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REHABILITATION OF THE AFSLUITDIJK

COEN KUIPER[1,2], EMIEL BOERMA[3]

1 Witteveen+Bos, Deventer The Netherlands, coen.kuiper@witteveenbos.com
2 Delft University of Technology, Delft The Netherlands
3 Ministry of Infrastructure and Water Management of the Netherlands, Utrecht The Netherlands, emiel.boerma@rws.nl

ABSTRACT

The ‘Afsluitdijk’ is a 32 km long dam, which divides the Wadden Sea from the Lake IJssel. The dam has been 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) commissioned Levvel, a consortium of BAM, Van Oord and Rebel, to carry out this renovation. Rijkswaterstaat encouraged contractors to offer innovative design solutions for the rehabilitation works as the dam is one of the icons in Dutch hydraulic engineering history. Levvel proposed two new armour materials to protect the dam against wave action and reduce the wave overtopping over the crest. A combination of Quattroblocks® a product of Holcim Coastal and Levvel-blocs, internationally known as Xblocplus® by BAM have both been introduced for the first time for the design of the dam. The application of innovative materials and/or techniques may incorporate uncertainties and because of the Afsluitdijk is one of the primary sea defenses preventing the Netherlands for flooding the contract included requirements for the Contractor to carry out physical model tests on the main failure mechanisms of the dam. Besides the contractual requirements, Levvel also used physical model tests to optimize the armour elements and the geometry of the dam. The verification of the design has been carried out with large scale 2D physical model tests in the Delta Flume of Deltares and small scale 2D model tests have been used to optimize design solutions.

KEYWORDS: Afsluitdijk, Block revetment, Levvel-bloc, XblocPlus®, Quattroblock®

1 Project Afsluitdijk

1.1 Project purpose and scope

Primary sea defences protect the Netherlands against flooding from the sea. These sea defences are subject to regular planned safety assessments in which the current state of the sea defences are evaluated on all relevant failure mechanisms. The Afsluitdijk, built in 1932 failed during the latest evaluation on armour stability and overtopping due to larger hydraulic loads as a result of climate change. Besides the rehabilitation of the dam, the project also includes:

- The construction of two storm surge barriers in front of existing shipping locks;
- The rehabilitation of the two monumental existing outlet sluices;
- The increase of the existing discharge capacity by:
  - Construction of two new pumping stations;
  - Construction of two new outlet sluices;
- The construction of a closable passage in the dam as part of the fish migration river;
- Reconstruction of the high way on the inner side of the dam.

Figure 1-1. Afsluitdijk 32km long with Waddensea (North side) and lake Ijssel (South side)

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This abstract focus on the rehabilitation of the dam only.

1.2 Client and contractor

The Dutch Ministry of infrastructure and Water Management (Rijkswaterstaat division) is the Client of this project and commissioned Levvel, a consortium of BAM, Van Oord and Rebel, to carry out this renovation as a design, built, finance and maintenance (25 years) contract.

1.3 Verification requirements

Rijkswaterstaat encouraged contractors to apply innovation in their design, execution methods and/or the material usage. To mitigate the risk of innovative applications the contract prescribed large scale model tests in the Deltaflume of Deltares, including a detailed verification program to minimize failure risks.

This verification program in the Delta flume included, amongst others:

- Prescription of the maximum damage after a storm with overload conditions;
- Minimum scale shall be less than 1:3;
- To allow for scale and model uncertainties the strength of the model needed to be 10% less than on prototype;
- The inclusion of overload conditions (10% on H_{m0}) to create robustness;
- Include the effect of uncertainties during the lifetime (wear, construction tolerances, settlements etc).

This verification program ensures a robust design of the dam and minimize the risk of failure of the primary sea defense during its lifetime.

2 Physical modelling at project Afsluitdijk

2.1 Geometry

The geometry of the dam is very similar over the length, however the hydraulic conditions and bed levels vary significantly due to the complex bathymetry of the Wadden sea. The new design is built over the existing dam structure; so the existing dam is still in tact inside the new dam. The typical cross-section is presented in the left panel of Figure 2-1. The lower slope has Levvel-blocs on a 1:2 slope with a berm around design water level. The berm's main function is to reduce the wave run-up levels, but is also assigned as maintenance road and bike path. The upper slope consists of Quattroblocks®, a placed block revetment consisting of columns (see Figure 2-2). To minimize the crest elevation and to meet the mean wave overtopping criterion of q = 10 l/s/m, artificial roughness was created on the upper slope by installing this revetment with different column elevations which resulted in a rib-pattern. The crest and inner slope consists of a grass cover on an impermeable clay layer to ensure the water tightness.

The Afsluitdijk project was the first application of both the Levvel-bloc and the Quattroblocks®

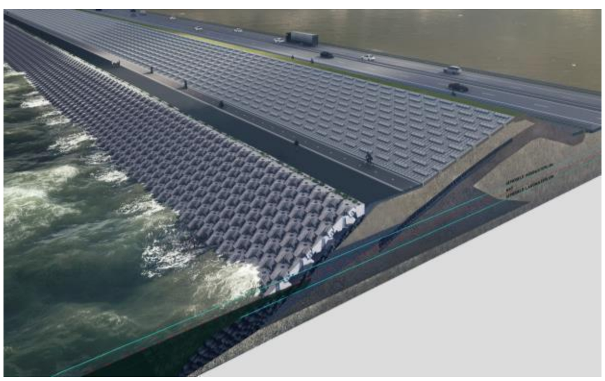
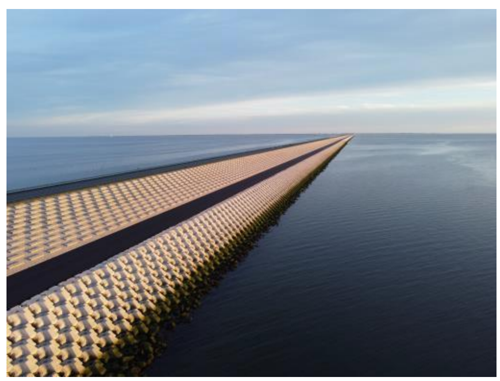

Figure 2-1. Visual of a typical dam cross-section (left) and after finishing construction (right)

2.2 The role of physical modelling within the project

Levvel used 2D scale modelling in different stages of the project. The model tests have been performed at Deltares laboratory and in the wave flume of the BAM. Table 1 provides an overview of the most relevant physical model tests. The small scale 2D model tests focused on the further development of the innovative armour elements (Levvel-bloc and Bermblocs), optimization of the toe berm and the mean wave overtopping discharges. The small scale physical model has also been used to reduce the amount of large scale model tests, because of the availability of the Deltaflume. Therefore, the design optimizations have been performed in a small scale physical model.

The large scale physical model tests have been performed for four typical cross-sections along the dam. These cross-sections have been selected because these cross-section differ in wave load and bed level in front of the toe. The selection of the different cross-sections enabled us to translate the model results of these four sections to all sections along the 32km of the dam.

Figure 2-2. From left to right, Quattroblock, Levvel-bloc, Bermbloc

Table 1. Physical modelling used for the design

Design stage	Type	scale 1:	Pupose	2D/3D
Development of the Levvel-bloc	small scale	32.6	Stability armour	2D/3D
Development of dedicated Bermbloc	small scale	32.6	Stability armour	2D
Design optimisation	small scale	20	Wave overtopping, toe and armour stability	2D
Design verification	Large scale	2.95	Wave overtopping, toe and armour stability	2D

Figure 2-3. Small and large scale physical model tests on scale 1: 20 (left panel) and 1:2.95 (right panel)

3 Results

3.1 Test conditions

The design is based on a typical storm duration of 35 hours. The model tests have been performed for hydraulic conditions around the peak of the storm with a total duration of 24 hours in prototype. During the tests, the water level and wave conditions have been varied to represent the tidal variations and the storm built-up (see Figure 3-1). Wave conditions up to H_{m0} = 4.58 m and T_p = 7.95s at overload conditions have been tested at the peak of the storm. The design wave conditions coincide with a return period of 10 000 year.

The large scale model has been tested with continuous varying water levels and wave conditions. This continuous varying conditions were not possible in the small scale facility, therefore we tested this with discrete water level and wave height steps. Also the situation after the peak of the storm has been modelled to be sure that the structure can survive, also in case (minor acceptable) damage occurred at the peak of the storm.

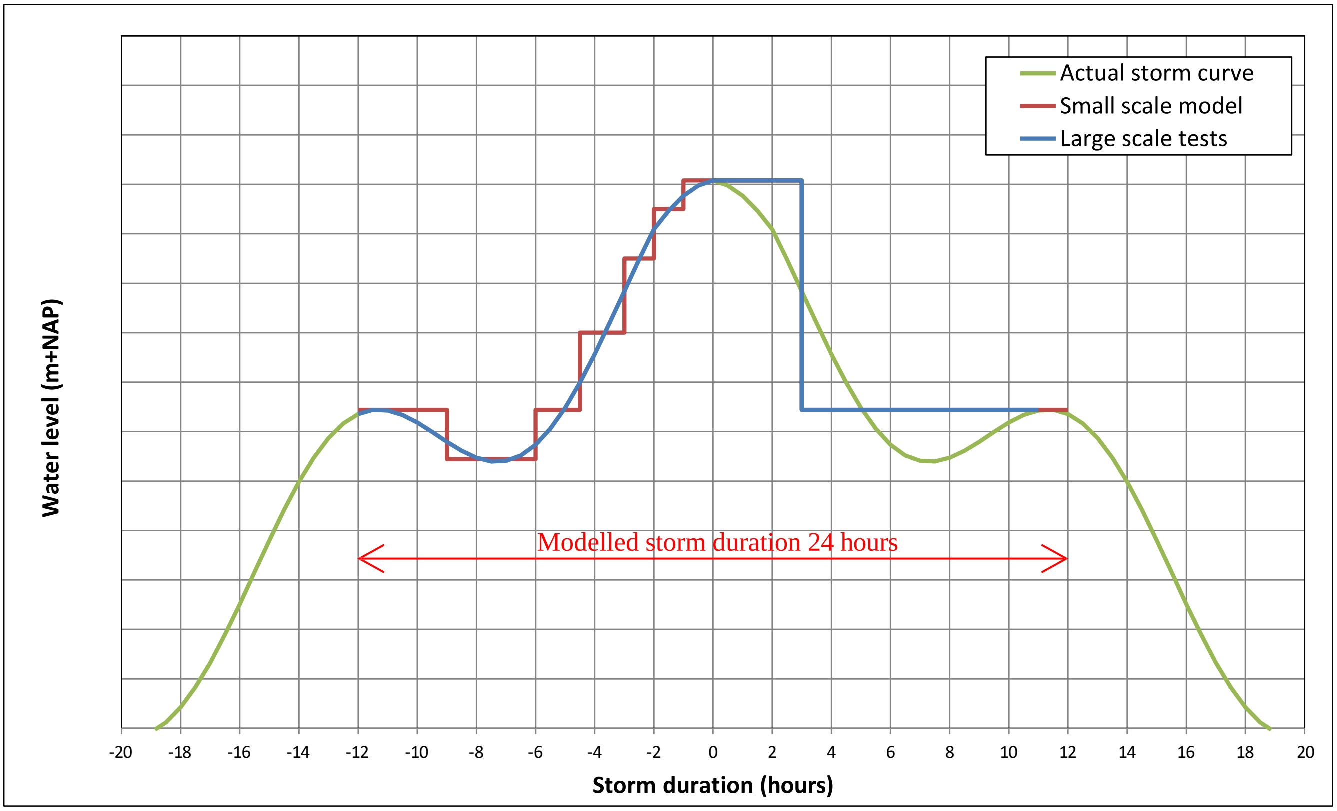

Figure 3-1. Modelled water level variations in small and large scale modelling

3.2 Stability

3.2.1 Quattroblocks® at upper slope

The stability of the amour layers has been presented in detail by Klein Breteler *et. al.* (2019). The stability of the protruded Quattroblock ribs on the upper slope of the dam is defined as the ratio of the rib height (D_{rib}) and the block height of the base column (D). The stability of the ribs in the zone of largest wave attack (lower part of the upper slope) is confirmed in case the clamping of the rib is at least 50% of the block height ($D_{rib}/D < 2$) and $H_{m0}/\Delta D_n < 15$. In the runup zone the clamping needs to be at least 40% ($D_{rib}/D < 2.5$). The test results have been presented in Figure 3-2. The rib heights have been designed larger on the upper slope to maximize the roughness in the run-up zone of the dam.

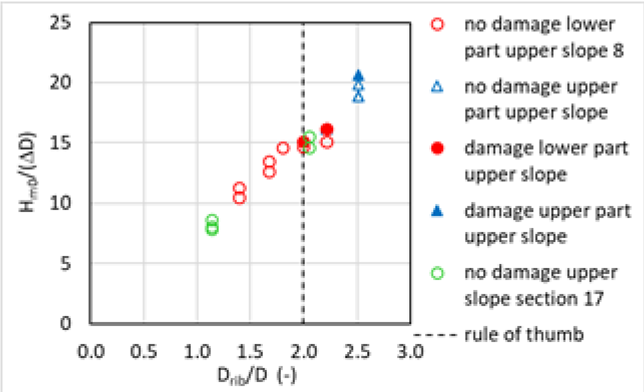

Figure 3-2. Test results Quattroblocks® and ribs above the berm as reported in Klein Breteler *et. al* (2019).

3.2.2 Levvel-blocs

All performed tests have shown no damage to the Levvel-blocs and Bermblocs on the lower slope. The design value of the stability number for Levvel-bloc is $H_s/\Delta D_n = 2.5$ (DMC, 2023). The large scale Deltaflume tests for Afsluitdijk show that stability numbers up to $H_s/\Delta D_n = 2.9$ (-) gave no damage for the tested design conditions. All results have been presented in Klein Breteler *et. al* (2019) and the test results are summarized in Figure 3-3.

The stability of the armour layers and the toe showed very similar results in the small scale and large scale physical model. No scale or model effects have been observed for the tested scales between 1:32.6 and 1:2.95.

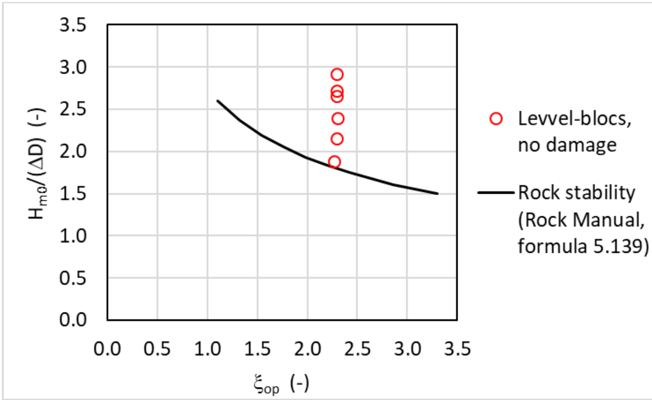

Figure 3-3. Test results Levvel-blocs as reported in Klein Breteler *et. al* (2019).

3.3 Overtopping

The wave overtopping measurements have been compared with Eq. 5.10 and Eq 5.11 from the EurOtop manual (Van der Meer *et. al.*, 2018) in Figure 3-4. The roughness coefficient, γ_f, for the Quattroblock ribs have been determined using the method described in Capel (2015). The model test results fit fairly well with the theoretical from Equation 5.10. The two outlying measurements indicated in the red circle are measurements with small ribs (5 cm in prototype), which are outside the range of applicability of Capel (2015). It appears that these very small ribs results in a very thin water layer on the slope, resulting in less roughness than expected.

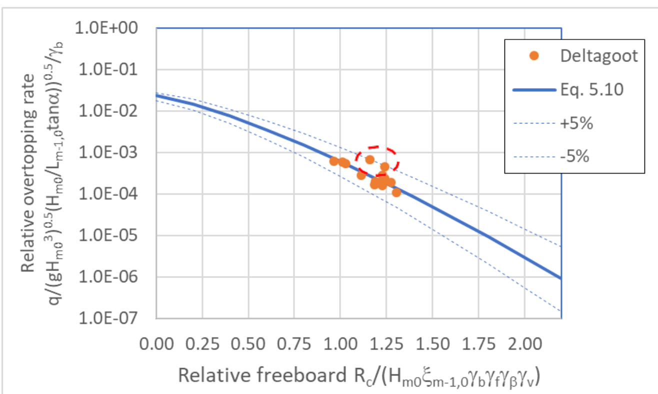

Figure 3-4. Test results wave overtopping as reported in Klein Breteler *et. al* (2019).

The wave overtopping results in small scale and large scale has been investigated by Jordans (2019). This study made a comparison of the measured wave overtopping in the small and large scale physical model. The small scale model resulted in lower measured wave overtopping than the large scale flume tests. The research work concluded that despite the available literature indicates no significant scale effects are to be expected, model effects had an influence on the results. These model effects could be caused by:

- The rougher behaviour of the ribs on the upper slope in the small scale flume might be caused by scale effects in the air entrainment. The water layer thickness of the run-up does not correctly scale from large to small scale.
- The squared edges of the ribs in the small scale flume result in detachment of the flow. This leads to energy reduction. Causing the upper slope in the Scheldt flume to act rougher.

As a result the remainder of the small scale tests have been performed with rounded edges of the ribs on the upper slope as indicated in Figure 3-5.

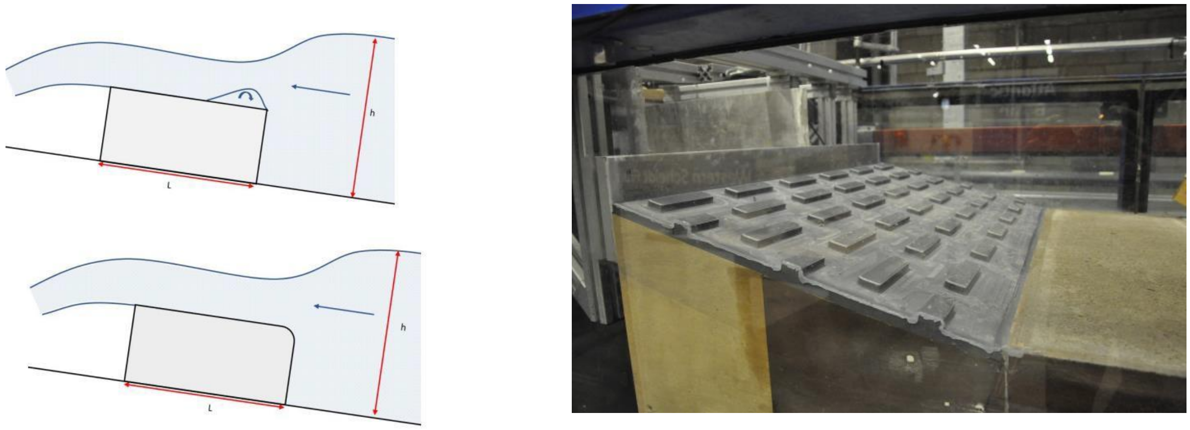

Figure 3-5. Left panel: model effect of the small scale model resulting in larger roughness than in reality; right panel, rounded ribs on the upper slope in the updated 2D small scale physical model

4 Lessons learned

The Afsluitdijk project used a large amount of small and large scale 2D physical model tests to measure stability and wave overtopping for the new design of the dam. The main lessons learned from these physical model tests for this project were:

- The combination of small scale physical model tests (optimising the cross-section) and large scale physical model tests (design verification) is an efficient way of working in case new innovative armour units will be applied. The small scale model is faster, but due to the smaller scale not all construction accuracies and tolerances could be incorporated.
- The acceptance criteria for wave overtopping and stability have been discussed and fixed prior to the start of the test campaign. This resulted in less discussion afterwards which lead to quicker acceptance of the design
- Applying varying water level was an advantage as the most critical combination of the stability of the toe can not always be correctly predicted based on the available design methods. Also the fact that the wave loads are not always at the same location gives a more realistic load situation
- (Large) scale physical model test are also a very strong tool to inform and convince (non-technical) stakeholders with regard to the impact of the design conditions and the need for the rehabilitation of the structure

The design verification of the innovative applications in the design of the new Afsluitdijk would not have been possible without the use of physical model tests, because with numerical hydraulic models we were not able to achieve comparable and validated results.

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