EXPERIMENTAL RESEARCH ON THE STABIILITY OF ARMOUR AND SECONDARY LAYER IN A SINGLE LAYERED TETRAPOD BREAKWATER

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Physical model tests were done on an armour of Tetrapods, placed in a single layer. The objective of the investigations was to study the stability of the secondary layer, and to see if the material of this secondary layer could be washed out through the single layer of Tetrapods. It was concluded that secondary armour is not washed out through an undamaged layer of Tetrapods, and that all damage to the secondary layer is related to damage in the primary layer. To prevent damage to the Tetrapod layer, a high placing density is needed. In case of low placing density, the area around the waterline will slide down, creating gaps in the main armour and exposing the secondary layer. Because of this process the placing density in lower sections of the breakwater increases, and consequently also the strength increases at those places.

1. Introduction

Traditionally armour layers are constructed in double layers. However, the newer armour units, like Accropode1, Core-Loc2 and X-bloc3 are designed for use in a single layer. Therefore it is interesting to investigate if it is possible also to use the older types of armour units in a single layer setting.

Previous research by d'Angremond *et al.* [1999] and Van den Bosch *et al.* [2002] on single armour layer breakwaters exposed to irregular waves, clearly demonstrated a positive relationship between an increase in the packing density of the armour layer and the stability of the structure. This relation particularly

[1] Accropode is a trademark owned by Sogreah, France
[2] Core-loc is a trademark owned by the US Army Corps of Engineers
[3] X-bloc is a trademark owned by Delta Marine Consultants, The Netherlands

held if the single armour layer consisted of Tetrapod units. A higher packing density increased interlocking, resulting in lesser displaced units. When decreasing the packing density, also a fairly stable top layer could be achieved. However, the single top layer with its slender shaped units caused the secondary layer to be rather exposed to wave attack, which in previous research often led to wash-out of the secondary layer rock material, thereby seriously undermining the stability of the structure. Rules of thumb were used recommended by Van der Meer to determine the dimensions of the secondary material used in these scale models. Therefore, this method seems to lead to underlayer rock material that is too small for use in a single Tetrapod armour layer.

This research is focused on both the stability of the single Tetrapod armour layer and the secondary layer. By means of several wave flume experiments, testing various combinations of secondary material, wave steepness and armour packing density, an attempt was made to establish the influence of these governing parameters on the stability of the structure.

2. Experimental set-up

The wave flume experiments were performed in the Fluid-mechanics Laboratory of the Faculty of Civil Engineering and Geosciences at Delft University of Technology. Each test series in principle consisted of 7 runs with increasing wave height and period, keeping the wave steepness constant. The irregular waves were generated according to the JONSWAP spectrum, while all runs consisted of approximately 1000 waves. A series was completed when failure of the structure occurred. The model was rebuilt after each series, but not after each test-run. To allow comparison with previous investigations, the physical model is basically identical to the model set-up of Van den Bosch *et al.* [2002]

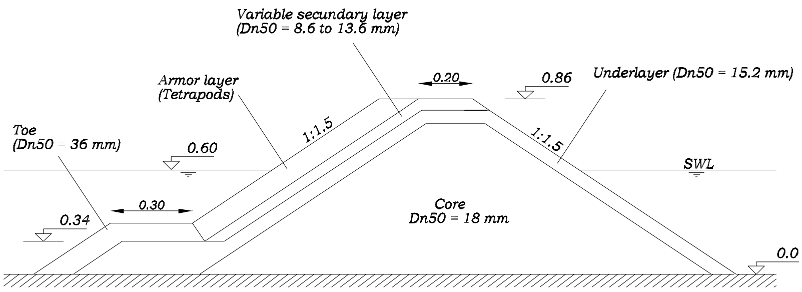

Figure 1. Model set-up.

However, contrary to the previous experiments, the core of the model was scaled according to Burcharth's method (Burcharth *et al.* [1999]), ensuring a flow field in the model that more accurately represents prototype design. This method of scaling led to rather course core rubble mound material.

Several digital images of the armour layer were taken at each run from a fixed position perpendicular to the slope. Through comparison of the images, displacement plots were generated. The erosion of the secondary layer was measured using an automatic surface profiler on a controlled carriage. Measurements were carried out at the beginning and end of each experiment.

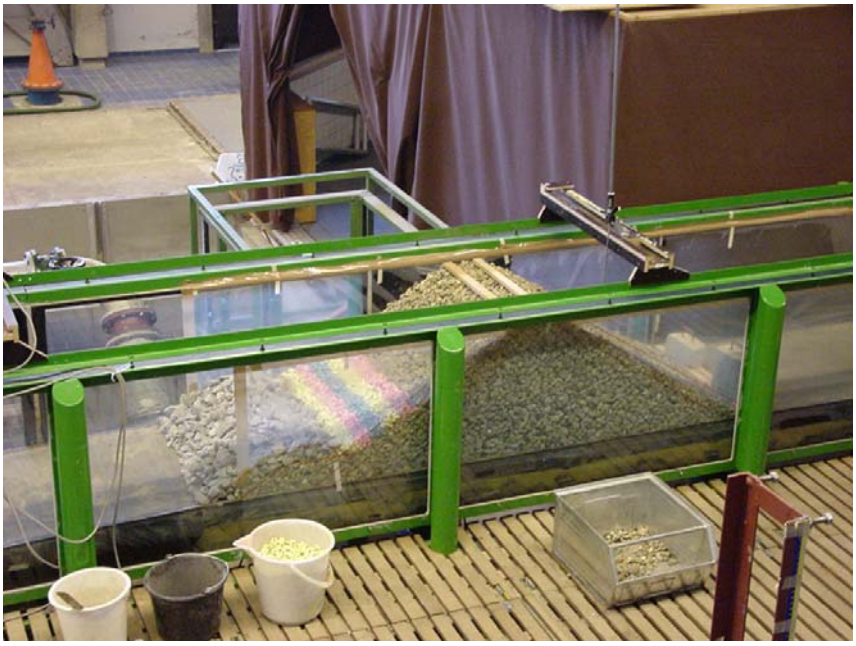

Figure 2. The physical model

3. Tests

A series of test were performed on the model breakwater, all with a single layer of Tetrapods. The packing density of the Tetrapods (n_v) was 0.25, 0.30 and 0.40. The wave height varied from H_s = 0.10 m to H_s = 0.22 m, the wave steepness varied from 2% to 6%. The packing density is defined by:

$$N_a = \frac{n_L k_t (1 - n_v)}{D_{n50}^2} \qquad (1)$$

in which N_a is the number of units placed, n_L is the number of layers and k_t is the layer coefficient (given as 1.04 for Tetrapods).

In the previous tests of Van den Bosch *et al.*[2002] for Tetrapods and secondary layer values of W_a = 206 g (mass of armour units) and W_s = 7.3 g (the mass of the median stone in the secondary layer) were used, so the ratio W_a/W_s = 14. It was expected that also for this test-series quite some damage to the secondary layers would occur. In order to get more insight into the relation between the damage and the size of the secondary armour, in these tests the following ratios for W_a/W_s were used: 31, 47, 119.

Damage is defined as the ratio between the eroded area (A_e) and the D_{n50} of that layer. See also figure 3. Apart from the damage number S also values for displacement (movement over $2D_n$) were defined as $N_{od} = N_0/(B/D_n)$ and sliding (movement between 0.5 D_n and $2D_n$) as $N_{os} = N_{sl}/(B/D_n)$. B is the flume width.

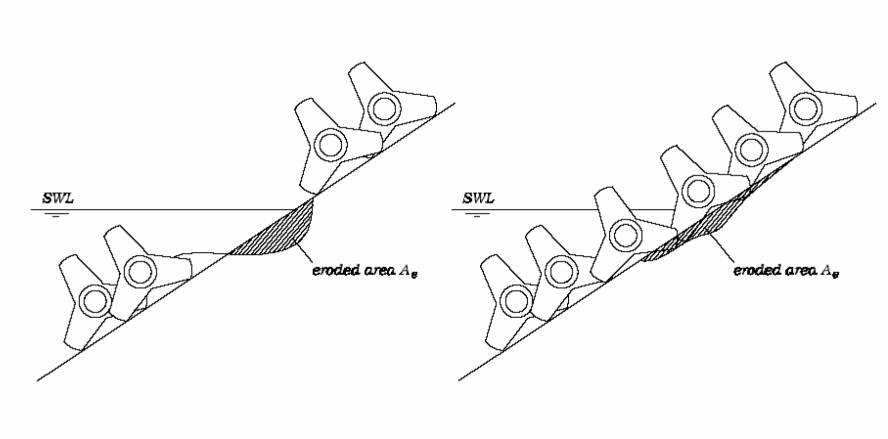

Figure 3: Definition of damage

As a first result it was observed that the secondary layer was much more stable than was expected. It was significantly more stable than according to the data from d'Angremont *et al.* [1999] and Van den Bosch *et al.*[2002]. It was expected that this difference was mainly caused by the fact that in the tests by d'Angremont *et al.* [1999] and by Van den Bosch *et al.*[2002] the core was not scaled according to the "Burcharth rules". In order to investigate this, a nearly impermeable sheet of plastic was placed between the filter and the core, simulating a too impermeable core.

As follows from figure 4, the permeability of the structure with the geotextile becomes rather similar to the permeability of the test of Van den Bosch et al.[2002]. Figure 5 shows the results of the stability tests to compare the permeable and non-permeable situation.

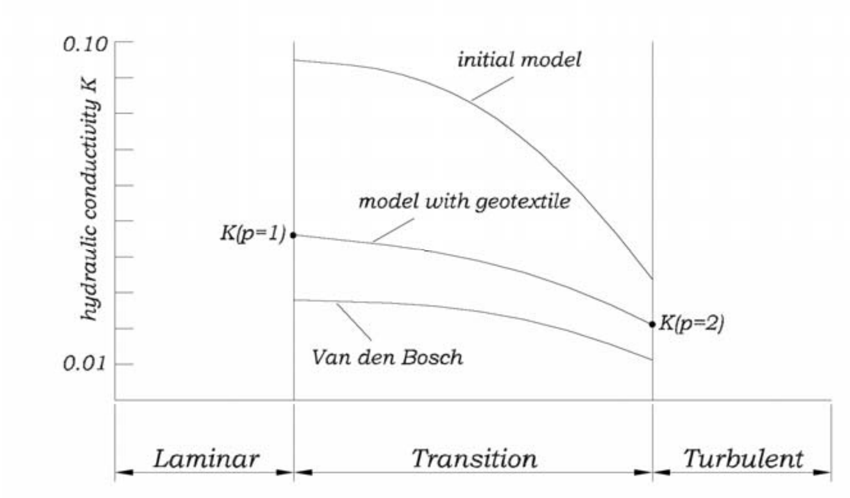

Figure 4. Permeability achieved by using an additional geotextile

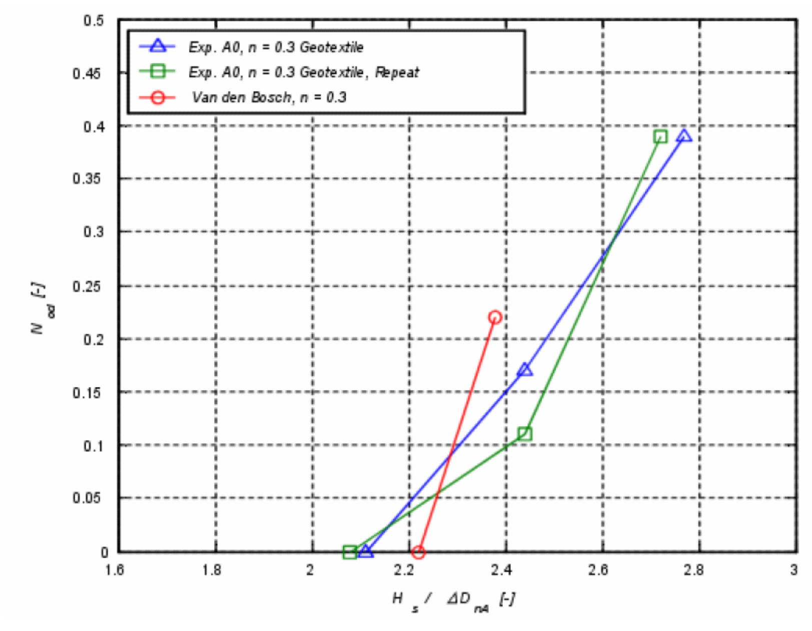

Figure 5. Armour stability tests with a geotextile and the stability tests of Van den Bosch *et al.*

These additional tests showed that there is a similarity between the test using the geotextile and the original these of Van den Bosch et al [2002], and consequently one may conclude that the high damage largely may be attributed to the incorrect scaling of the core section.

In order to have the erosion well documented in this case , the surface of the secondary layer was measured carefully with profile followers, after removal of the Tetrapods. This resulted in detailed contour maps of the slope. Because of the high degree of detail, these graphs cannot be reproduced in this publication, but are available in the original report of the test [De Jong, 2003].

The results of the secondary layer stability are summarised in figure 6. In this figure is S_s the damage of the secondary layer. The best fit line through the data can be described by:

$$\frac{H_s}{\Delta D_{n50s}} = 4.68 + 0.32 S_s \qquad (1)$$

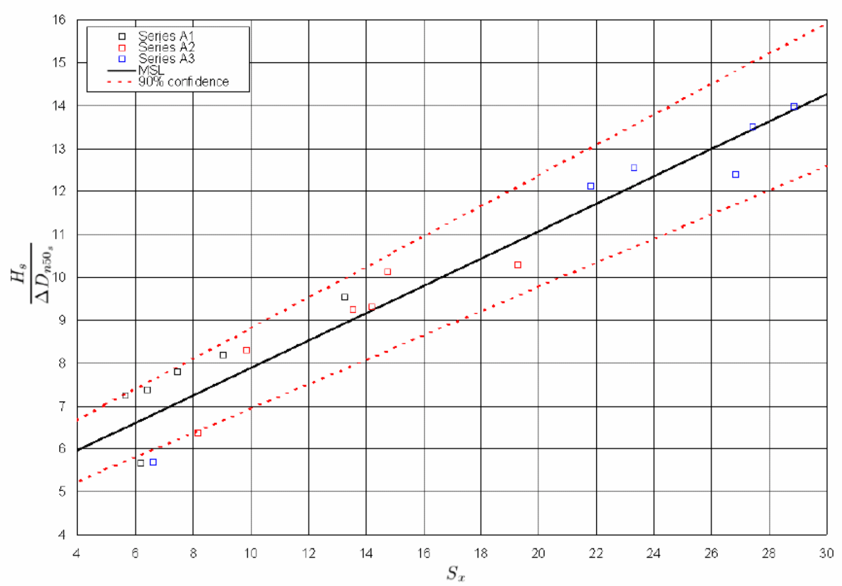

Figure 6. Stability of the secondary layer

4. Conclusions related to the secondary layer

Contradictory to previous research, no considerable wash-out of the secondary layer was observed; damage occurred due to local scour holes around the still water level. In nearly all cases the material of the secondary layer was not washed through the Tetrapod layer as long as the Tetrapod layer was in perfect condition. Even with very fine material in the secondary layer (W_a/Ws > 120) damage was not initiated by washout in the secondary layer.

At places where initial damage occurred in the Tetrapod layer (e.g. because of some sliding down of Tetrapods within a layer and creating in this way locally some more space between the Tetrapods) the damage to the secondary layer started. The depth of the erosion holes in the secondary layer never exceeded $3D_{n50s}$.

The influence of the permeability is considerable. Not only the permeability of the core is important (a relatively high core permeability increases the stability of the secondary layer), but also a large permeability of the primary layer decreases the stability of the secondary layer.

The amount of damage mainly depends on H_s and D_{n50s}.

5. The main armour

The damage development of the top layer agreed with results of previous research. An increase in packing density improved the overall stability of the top layer. The results also showed a general decrease in stability with increasing wave periods. During the experiments, the armour packing density increased until a 'natural' packing density was reached.

From all tests a stability relation could be derived with an identical form as the Van der Meer - relation for double layer Tetrapods:

$$\frac{H_s}{\Delta D_{nA}} = a_5 \left[3.7 + 8.0 \left(\frac{N_{od}}{\sqrt{N}} \right)^{0.5} \right] s_{m0}^{0.2} \tag{3}$$

It was found that the coefficient a_5 in this equation depends on the stone size in the secondary layer, leading to the following equation:

$$\frac{H_s}{\Delta D_{nA}} = \left(\frac{D_{nA}}{D_{n50s}} \right)^{0.05} \left[3.7 + 8.0 \left(\frac{N_{od}}{\sqrt{N}} \right)^{0.5} \right] s_{m0}^{0.2} \tag{4}$$

Smaller material in the secondary layer results in a smoother surface, which eases the sliding of the Tetrapods over the secondary layer. Equation (4) is presented in figure 7, together with the test data. In figure 8 the differences in stability of a single layer and a double layer of Tetrapods is indicated. This example is made for a wave steepness of 4% and for tests with 1000 waves.

From the test followed that also for single layers of Tetrapods it was confirmed that an increased packing of the Tetrapods increases the stability of the Tetrapods. Especially at low packing densities (n_v <0.4) resettlement of the Tetrapods occurred, even with low waves. This caused gaps between the Tetrapods around the waterline, and consequently failure. After resettlement the lower layers had a placement density between 0.23 and 0.27. This implies that the area around the waterline becomes weaker, and the area below the waterline becomes stronger.

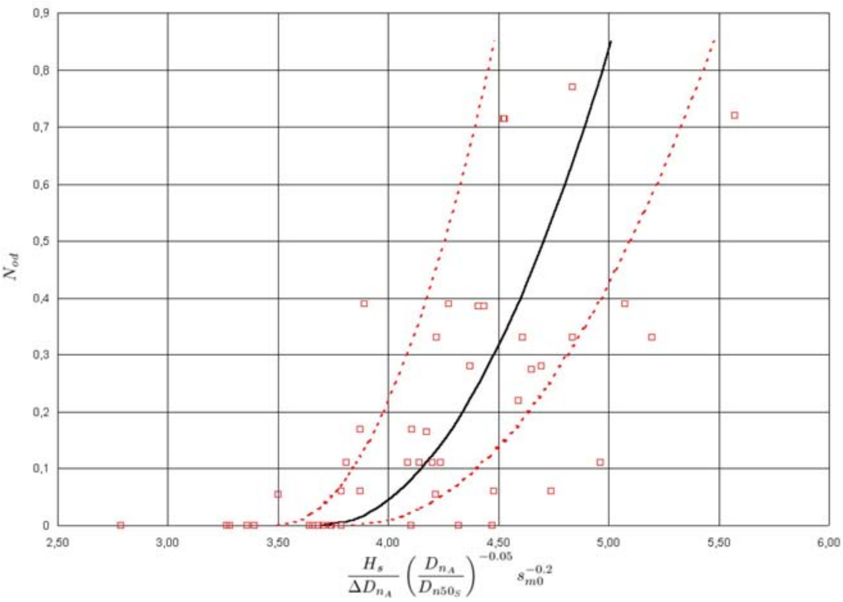

Figure 7. Stability tests of single layer Tetrapods

The behaviour of the secondary layer material, however, was rather surprising. Wash-out of the secondary layer material did not occur at all series. Though the erosion increased with a decrease in secondary rock size, it was the damage development of the armour layer rather then excessive erosion of the underlayer that caused an overall failure of the structure. The experiments further demonstrated that the erosion of the secondary layer was a function of the incident wave height rather than of the top layer packing density or the wave steepness.

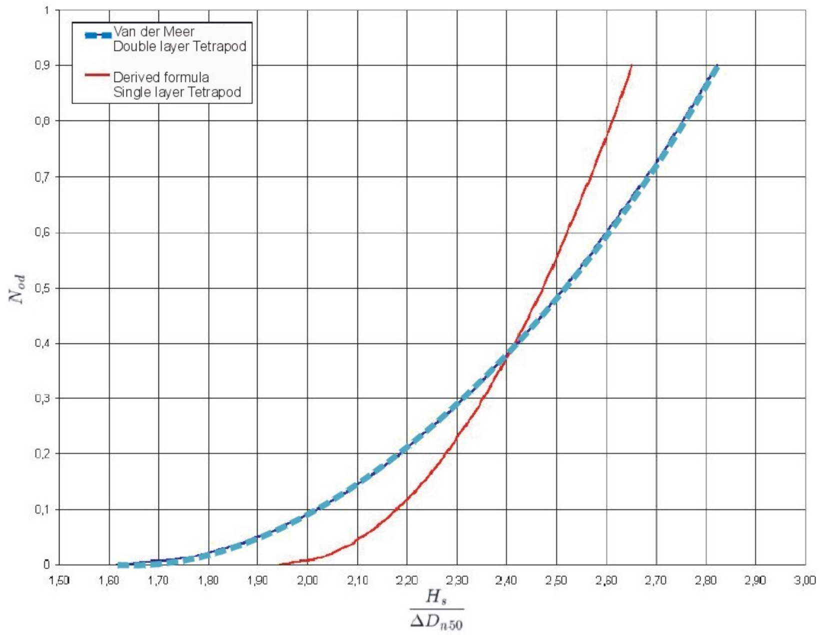

Figure 8. Comparison of the stability of a single and a double layer of Tetrapods, for a wave steepness of 4% and for 1000 waves

A possible explanation in the different outcome between the results of the conducted experiment and the research by Van den Bosch et al. (2002) was sought in the difference in permeability of the scale models. To verify this, an extra series was performed with a geotextile placed between core and secondary layer, thus decreasing the permeability to approximate the set-up used in previous experiments. Though the overall erosion of the secondary layer increased due to the decrease in permeability of the core, still it was within tolerable limits.

Acknowledgments

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