a 3.2 m wide berm of concrete with thickness of 5.5 cm and an upper slope of Quattroblocks with thickness of 10.2 cm on a slope of 1:4 with ribs of 6.8 cm made of 17.0 cm Quattroblocks. On the upper half of the upper slope Quattroblocks with thickness of 6.8 cm with ribs of 10.2 cm (made of 17.0 cm Quattroblocks) are applied. Also some alternatives for the upper slope have been tested, see chapter 5. The filter layer under the block revetment was the same as in section 17.

Details of the structure and the foreshore are given in Figure 8 and 10. These are given on model scale. Note that also alternative revetments on the upper slope have been tested with a different revetment thickness and rib height.

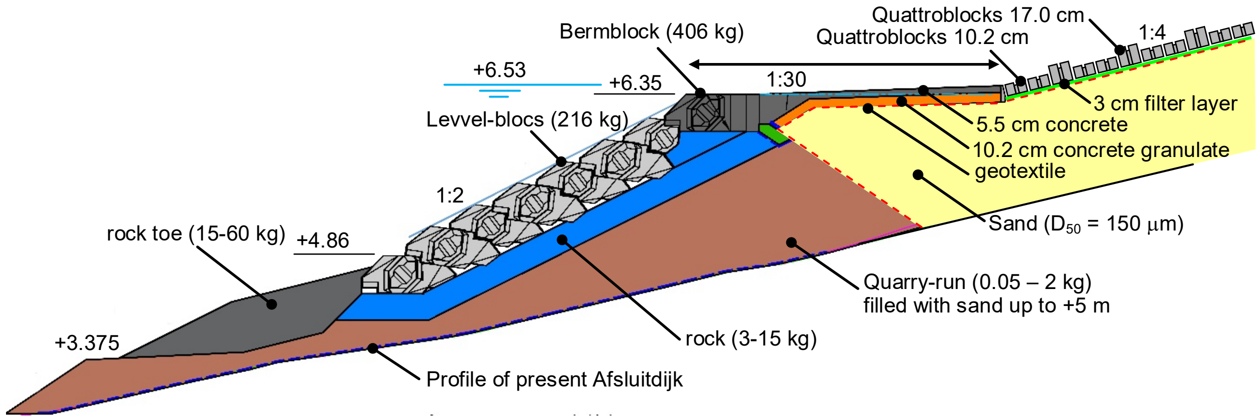


Fig. 10. Cross section of dike at the berm of section 8 (model dimensions).

# 5 Test programme and results

## 5.1 *Stability of Quattroblock revetment*

The stability of the structure has been verified with a specific long duration test, and dedicated tests to check the stability of the rock toe and wave overtopping. The stability test represents a 24-hour design storm with varying water level and wave conditions, which is 14 hours on scale 1:2.95 in the Delta Flume, see Figure 11. It contains a part with gradually changing water levels and wave conditions and a part with a constant water level and wave conditions. In this way all possible water levels are used in the test, which is necessary because the decisive water level is difficult to predict. Also a long duration wave load at a certain level is included. The latter is especially important for structural components that suffer from fatigue.

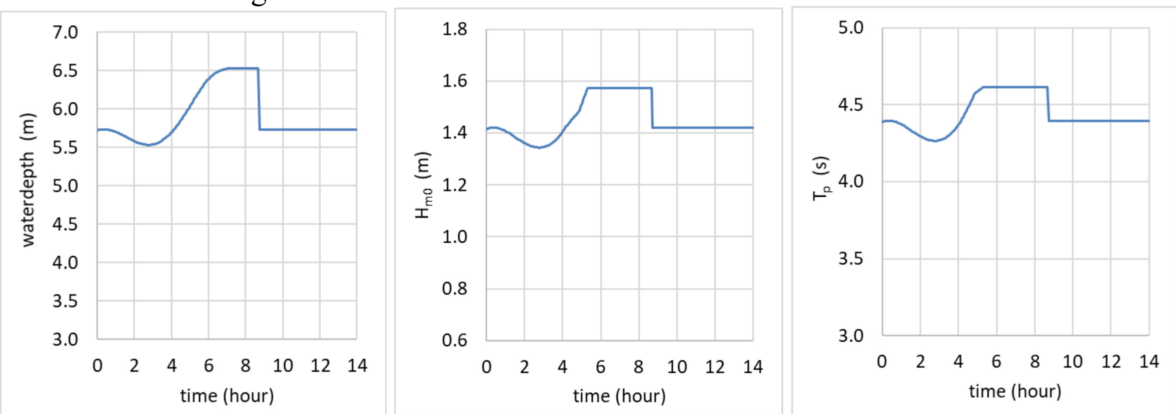


Fig. 11. Water level and wave conditions during long duration test.

The tests were carried out with the maximum water level approximately at berm level.

The test results regarding the stability of the Quattroblocks on the slope below the berm (wave impact zone; without ribs; dike section 17) have been given in Figure 12, together with the results of calculations with 'Steentoets'. The calculation model Steentoets is based on the leakage length theory, as explained in section 3.1, and is calibrated on Delta Flume tests carried out during the development of the Quattroblocks. The latter tests have also been included in the figure. The following parameters are used on the axis of the figure:

- breaker parameter: $\xi_{op} = \dfrac{\tan\alpha}{\sqrt{H_{m0}/(gT_p^2/(2\pi))}}$ and stability number: $\dfrac{H_{m0}}{\Delta D}$ (7)

The figure shows that the Quattroblocks (without ribs) have a very high stability in the wave impact zone, even higher than calculated with 'Steentoets'. At a value of $H_{m0}/(\Delta D) = 8.6$ there was no damage. Note that $H_{m0}$ is measured at deep water ($h/H_{m0} \approx 4$), while the relevant water depth in front of the dike is $h/H_{m0} \approx 2.4$.

The high stability is achieved by the relatively smooth surface, which leads to only minor drag forces during wave run-up and wave rundown. Only pressure gradients during wave impact can cause instability, but the resulting uplift pressures are efficiently reduced by the relatively high permeability of the revetment. Any uplift pressure is easily relieved through the openings in the Quattroblocks. And the interaction between the blocks is very high because of the filling of the joints with gravel.

Figure 13 gives the results of the tests on the upper slope (above the berm), which was not smooth as below the berm, but made rough by including artificial ribs, see Figure 9 and 10 (also the results of the tested revetments with other thickness and rib height are given). The stability above the berm is higher than below the berm, because the hydraulic load is primarily wave run-up and rundown, without wave impacts. But the artificial ribs lead to hydraulic (flow) forces on the blocks, which will reduce the stability. On the horizontal axis in the figure the ratio between the height of the blocks in the ribs and the height of the other blocks is given: $D_{rib}/D$. The higher this value, the larger the hydraulic forces will be on the ribs and the lower the stability. This can also be seen in the figure, where instability occurred for the cases with a high value of $D_{rib}/D$ and high value of $H_{m0}/(\Delta D)$. Based on this figure we can conclude that for this particular case no damage occurs as long as $D_{rib}/D < 2.0$ and $H_{m0}/(\Delta D) < 15$. Note that many of these tests have been carried out with a very porous and rough slope below the berm (section 8 with Levvel-blocs), which gives smaller hydraulic load than for cases with a smooth slope below the berm, or no berm at all.

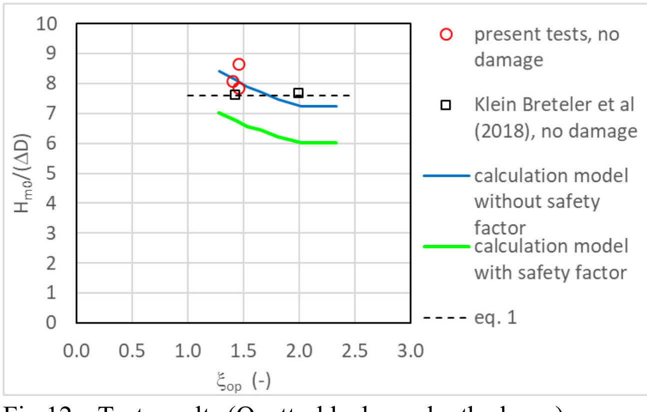


Fig.12. Test results (Quattroblocks under the berm)

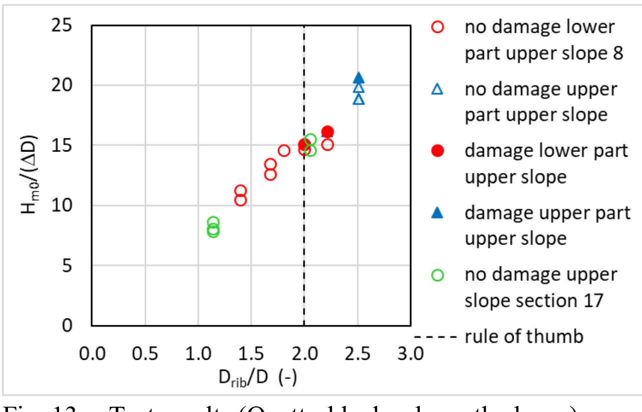


Fig. 13. Test results (Quattroblocks above the berm).

### *5.2 Stability of Levvel-bloc revetment*

The Levvel-blocs, protecting the slope below the berm, were subjected to the same wave conditions as the Quattroblocks (see Figure 11). The stability of the Levvel-blocs is given in Figure 14. For comparison the stability of a rock slope is given also, calculated with the Van der Meer formula modified by Van Gent for a shallow foreshore, as is the case in the present project (Rock Manual 2007, formula 5.139). The Levvel-blocs turned out to be very stable during all the tests, which results in the conclusion that there is a significant safety factor included in the stability number of $H_{m0}/(\Delta D_n) = 2.5$ as given in the design guide for Levvel-bloc (Delta Marine Consultants, 2018), for the applied foreshore and wave characteristics. The Figure shows that no damage occurred at $H_{m0}/(\Delta D_n) = 3$, which implies an even higher stability. This high stability is achieved by the dedicated shape of the elements, which enable the interlocking capacity of the blocks, but at the same time allow for regular placement.

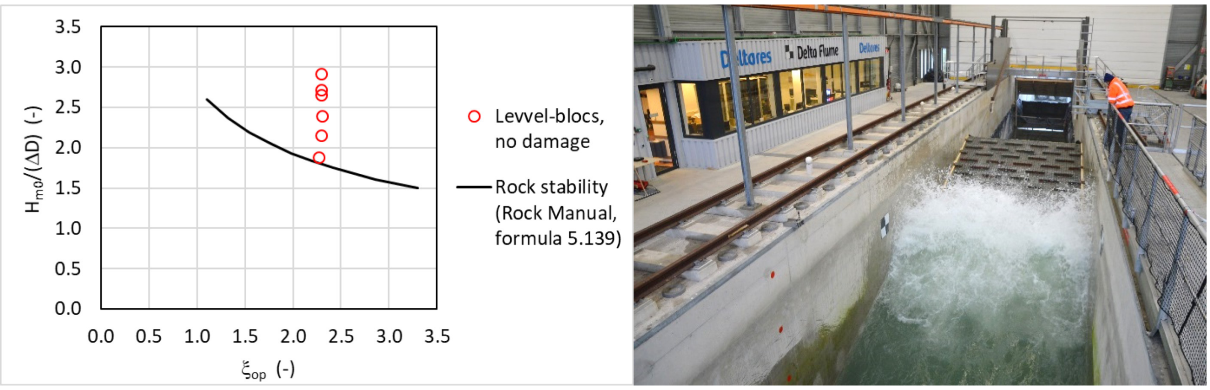


Fig. 14. Test results of the Levvel-blocks, compared to calculated stability of rock (left) and test in the Delta Flume (right).

## *5.3 Wave overtopping*

The wave overtopping measurements have been compared with Eq. 6 (EurOtop manual 2018: Van der Meer et al, 2018). The roughness of the upper slope with ribs has been determined with the method by Capel (2015). The combined roughness from the lower slope (Levvel-blocs), the berm (asphalt) and the upper slope (Quattroblocks with ribs) have been determined using a weighted influence factor for roughness according Eq. 5.25 from the EurOtop manual. The wave measurements in the Delta Flume are only measured at deep water, just in front of the wave paddle. The method of the EurOtop manual prescribes the wave conditions at the toe of the structure. To exclude the effect of the foreshore, measured wave conditions in the Delta Flume have been recalculated at the horizontal part of the foreshore, in front of the toe of the dike using SWAN.

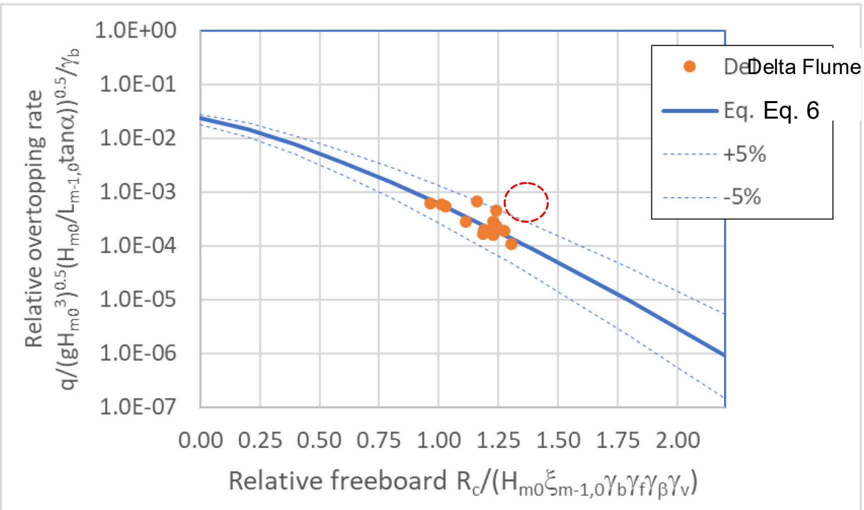


Fig. 15. Overtopping results from Delta Flume tests for dike section 8 and 17.

The results of the overtopping measurements in the Delta Flume fit fairly well with the theoretical design formula as shown in Figure 15. Two measurements show larger deviations from the average line (see red dashed circle in Figure 15). These measurements have very small ribs (1.7 cm) and are outside the range of validity of the Capel (2015) method. These small ribs indicate a very smooth slope. During the tests it seems that a thin water layer was present at the slope which resulted in a smoother slope than could be expected from the prediction formula. The following tests have all been performed with larger ribs ($0.014<(D_{rib}-D)/H_{m0}<0.070$) on the upper slope, resulting in good results according to the prediction formula.

## 6 Conclusions

The innovative design of the renovation of the 32 km long Afsluitdijk, in which two newly developed armour units (Quattroblocks and Levvel-blocs) have been applied, has been verified with large-scale tests in the Delta Flume of Deltares. The verification focused on stability of the rock toe, stability of the new armour units and wave overtopping, which was contractually limited to 10 l/s/m.

The design verification was very successful, confirming the high stability of the new armour units. Also the designed ribs on the upper slope to create artificial roughness showed to be very effective in reducing the wave run up and wave overtopping.

The stability number of the Levvel-blocs and Quattroblocks in the wave impact zone turned out to be high: $H_{m0}/(\Delta D) > 3$ for the Levvel-blocs and > 8.6 for the Quattroblocks. Note that $H_{m0}$ is measured at deep water ($h/H_{m0} \approx 3$), while the relevant water depth in front of the dike is $h/H_{m0} \approx 2$.

In the run-up zone the surface of the block revetment was made rough by applying higher Quattroblocks in some rows of the revetment (the artificial ribs). This reduced the wave overtopping substantially, but also reduced the stability of the revetment. Nevertheless, the stability was sufficient if the following criteria are met: $D_{rib}/D < 2.0$ and $H_{m0}/(\Delta D) < 15$. Note that these criteria were only derived for this specific case and could be different for other cases.

The wave overtopping tests showed that the method to predict the enhanced roughness (Capel, 2015) is capable of predicting the roughness of the ribs on the upper slope for rib heights within the validity range.

The authors want to acknowledge Levvel (a consortium of BAM, Van Oord and Rebel), Deltares and the Rijkswaterstaat Division of the Dutch Ministry of Infrastructure and Water Management for the cooperative support in making it a joined success.

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