# INTEGRAL DESIGN OF HARD SEA DEFENSE OF MAASVLAKTE 2
# PART II: PHYSICAL MODEL TESTING OF CUBE REVETMENT & REEF

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## Abstract

In early 2013, the design and build of Maasvlakte 2 will be completed. This dual paper provides a retrospective on the design of the hard sea defense constructed between 2010 and 2012. Part I focuses on the re-use of material and constructability. Part II summarizes some physical model test findings of cube revetment and reef. The paper demonstrates the result of an integral design approach in which functional system-oriented requirements were verified by combining expertise on physical and numerical modeling, re-usability, and constructability.

## 1. Introduction

In early 2008, the Port of Rotterdam Authority ("PRA") awarded the design, build and maintain ("DBM") contract for the first phase of the seaward extension of the Rotterdam port area to PUMA, a joint venture between Boskalis and Van Oord. This mega marine construction project, known as Maasvlakte 2 ("MV2"), was to create around 2,000 hectares of harbor area in marine waters up to 18 meters deep, protected by a sea defense of approximately 11 kilometers long. The northern sea defense consists of a 3.6-kilometer cobble shore with a reef of concrete cubes on the foreshore. The key design features are a dynamic thick layer of quarried cobbles over a sand core and a robust foreshore reef made of re-used material from the Maasvlakte 1 ("MV1") sea defense. Figure 1 gives a bird's eye view of the MV2 reclamation.

Figure 1. Maasvlakte 2 with hard sea defense designed and built (cobble shore with cube reef).

Unlike traditional construction contracts, the DBM bid required PUMA to develop its own design, based on a system-oriented Program of Requirements (“PoR”). During the tender phase, PUMA elaborated on the PoR from the top-down in frequent dialogue with PRA’s experts. Simultaneously, the sea defense design was developed from the bottom-up by an integrated design team. The primary driver for the design of the hard sea defense was the re-use of the armor rock and concrete cubes from the superfluous MV1 sea defense section to be dismantled. The design was tailored to the estimated material re-use and constructability by reverse engineering. Physical scale model testing played a paramount role throughout the process of design optimization and verification.

### 1.1 Cube revetment

In hindsight, two design processes may be distinguished, each resulting in an optimized design for the hard sea defense that fully met the PoR. The first design process comprised the tender phase and concluded with the final bid design for amongst others the hard sea defense as shown in Figure 2. It consists of a berm-type sea defense, partly armored by re-used concrete cubes and partly by re-used armor rock. The bid design had to be verified through an elaborate Requirement Breakdown and Verification Matrix (“RBVM”) becoming a contract document.

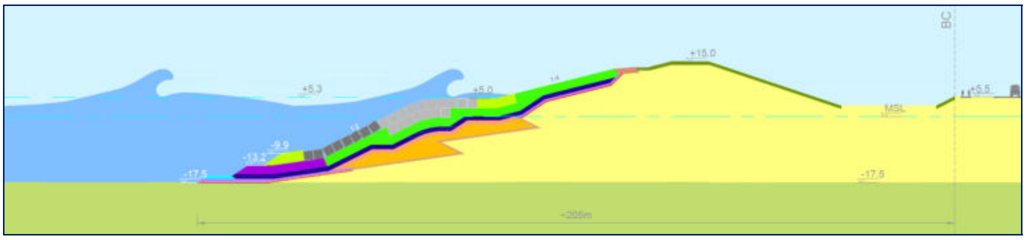

Figure 2. Design of hard sea defense (stepped cube revetment) of Start Contract I RBVM (2008).

### 1.2 Cube reef

The second design process started after the contract was awarded, partly in partnership with PRA (Loman, *et al.*, 2012). The starting point for further optimizations in partnership with PRA was the extension of the cobble shore that was envisaged as the transition between the original static-stable hard sea defense and the sandy beach. Increased insight into the physical behavior of the dynamic cobble shore, gained through physical scale modeling, culminated in a final design of a cobble shore with a robust cube reef on the foreshore (see Figure 3), replacing the optimized design of the 2.3-kilometer long cube berm revetment (see Figure 2) and the 1.3-kilometer long cobble shore (Loman, *et al.*, 2012).

Figure 3. Design of hard sea defense (cobble shore with cube reef) of Variation Order RBVM (2011).

### 1.3 User criteria

As mentioned above, both of the designs shown in Figures 2 and 3 fully met the PoR. The main user requirements, defined in the PoR and related to the hard sea defense, are listed below.

1. The hard sea defense must be stable against storm conditions having a return period ("RP") of 10,000 years with significant wave height increased by a factor of 1.1, and corresponding wave peak period and water level.
2. The hard sea defense must not need repair up to once-in-100-years storm conditions.
3. The hard sea defense must protect the harbor area of MV2 against wave overtopping:
   - q < 1 liter per second per meter during once-in-10-years storm conditions; and
   - q < 10 liters per second per meter during once-in-10,000-years storm conditions.
4. The wave reflection coefficient of the hard sea defense must not exceed 0.3 for prescribed unidirectional, perpendicular waves representing operational conditions.
5. The hard sea defense must have a lifetime of at least 100 years.
6. Uncertainties related to verification of the hydraulic stability of the hard sea defense by the prescribed physical scale modeling must be taken into account.

The setup of the physical modeling, the test conditions, the parameters to be measured were chosen to allow verification of the design of the hard sea defense against above criteria.

### 1.3 Physical modeling

Physical modeling was fundamental to both design processes. Model tests were done at three different hydraulic laboratories: HR Wallingford ("HRW"), Danish Hydraulic Institute ("DHI") and Deltares. Testing by independent, ISO 9000 certified institutes was prescribed by PRA as design verification method of stony sea defenses in the final bid and contractual requirements. Before verification, many scale model tests were carried out for the design optimization. This paper focuses on the 2D wave flume test for the concrete cube revetment as well as the cube reef, carried out at DHI and at Deltares. Functional tests on the cobble shore behavior (2D and 3D) were reported in two earlier papers (Loman, *et al.,* 2010a; 2010b).

## 2. Physical Model Set-up

### 2.1 Scale

A length scale $n_L$ of 54 was applied. For the water motion in free surface waves, Froude scaling was applied: the Froude number in model and prototype must be equal to preserve dynamic similarity. The Froude number is defined as Fr equal to $\sqrt{u/gL}$, where u (m/s) is the velocity, g (m/s$^2$) the gravitational acceleration and L (m) a length measure. From the Froude law the following scale factors, expressed in terms of the length scale factor $n_L$ as well as the water density scale factor $n_\rho$, can be derived. These factors represent the ratio of prototype values to model values, e.g.:

- wave height H (m): $n_H = n_L$
- wave period T (s): $n_T = n_L^{0.5}$
- armor mass M (kg): $n_M = n_\rho * n_L^3$
- overtopping q (l/s/m): $n_q = n_L^{1.5}$

The scaling of the hydraulic stability of the rock materials was achieved by ensuring that the stability number, $N_s$, was the same in the model and in the prototype. The differences in water density (salt water in nature and fresh water in model) and in the armor unit density are accounted for in this parameter. The stability number is defined as:

$$N_s = \frac{H_s}{\Delta D_{n50}} \text{ or } N_s = \frac{H_s}{\Delta D}$$

where Δ is relative mass density equal to $(\rho_a - \rho)/\rho$, $\rho_a$ the density of armor ($kg/m^3$), ρ the density of water ($kg/m^3$), $D_{n50}$ the nominal diameter of the armor units (m), D the cube rib size (m), and $H_s$ the significant wave height (m). Thus, the stability of the armor units is modeled correctly when the stability number in the model is the same as the stability number in the prototype. Using this relation, the required armor mass and armor size for the model, which is equivalent to a given prototype armor mass, can be calculated as:

$$n_D = n_L n_\Delta$$

The rock was modeled by natural stone. The density differences in water and rock between the model and the prototype were taken into account by slightly adjusting the grading. The size of the re-used cubes was modeled following the estimated weight and density distribution (Loman, *et al*., 21012). The density of the cubes was tuned such that $n_\Delta$ was 1. The Reynolds number based on wave height and armor size was high enough that the hydraulic stability was modeled well according to Dai and Kamel (1969).

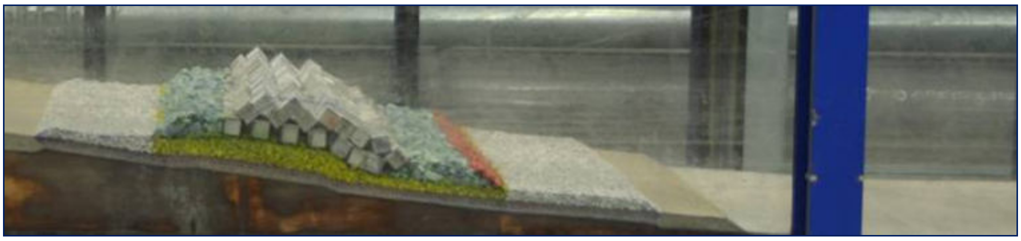

Figure 4. Side view of cube reef at model scale of 1 : 54 (“Scheldt Flume” at Deltares).

## 2.2 Cubes

First, the mass distribution of the cubes after 100 years’ lifetime was estimated (Loman, *et al*., 2012). Applying the above scale rules, these cubes were represented by newly cast model cubes with a rib size of 47 millimeters (2.54 meters in the prototype). The model cubes were manufactured by DHI and used in all of the small wave flume tests at DHI and Deltares.

Figure 5. Placement of model cubes according to a protocol that represents reality in prototype.

## 2.3 Model construction

The model construction was monitored by PUMA's construction experts, ensuring the placement of cubes and rock in accordance with the envisaged constructability constraints. The cube placement in prototype was done by a very large hydraulic crane (Loman, *et al.*, 2012). The degrees of freedom of this crane, and the possibilities for monitoring the movement of the cube, were copied to the construction of the model. Cubes were lowered at target positions and released when contact with the structure was made. Cubes that tilted or moved to an off-target position after release were not replaced in order to mirror the prototype placement procedure. As a consequence, the actual porosity and cube pattern of the structure were a function of pre-defined target positions based on a chosen distance between cubes in a row.

The above protocol resulted in irregularities in the placement pattern of the model cubes, which were accepted and subsequently included in the design verification. The importance of copying the placement method in the flume was recognized previously, e.g., by Medina (2010). To date, however, the relevance of the roughness of the rock under layer has not received much attention in publications. The tests presented in this paper show that placement pattern (i.e., the number of irregularities) of the cubes was mainly dependent on the roughness of the rock under layer. Therefore, the under layer was roughened by hand until a placement irregularity (standard deviation) of at least $0.4*D_{n50}$ was obtained, matching the envisaged constructability constraints. As the cubes were placed in a fixed pattern, the porosity and top-layer thickness were not regarded, as they are difficult to define for measurement. The geometry of the cube pattern in the cross profile, the number of cubes per meter of reef length (flume width), and the heights of the crest rows (average over the flume width) were the main parameters that were monitored.

## 2.3 Scheldt Flume and measuring equipment

Most of the 2D physical model tests were performed in the Scheldt Flume at Deltares. This wave flume is 2 x 55 meters long, 1.0 meter wide and 1.2 meter deep. The facility is equipped with a piston-type wave board for generating regular and irregular waves. The wave generator is equipped with online "Active Reflection Compensation". The profile of the rock under layers that extended from under the rock toe, as well as the crest elevation of the cubes, and the cobble shore profile, were measured using an automated mechanical profiler. Waves were measured using standard resistance-type wave gauges. The incoming and reflected waves were measured at the toe of the structure using a three-gauge array. The signals were processed using the Mansard and Funke (1988) method for determining the incoming and reflected wave signals.

Damage to the (cube) armor layer and the toe berms was measured. After each test, a photograph was taken of the test section from a fixed point above the structure. By comparing these photographs to a photograph of the initial situation, it was possible (using overlay techniques) to determine the damage number related to the number of displaced rocks or units. The results of this measurement are represented by this damage number $N_{od}$, the number of stones or units displaced from a strip with a width of $1.0*D_{n50}$ (rock) or 1D (units) (CIRIA, *et al.*, 2007):

$$N_{\mathrm{od}} = \frac{N_{\mathrm{displaced}} D_{\mathrm{n50}}}{W}$$

where $N_{displaced}$ is the number of displaced stones or units in a test section, W is the width of the test section, and $D_{n50}$ is the nominal stone diameter (or cube rib D in the case of a concrete block). In all 2D physical model testing the tested section width W was the flume width, representing 54 meters.

## 3. Test Results for Cube Revetment

### 3.1 Test program

To verify the stability of the cube revetment against the user criteria given in section 1.3, a test program was developed to measure:

- the wave reflection coefficient;
- armor stability (rock and cubes);
- toe stability; and
- wave overtopping.

Figure 6 shows the test program that was used to verify hydraulic armor stability and overtopping. The program consisted of a storm with RP of 100 years followed by a storm with RP of 10,000 years plus 10% extra wave height. The armor layer was not repaired between two storms. This met the requirement that the hard sea defense must not need repair up to a once-in-100-years storm. The peak value and time development of each storm condition were determined at the toe of the hard sea defense in accordance with the PoR. The testing included two steps of the storm onset, the storm peak, and one down set step, each lasting 3 hours.

For the verification, the uncertainties in the 2D flume tests were compensated in two ways:

- taking an additional test step with 5% wave height overshoot into account (see Figure 6); and
- applying safety factors of 1.5 (slope) and 2.0 (toe) to the damage number.

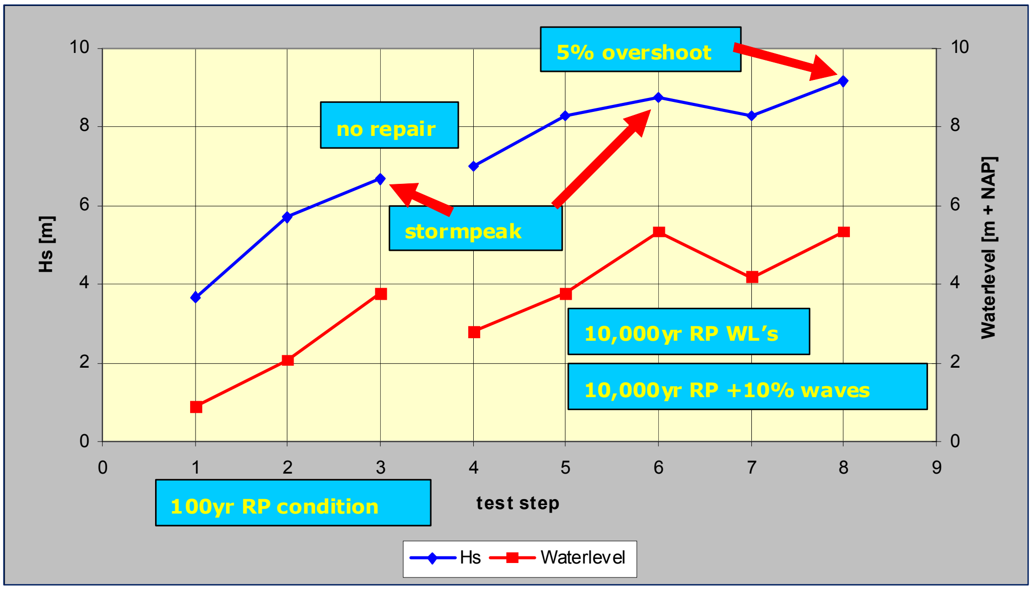

Figure 6. Summary of test program for verifying hydraulic stability of cube revetment of hard sea defense.

### 3.2 Hydraulic stability criteria

To allow for a quantitative verification of the user requirements with respect to stability, an agreement was reached with PRA regarding a set of damage criteria to be used in combination with the test results.

As for the cubes, distinction was made between:

- cubes placed in a double layer: $N_{od}$ * safety factor < 2.0; and
- cubes placed in a single layer: $N_{od}$ * safety factor < 0.2.

The damage number $N_{od}$ was measured:

- for the cubes in a double layer, by counting the number of cubes with a displacement exceeding the cube size D; and
- for the cubes in a single layer, by counting the number of gaps exceeding the size of one cube, increased by the number of missing cubes.

### 3.3 Results

The flume tests carried out at both DHI and Deltares allowed for considerable design optimization. At first, test results were used to tune the armor layer stability - expressed in armor grading, cube placement density and construction geometry - with the actual hydraulic loads. Then the design adjustments to optimize constructability and material re-use were verified against the hydraulic stability criteria.

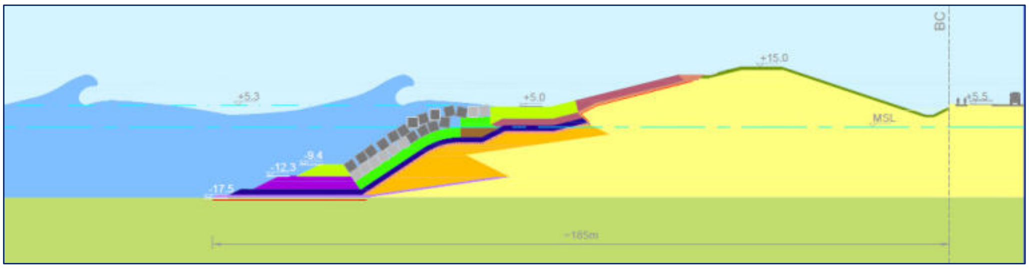

Figure 7. First bid design of static-stable hard sea defense (2006), to be tested in a physical model.

Figure 7 shows the design of the hard sea defense at the start of the test program. The key elements of this design were:

- the lower slope fully covered by a double cube layer;
- placement density with 0.4*D distance between cubes;
- rather steep 1v in 1.5h slope, considered to be necessary for cube stability;
- berm 30 meter width to reduce the wave loads on the upper slope;
- rather heavy armor layer of 6-10 ton on toe and berm;
- rather light armor layer of 1-3 ton on the upper slope; and
- crest elevation of 15.0 meters above Mean Sea Level ("MSL") to meet overtopping requirements.

Comparison of Figure 7 with the final bid design as shown in Figure 2 reveals that the following optimizations were achieved by physical model testing during 2008:

- Instead of a double layer of cubes, a partly single composite cube layer could be used.
- A distance of 0.4*D to 0.5*D between cubes appeared to be optimal with respect to stability and reflection coefficient.
- A 1v in 2.0h slope (less steep) was required to meet the reflection criterion.
- A berm 15 meters width (narrower) was sufficient to reduce wave loads.
- Re-used material was introduced in the upper slope and in the berm.
- A lower crest elevation of 13.7 meters above MSL was achieved.

- An interesting design concept for the toe (1-6 ton with dynamic toe protection) was successfully verified (see Figure 8).

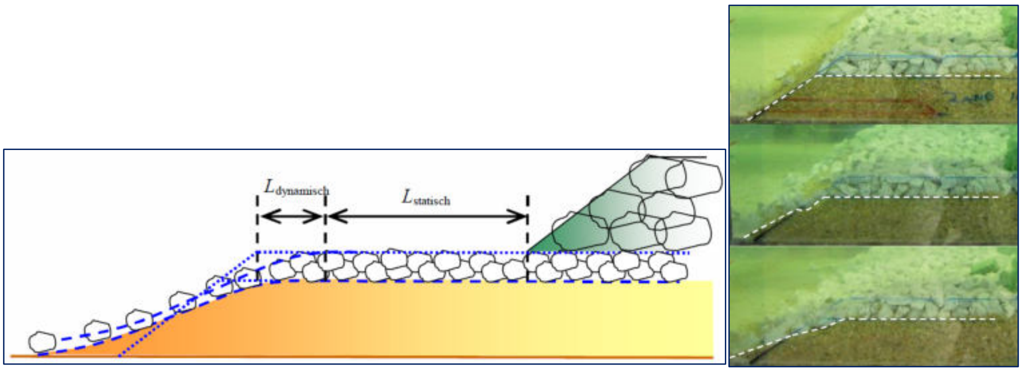

Figure 8. Toe structure of hard sea defense with 1-6 ton top layer and dynamic toe protection.

Verification of the toe structure shown above involved two criteria:

- The static part of the toe (indicated with Lstatic) must meet the stability criteria that apply to standard toe structures.
- The dynamic part of the toe is allowed to re-shape it but must reach a stable non-progressing shape during the test program.

## 4. Test Results for Cube Reef

### 4.1 Test program

The main functional requirement for the cube reef (see Figure 3) is to guarantee the wave transmission conditions as considered in the verification of:

- the year-round nourishment and recycling of the cobble shore due to along-shore losses; and
- the dynamic stability and wave overtopping of the cobble shore during the design storm.

To verify the stability of the cube revetment against the user criteria given in section 1.3, a test program was developed to measure:

- the hydraulic stability of the cubes;
- the hydraulic stability of the armor rock of seaside toe and landside toe; and
- wave transmission over/through the reef.

For the verification, the uncertainties in the 2D flume tests were compensated for by:

- testing cumulative damage after three storms with RP of 100 years, 10,000 years at low water and 10,000 years at high water plus 10% extra wave height peak with 5% wave height overshoot (see Figure 9);
- applying a safety factor of 1.5 to the damage number;
- testing basalt-type cubes (see dark grey cubes in Figures 3 and 10) as gravel-type cubes; and
- testing under layer damage with an extra test equal to test step #19 with 2 cubes removed.

Verification was based on the cumulative damage after the full sequence of the three storms shown in Figure 9. This resulted in a conservative verification with respect to load duration.

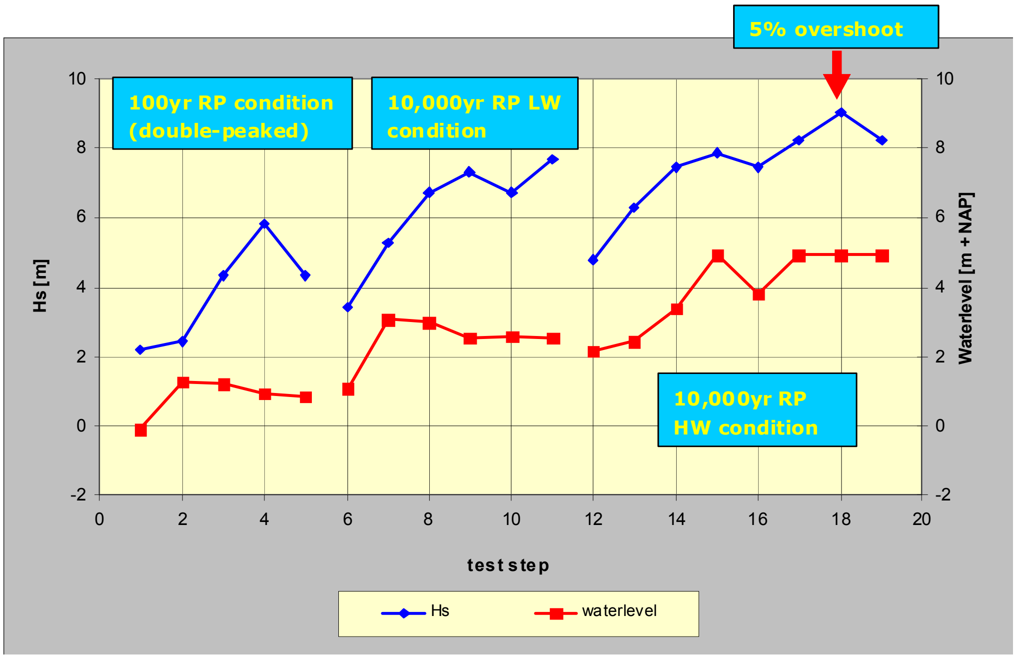

Figure 9. Summary of test program for verification of hydraulic stability of cube reef.

### 4.2 Hydraulic stability criteria

The wave-damping function of this cube reef was verified with the following cube stability criterion as agreed with PRA: Nod * sf < 1.8 (total damage of crest, front slope and rear slope). This criterion had to be met for the cumulative damage after test #19 (see Figure 9). The damage number $N_{od}$ was measured by counting the number of cubes with a displacement exceeding the cube size D.

### 4.3 Results

There were far too many results to present in this paper. Alternative reef configurations were developed, tested, optimized and improved by an integrated design team. This process was concluded with two successfully tested and verified alternative reef structures (see Figure 10):

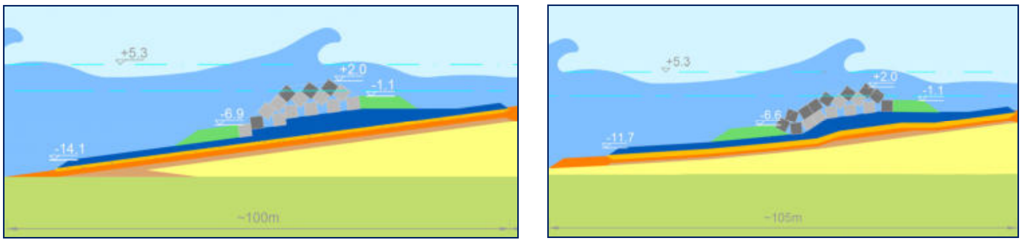

Figure 10. Cube reef profile 1:54 scale tested with staircase toe (left) and gutter toe (right).

- A reef characterized by a "staircase toe" of the cube profile, consisting of 15 cubes per 3.5 meters of reef length with an armor rock toe at 6.9 meters below MSL. Here, the armor stone adjacent to the staircase toe was placed after the cube toe row.
- A reef characterized by a "gutter toe" of the cube profile, consisting of 17 cubes per 3.3 meters of reef length with an armor rock toe at 6.6 meters below MSL. Here, the seaward armor stone toe forming the gutter toe was placed before placement of the cubes.

## 5. Conclusions

Apart from many findings and conclusions of scientific interest, the main conclusion worth presenting here is that important aspects of physical modeling were identified because of the specific setting of the tests as a prescribed verification method. These aspects include:

- tuning model construction to construction methods that were actually foreseen;
- compensating for different sources of uncertainties by overshoot testing;
- translating functional requirements into quantitative hydraulic stability criteria; and
- verifying the as-built cube pattern against the cube pattern tested (see Figure 10).

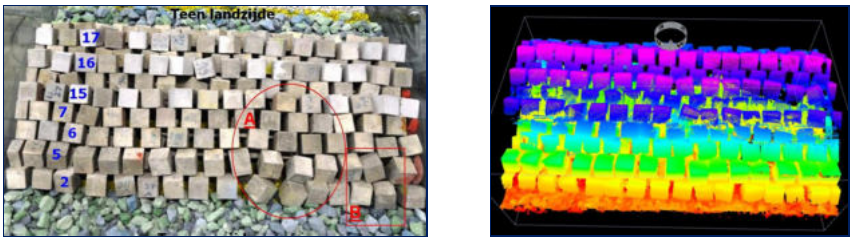

Figure 10. Cube pattern 1:54 scale tested in Scheldt Flume (left) versus cube pattern as-built and surveyed in 2011 in prototype (right).

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