Investigation and Simulation of Failure Mechanism of a Port Basin Revetment, Generation of Remediation Design and Re-construction Works

Eelco Bijl, CDR International, Amersfoort, The Netherlands
Jentsje van der Meer, Van der Meer Consulting bv, Akkrum, The Netherlands
Flavia Bonfantini, CDR International, Amersfoort, The Netherlands
Steven te Slaa, CDR International, Amersfoort, The Netherlands

Abstract
Within two to three years after completion the revetment of a Port Basin in south-east Asia, see Figure 1 for a representative cross-section, showed unexpected displacements of concrete interlocking units, resulting in gaps in the armour facing around the waterline. To understand this failure of the armour facing and determine an effective remediation solution, a failure investigation and remediation design study has been performed by CDR International BV, including high-accuracy survey of the revetment works, local site investigations and 2D physical model testing. This 2D physical model testing included the actual simulation of the failure mechanism and testing of alternative remediation designs.

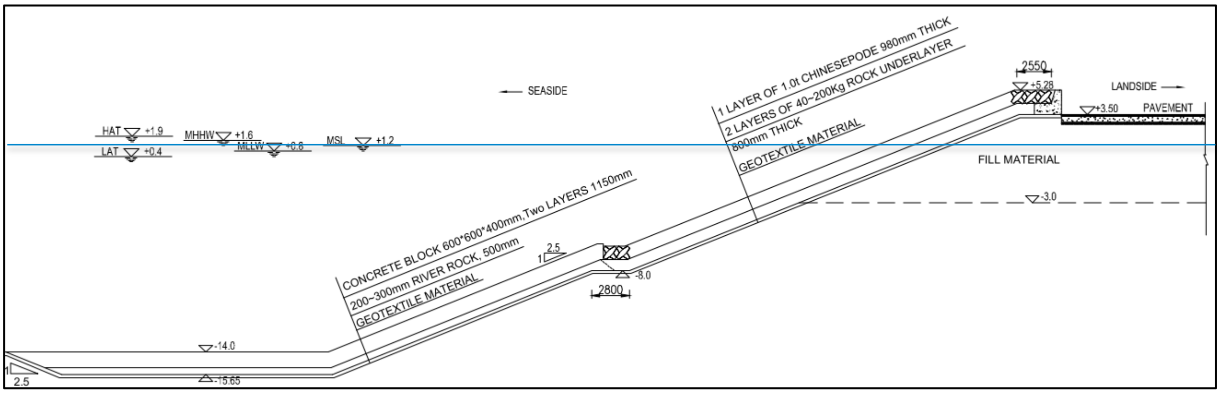

Figure 1 – Representative cross-section design of the Revetment of the Port Basin

Results from the simulation of the actual situation were similar to observations in reality, which proved that 2D physical model testing could be used to investigate and verify the optimum remediation design. As the port was located in a seismic active area the revetment slope was 1:2.5. No design formulae are currently available for the design of single layer interlocking concrete elements on such a slope. The testing of different options included the application of a second (double) layer, interlocking re-construction from different depths and the filling of gaps in deeper parts of the revetment.

The selected remediation design consists of removal of sediment covering part of the revetment, removal of concrete units up to a certain depth, trimming of the underlayer and re-placement of the concrete units to obtain effective interlocking with neighbouring units. Construction of the remediation works for 1.1km of revetment has started end of July 2016 and was finished early January 2017. Construction works were performed using specialised placement equipment and involvement of some construction specialists.

Lessons learnt from the project show the importance of proper documentation and communication between the design process and construction preparations. The experience and knowledge is different between designer and contractor and because of that the intention of the design and important design aspects were not correctly interpreted or handled during construction. For correct construction a clear design with specifications, tolerances and requirements are required, to be translated into a detailed Method Statement with corresponding Inspection and Test Plan. Such a Method Statement should be feasible and show how the design can be constructed in reality in accordance with the given requirements and specifications, e.g. by the use of specialised equipment.

Background

Within two to three years after completion, the revetment at a Port Basin in south-east Asia showed unexpected displacements of concrete interlocking units, resulting in gaps in the armour facing around the waterline. The original design of the revetment consisted of 1-3t rock protection on a 1:2.5 slope and for less exposed areas 300-1000kg rock on a similar slope. The gentle slope of 1:2.5 was required because of the seismic active location. Due to lack of suitable rock in the nearby area the selected contractor proposed an alternative design using relative small, 1.0 ton concrete interlocking elements in a single layer, while maintaining the 1:2.5 slope, however. For the less exposed areas so called 'Hollow Blocks' were applied as armour above MSL. These are in fact concrete slabs with local orifices and 4 legs on the corners (both top and bottom). Displacements of both concrete blocks were mainly visible around water level, which means also below water level displacements of units were to be expected.

During construction the independent supervisor of the works had instructed the contractor to place all interlocking units (originally to be random placed) in a regular pattern above the mean water level. This resulted in a transition between random placement and regular placement exactly at the waterline.

As the Contractor would bear all costs of the remediation works, the remediation design should re-use as much material as possible, manufacturing of additional construction material should be minimized or avoided and the work itself should remain practical to minimise construction costs. Still the remediation design should function correctly and should be accepted by the client and his technical consultant.

Outline of This Paper

This paper describes all elements of the remediation works, starting at the initial investigation of the damaged revetment, analysis of possible failure modes, physical model testing including generation and optimization of remediation designs and the execution of the remediation design works.

The paper describes a state-of-the art method to gather high detailed data and information on the actual state of the damaged works and provides interesting insights on the behaviour of concrete interlocking units on a gentle slope and the stability of a double layer of single-layer units.

Site Investigations

To assess the damage of the revetment and obtain vital data for a reliable failure investigation and remediation design study, a site investigation study was performed first. This investigation study included visual site inspections (above water), removal of armour and underlayer material to assess layer thicknesses and actual rock gradings and a high detail survey of the facing above and below water level. Especially below water level the armour facing of the revetment should be properly visualised to be able to determine the extent of damage and actual positioning of the concrete units. This was combined with a detailed topographic survey to analyse the current revetment profiles in relation to the original design as geotechnical instability due to seismic events could be one of the failure mechanisms.

Site inspections

Site inspections were performed by experts both from land and from the water in order to visually inspect the damage of the revetment. It was clear that the concrete units were mainly displaced below the transition between random and regular placed units. It was also visible, just below water level, that several random placed units were not within the original design slope anymore. This can for example clearly be seen in Figure 2.

Figure 2: Images of the damage obtained during site inspections

Small rocks, gravel and sand material were visible in the 40-200kg underlayer above Mean Sea Level, which raised the question which grading was used for the actual underlayer. To further investigate the actual construction in relation to the design, a number of armour units were removed at random locations after which the underlayer thickness was measured and samples were taken to measure the underlayer grading. A wider grading than design was used, however still including large rocks. Part of the smaller material was added later during construction by mistake. The results of this analysis have been included in the physical model testing to accurately represent reality. Results furthermore showed that above water the underlayer was partly filled with sand, which was mainly caused by high concentration of sediments in the water and continuous sedimentation of the revetment due to various processes.

Bathymetric and topographic high-detail survey

A high-accuracy combined bathymetric and topographic survey was performed to visualise the current state of the completed revetment with high detail and to enable further analysis of the revetment and its single units. The current state of the underwater facing needed to be visualised to investigate the cause of the unexpected settlements; e.g. to check interlocking placement, the slope stability and possible other defects. Due to heavy turbidity of the water a dive survey could not be performed and a high-detail bathymetric survey was the only option.

The bathymetric survey was performed using a dual multi-beam system where the sonars were placed at an angle and pitched to minimize blind spots, providing high detail data and highly accurate images of the armour facing below water level, see Figure 3 for an example. Both sonar heads were tilted 45 degrees sideways and each pitched 10 degrees, fore and aft looking, to reduce the amount of shadow between the blocks. Analysis of the cloud of actual survey data points (without any interpolation) provided the best visualisation of the underwater facing, see Figure 4 for an example. The technology to survey the features above water level is by the use of photogrammetry. More information on the survey can be found in Van de Sande et al. (2016).

Survey results indicated that concrete units were placed at random but without interlocking. This resulted in areas with units placed on top of each other, and areas with gaps in the armour facing. Also the lack of interlocking between units seriously affected the overall stability and it was expected that units were able to move along the armour facing. Analysis of the survey results plotted on top of the design showed that the original 1:2.5 slope is almost intact, which means no geotechnical failure due to sliding or seismic activity had occurred.

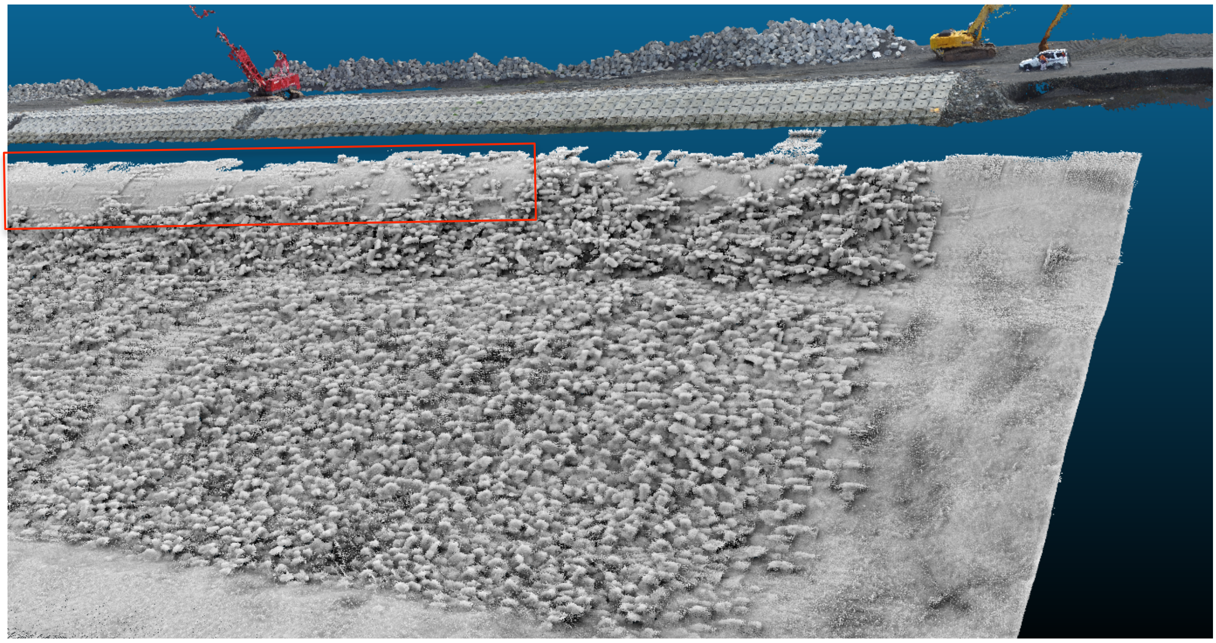

Figure 3: Snaphot of the 3D model built from the combined drone (above water) and multibeam (below water) survey, showing small cubes on the lower part, concrete units on the upper part and quite some siltation (red rectangle).

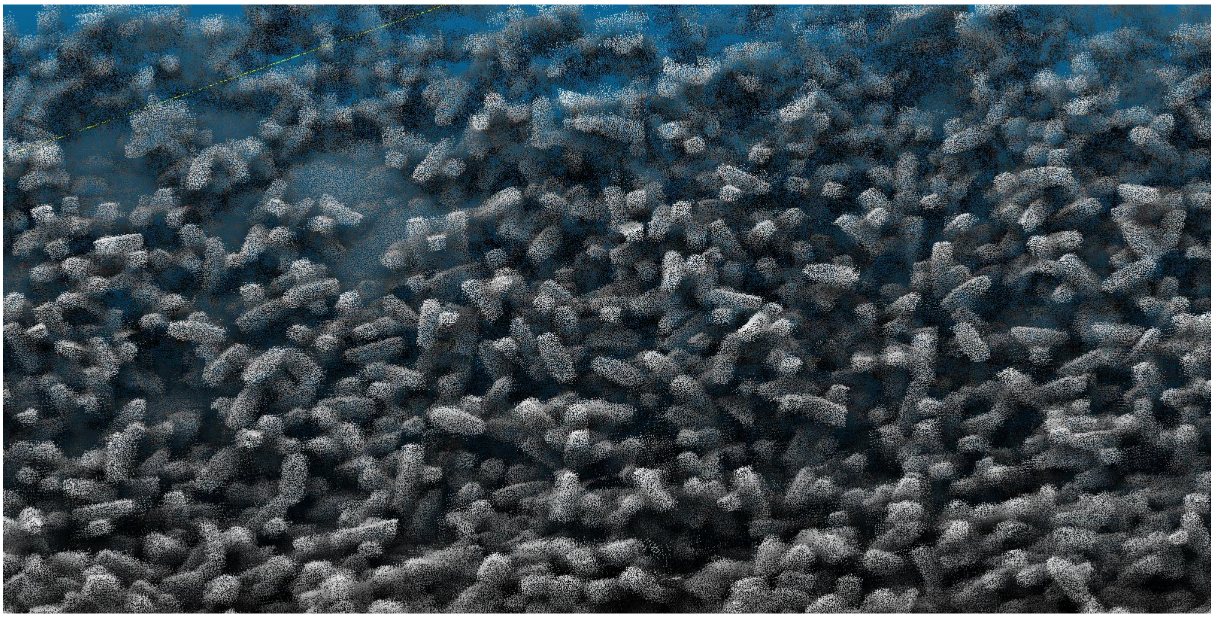

Figure 4: Zoomed snapshot of individual units, made visible by the detailed bathymetric dual multi-beam survey

Physical model testing and remediation design study

The remediation design study was combined with and fully based on the 2D physical model testing study, as the design parameters for this case lie outside the range for which available design formulae for concrete interlocking units have been developed. The 2D model testing campaign started with the simulation of the actual situation, after which remediation designs were generated using the knowledge and information obtained from the first 2D model testing results. The goal of the design study was to determine a remediation design which proved to remain stable, while costs for the remediation works were to be minimized for the contractor.

Model tests were performed in the wave flume of INHA, Barcelona, having a length of 52m, width of 1.8m and depth of 2.0. Because of these dimensions a scale of 1:15.7 could be applied. The wave generator produced irregular waves based on a JONSWAP spectrum and has active wave absorption to compensate for wave reflection. The model has been scaled according to Froude similarity.

In the model testing result figures the Mean Sea Level (MSL) has been indicated by a dashed black line. In the lower part of the figure beige blocks can be seen, this is the transition to the 'concrete blocks' part of the Revetment around -6.0m CD (refer to the design in Figure 1)

Simulation of the failure mechanism – 'Actual Situation' test

The actual situation to be tested, just after construction 2 to 3 years ago, was based on results and information obtained from the site investigation study. To simulate the failure mechanism, the as-built structure has been reconstructed in the model to represent reality as accurate as possible. This included the actual placed underlayer thicknesses, used rock gradings, filling of the underlayer with sand and actual placement of the concrete units: randomly dumped without interlocking.

The 'Actual Situation' test to investigate and verify the expected failure mechanism was then performed using extreme yearly wave heights as occurred in reality. Results of the physical model testing showed similar unit displacements as observed in reality, see Figure 5 for comparison. Units rolled down the slope resulting in a gap around and just below the water level (MSL). It was furthermore clear that non-interlocking units started rocking heavily under high wave conditions and free-lying or extracted units started to roll up and down the slope. This shows that under non-extreme conditions the concrete units are unstable when not interlocked. As soon as a unit is outside of the Armour layer it behaves like a rock. The single-layer 'interlocking' armour layer is not 'self-healing' in this case as downward pressure from upper units is (almost) not present.

It is noted that in reality waves arrive oblique at the structure, which is not included in the 2D model test. Consequently the run-up and run-down is much higher in the model testing, which resulted in significant displacements of the pattern placed units above water level which has not occurred in realty. Therefore these units have been re-placed in their original regular pattern after the 'actual situation' test.

The actual situation test showed that the 2D physical model sufficiently represented reality and that remediation design options could be tested, mutually compared and verified by means of 2D physical model testing.

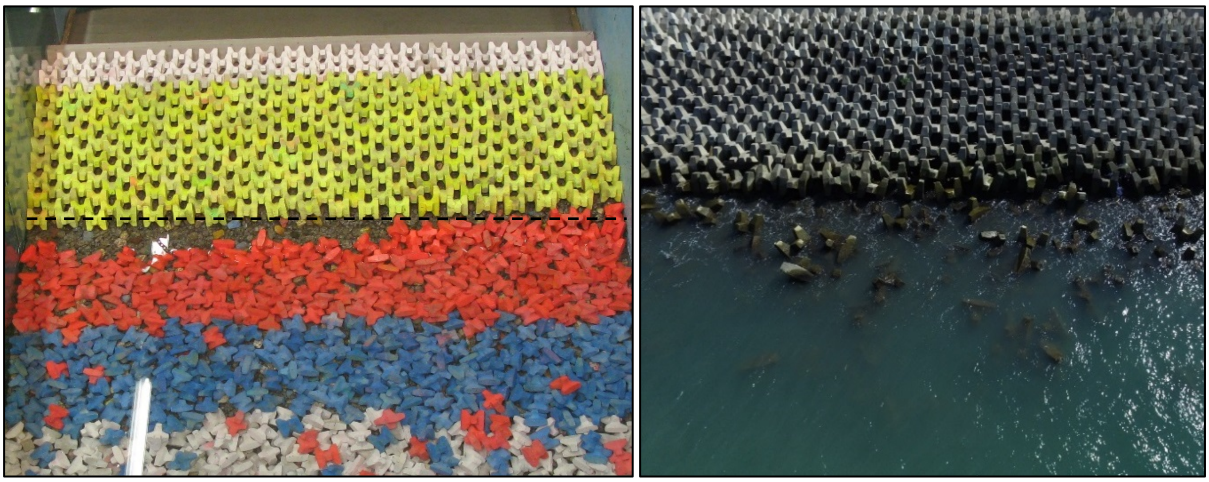

Figure 5: Comparison between simulation of the 'Actual Situation' and the Actual Situation in reality

Remediation design study by physical model testing

During the site visit and first model tests possible remediation designs were derived. The two main options were: 1) add a second layer of units to obtain a double-layer system (same as for Tetrapods), and 2) removal and interlocking re-construction of the 1.0 ton concrete units. The advantage of the first option was that construction works were practical and could be done using the available equipment on site. The solution however requires a large number of additional units to be manufactured and placed in the works; it has to be noted that a large number of additional units was already available on site. The second solution requires almost no additional units to be placed in the works, but it requires specialised placement equipment and preferably experienced staff to place the units. Also construction time was expected to be longer than for option 1.

The functioning of both options was difficult to predict based on available formulae as interlocking elements have never been used in a double layer, the 1:2.5 (gentle) slope is never applied and the 1.0 ton units were theoretically only marginally stable. This means that the theoretical ‘safety factor’ was reduced significantly. Correct placement of the underlayer and units is then essential.

For both options different model tests were performed to optimise the number of additional units required for construction or to optimise the number of units to be removed and re-placed. For construction reasons also model tests were performed for an incorrect placed underlayer and the stability of gaps simply filled with units (non-interlocking) in deeper water. The list of performed tests is presented in Table 1.

Except for tests 2 and 3, the armour facing was removed and replaced before each tests after which yearly waves were generated in the flume to simulate the ‘actual situation before remediation works’, similar to test 1. This was called ‘settlement test’.

Table 1: Summary of model tests

Test no.	Name	Remarks
Test 1	Actual Situation	Reproduction of occurred conditions
Test 2	Remediation T1 Exposed	Loosely packed 2-layer solution from -4.5m CD to +2.5m CD
Test 3	Remediation T2 Exposed	Interlocking re-construction above MSL - no model reconstruction
Test 4	Remediation T3 Exposed	Interlocking re-construction above MSL - including model reconstruction, bad underlayer and gap filling in deeper waters
Test 5	Remediation T4 Exposed	Interlocking re-construction starting at -3.0m CD
Test 6	Remediation T5 Exposed	Interlocking re-construction above MSL - including gap filling in deeper waters
Test 7	Remediation T6 Exposed	Tightly packed 2-layer solution from -3.0m CD to +1.5m CD
Test 8	Remediation T7 Exposed	Interlocking re-construction starting at -3.0m CD
Test 9	Remediation T1 Sheltered	Interlocking re-construction from -2.0m CD
Test 10	Remediation T2 Sheltered	Normal-packed 2 layer solution using interlocking units
Test 11	Remediation T3 Sheltered	Interlocking re-construction from -1.0m CD

Depths mentioned in the above and below tables are measured at the top of the underlayer / bottom of the armour layer. Results of the physical model testing are summarized in
Table 2. The double layer solutions showed significant displacements of units which rolled up and down the slope under higher waves. Although the design could be considered stable, as the original 1st layer remained in place, a lot of units would break in reality. Also, a remediation solution which shows ‘visible damage’ after a storm cannot be considered attractive and would not be preferred by the client.

Tests 4, 6 and 7 are considered to have ‘failed’ as sufficient protection of the original layer was not achieved. In both tests 4 and 6 the failure started between -1.0m CD and -2.5m CD, where units were not re-constructed in an interlocking way (they remained in place). Visual observations indicated the wave trough of the highest waves reached -3.0m CD as maximum; hence the damage started above this level. Gaps in the original armour facing below -3.0m CD were simply filled by units, and not iin an interlocking way, remained stable during design and overload conditions. This showed that reconstruction from -3.0m CD upwards was expected to be sufficient, which was then validated by the 2D physical model testing.

Table 2: Summary of model test results

Test no.	Description	Result
Test 1	Actual Situation	Observed settlements similar to reality.
Test 2	2-layer solution	Significant displacement of 2nd layer units, 1st layer remained fully in place and the revetment remains functioning.
Test 3	Interlocking from MSL	Armour remained stable, probably due to significant settlement during first 2 tests.
Test 4	Interlocking from MSL, incl. underlayer and gaps	Failure or Revetment between -1.0m and -2.0m CD. Gaps in deeper water remained stable.
Test 5	Interlocking from -3.0m	Revetment remained stable, only limited rocking of units.
Test 6	Interlocking from MSL, incl. gap filling	Failure / large displacements of the Armour facing between -2.0m CD and +1.0m CD. Filled gaps remained stable.
Test 7	2-layer solution, smaller area	All units rolled down, some units were extracted from the 1st layer. This means failure.
Test 8	Interlocking from -3.0m	Revetment remained stable, only limited rocking of units. Tests was done again as the Client visited the Flume.
Test 9	Only gap filling	Revetment remained stable.
Test 10	2-layer solution	Most units rolled down the slope. 1st layer remained stable.
Test 11	Interlocking from -1.0m	Revetment remained stable.

Results from tests 2, 6 and 8, which are most interesting to present here, are shown in Figure 6 to Figure 8 respectively. In all these figures the left figure is the revetment state at start of the stability model testing, so after the settlement tests and remediation works. The right figure shows the revetment state after the overload condition or after failure.

Figure 6 shows the model testing results for the double layer solution. Placement of the units is loosely packed, simulating easy and practical placement. Above water the placement density is higher. Due to the large depth of the original berm in the design, acting as toe for the concrete blocks, the units are placed until -4.5m CD only which means there is no toe support for the second layer. This influences stability significantly as can be seen in the right figure: most of the units rolled down the slope and also above water level units rolled down. The second layer acted as resilience for the first layer, which is still in place. In reality, however, there would be significant breaking of units which makes this option unacceptable. Also aesthetically this solution is not attractive. Concrete interlocking units clearly need to interlock in a single layer to function properly.

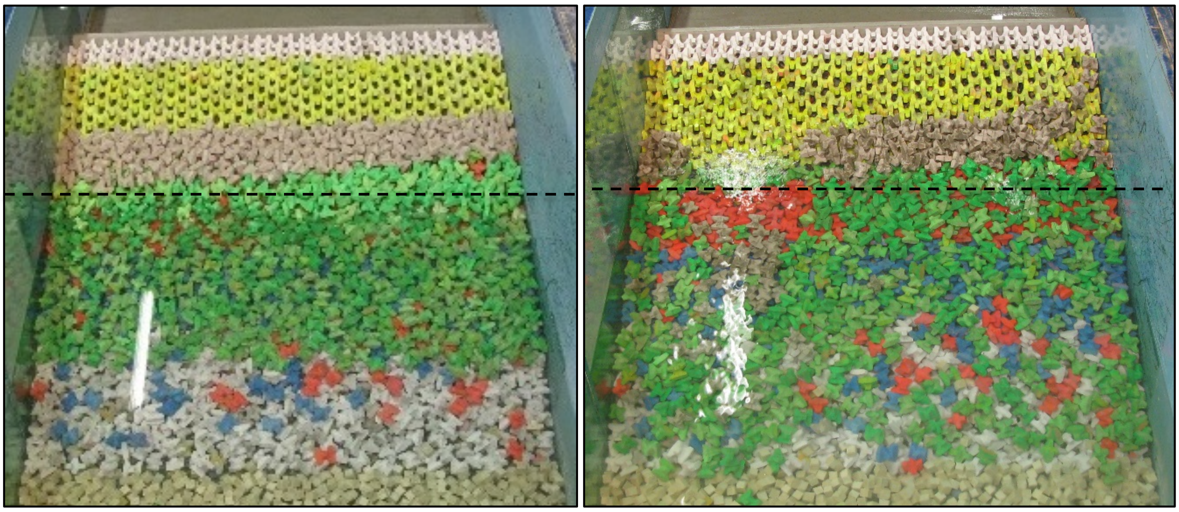

Figure 6: Results before (left) and after (right) testing of the 2-layer solution

Figure 7 shows the results for model test 6: re-construction works from -3.0m CD. The grey units inside the red and blue band are units placed in ‘gaps’, so without any interlocking. As can be seen in the right figure the failure started around the red band, which is between -1.0m and -3.0m CD. Failure did not start at the location of filled gaps, filling gaps therefore has no significant influence in stability (this has been confirmed in another test as well). A large number of units below the MSL line rolled down, leading to the eventual failure of the armour facing. Correct interlocking of the facing just below water level is hence essential for proper functioning of the structure.

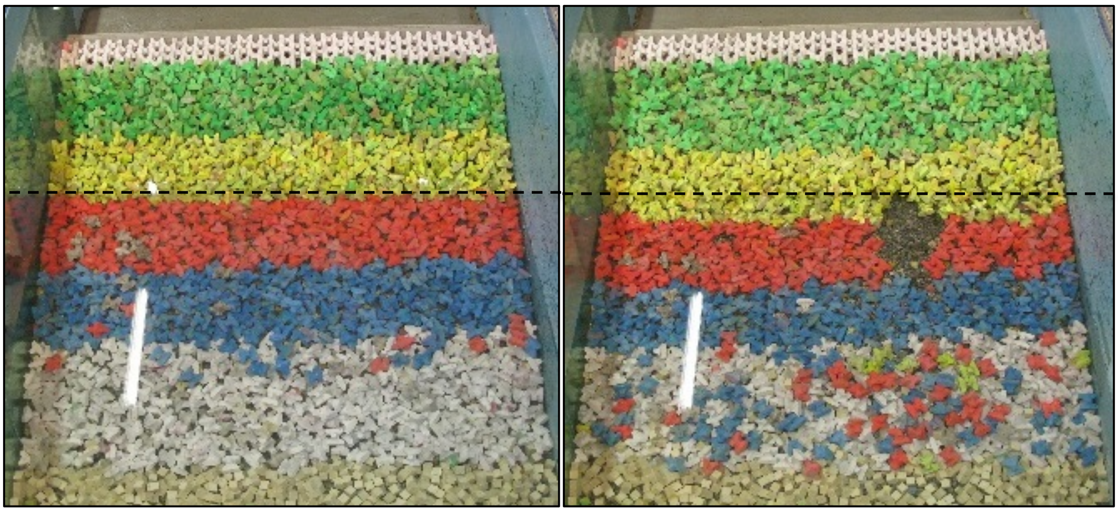

Figure 7: Results before (left) and after (right) testing of the re-construction from MSL solution

Figure 8 shows the model testing results for the eventual remediation solution: re-construction from -3.0m CD upwards. This level has been selected as failure started in the area between -1.0m and -2.5m CD and it could be visually observed that the wave trough of the highest waves reached the approximate level of -3.0m CD. This means that the largest wave forces due to run-down were exerted on the area until -3.0m CD. Below this depth the wave forcing is still present, but not significant enough to extract units from the armour facing.

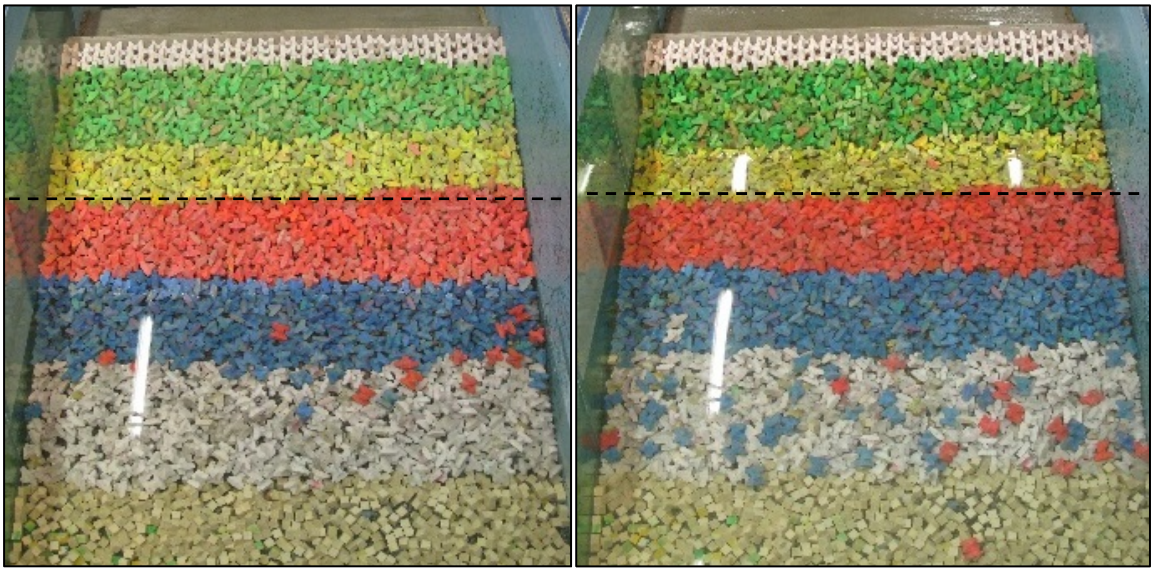

Figure 8: Results before (left) and after (right) testing of the re-construction from -3.0m CD solution

Final remediation design and construction requirements

The selected design was to remove all units above -3.0m CD, profile the underlayer into a smooth layer and to re-construct in an interlocking way the removed units. Special attention was to be paid on a proper and interlocking transition between units remaining in place and re-placed units. Locally along the Port Basin Revetment the re-construction depth was optimized at more sheltered locations or areas with continuous sedimentation of the armour facing. Here the minimum re-construction depth could be reduced to -1.5m CD. Along the most sheltered area, where the Hollow Blocks were used above MSL, re-construction from -1.0m CD was selected as remediation design. Due to significant sedimentation near and inside the basin, sediment was to be removed first from the revetment armour before re-construction works could be performed. An example of the final remediation design is visualized in Figure 9.

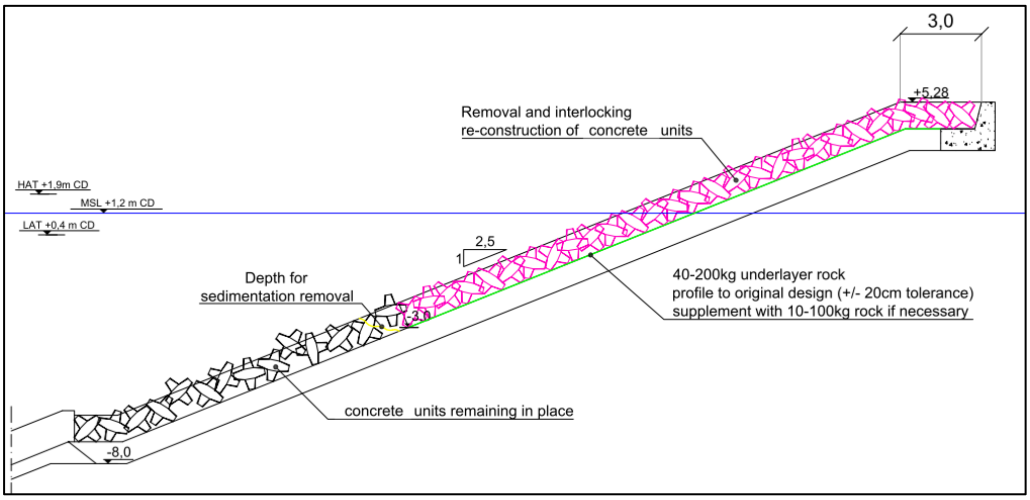

Figure 9: Drawing of the final remediation design

The design was accompanied with clear construction specifications, tolerances and requirements. The main construction requirements included: clear underlayer tolerances to achieve a sufficiently smooth underlayer for interlocking placement, placement requirements and practical guidelines for the interlocking placement of the concrete units, specialised placement equipment (excavator), experienced operator for the excavator and independent checking of the interlocking. Criteria were set for the training of staff on site, both local staff, foreman, divers as well as crane and excavator operators. It was decided by the client that CDR International, involved in the investigation and remediation design study, would remain involved during construction to support the contractor in drafting the Method Statement, Inspection and Test Plans (ITP's), to provide support during construction and to perform the Quality Control.

Due to this set-up the design requirements could be updated or fine-tuned during the construction works based on increasing insight of practical construction works, actual survey results (e.g. of the underlayer) and experience of the site personnel. Eventually, construction of the remediation design should be *practically feasible* to be performed using the available equipment and personnel on site.

Construction of the Remediation Works

Construction of the remediation works started middle of July 2016 with the mobilisation of a 120t excavator from the Netherlands. The operators of this excavator were highly experienced in the placement of interlocking concrete elements. This large excavator had sufficient reach to work until the -3.0m CD depth from behind the crest wall. An efficient work plan was prepared where the production of each equipment (e.g. crane to remove units, long-reach excavator for profiling the underlayer) was optimized; mainly to minimize idle time of the large excavator.

Figure 10: Training of local staff to become fully aware of the design and construction requirements

Before start of the remediation construction works all site staff was informed of the eventual remediation design, rationale behind this design and important design items, see for example Figure 10. This is important as else the knowledge on the selection of design would remain with the designers only and not contractor's site staff. All staff, both local workers, foreman, divers and operators, received training on the method statements of each construction item. This included the method to profile the underlayer, assure proper connection between the units remaining in place and new placed units, interlocking placement, planning, etc.

Where the underlayer was below design level additional material was to be added to achieve the design level. If the surveyed underlayer was however above the design level, material was not allowed to be removed to prevent damaging of the filter (geotextile). At these locations material was to be supplemented until a smooth underlayer and transitions to neighbouring sections was achieved. Practical tips for underlayer profiling included trial tests on land (e.g. to work using DGPS data only) and placing markers along the profile for the final situation. Examples are presented in Figure 10 below.

Figure 10: Remediation works in progress.

During the first weeks of construction works the planning and construction methods were changed continuously to optimize the overall progress to practical work methods. Training of the site staff resulted in more understanding of the work to be done on site, focus points and quality to be achieved. This resulted in a more positive work attitude and efforts were made to increase quality even stricter than the given tolerances. Most important was the experience of the operator to place the interlocking elements, as this experience was visible in the way the units were lifted, placed and turned, based on the orientation of the previously placed units. After placement, divers checked the placing density and interlocking which was in accordance with the given requirements along the complete revetment.

The involvement of the contractor during the remediation design study, indicating their preferences, limitations and opportunities to optimize the remediation design study has resulted in a smooth design and construction process. Understanding of the design and its rationale was important to the contractor to be able to transform the design into a practical and feasible Method Statement and (equipment) planning with clear ITP's, fully in line with the given design tolerances, specifications and requirements. This transition from (remediation) design with given requirements into a Method Statement and ITP is often underestimated, resulting in impossible or non-practical designs or method statements which are not suitable to construct the design in reality, e.g. due to unsuitable available equipment or inadequate construction tolerances, specifications and requirements. Clear communication and understanding of the work and preferences between the designer and contractor can increase the overall quality of a project significantly.

Unfortunately this was not done before the original construction works, which was one of the main reasons mistakes were made during construction at that time.

References

Van de Sande B. e, Bijl, E. & Tamminga, J. (2016) *Raw data as information source*, Hydro International March 2016, Netherlands.