BREAKWATER STABILITY WITH DAMAGED SINGLE LAYER ARMOUR UNITS

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The effect of single layer interlocking armour unit breakage on the hydraulic armour layer stability and potential damage progression is addressed in this paper. A 2-dimensional scale model of a rubble mound breakwater with an armour layer consisting of Xbloc armour units was tested. The residual armour layer stability with broken units was determined. The armour unit displacement and damage progression was assessed. According to the test series breakage of the single layer armour units has a significant negative effect on start of damage of the armour layer. Breakage of units has however no significant effect on failure of the armour layer. This leads to a long and gradual damage progression compared to an armour layer without broken units.

INTRODUCTION

At breakwater and revetment projects at the coast of Sines (1978) and Scarborough (2004) severe damage to concrete interlocking armour units was observed at wave conditions lower than the design conditions.

For double layer interlocking armour units physical model tests have been performed to determine the influence of damaged armour units on the hydraulic armour layer stability (Davidson and Markle 1976). These tests and breakwater projects like the one at the coast of Sines (Baird et al. 1980) show that breakage of double layer interlocking armour units has a significant negative effect on the hydraulic armour layer stability.

The significant decrease of the interlocking capacity and mass of the broken units leads to displacement of these units and the surrounding ones. The broken parts of the damaged units act like projectiles. The waves "throw" these parts back and forth to the armour layer during run-up and run-down. More armour units may break due to the impact of these broken parts. This behaviour leads to rapid damage progression of the armour layer and finally to failure of the total construction.

Several cases are known of breakwater and revetment projects, like the one at the coast of Scarborough, with breakage of single layer interlocking armour units. Little information is however known about details regarding the decrease of armour layer stability. The information that is known is very general and does not give any technical information with respect to the damage due to breakage.

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It is however generally assumed that breakage of single layer interlocking armour units has the same effect on the hydraulic armour layer stability as for breakage of double layer armour units. Damaged single layer interlocking armour units would have a significant negative effect on the stability of the armour layer. Start of damage and failure of the armour layer would occur at significant lower wave heights as in comparison to an armour layer with no damaged units, see Figure 1. This behaviour has however never been confirmed.

Damage progression armour layer

failure

2   1

start of damage

Wave height

— 1 Armour layer with no damaged single layer armour units
— 2 Armour layer with damaged single layer armour units

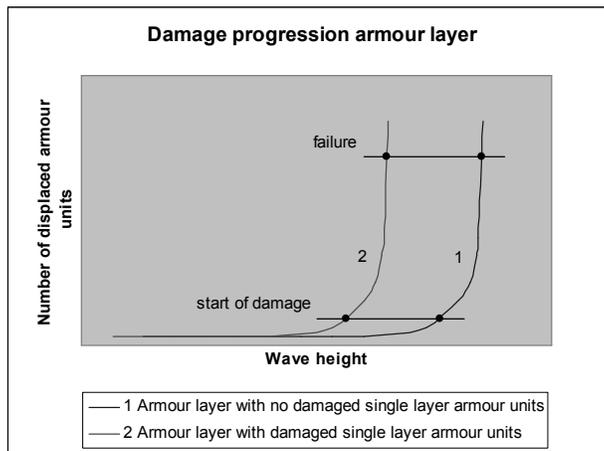*Number of displaced armour units*

Figure 1. Expected damage progression of an armour layer with damaged single layer armour units with respect to the damage progression of an armour layer with no damaged single layer armour units.

The main objective of this research is therefore to determine the effect of single layer armour unit breakage on the hydraulic armour layer stability and potential damage progression.

HYDRAULIC MODEL TESTS
Hydraulic model tests were performed in a wave flume of the Fluid Mechanics Laboratory of the faculty Civil Engineering and Geosciences at Delft University of Technology. This wave flume has a length of approximately 38 m, a width of 0.80 m and a depth of 1.0 m.

Breakwater Model
A 2-dimensional scale model of a rubble mound breakwater with typical cross section was used for the hydraulic model tests.
In front of the breakwater model a foreshore with a slope of 1:30 was used to represent a foreshore in reality. This foreshore had a height of 0.20 m, which leads with a slope of 1:30 to a length of 6.0 m. The breakwater had a front slope

of 3:4. For the armour layer of the breakwater model Xbloc armour units were used with the following parameters:

$$D \quad = \quad 40 \text{ mm};$$
$$D_n \quad = \quad 27.7 \text{ mm};$$
$$W \quad = \quad 49 \text{ gram};$$
$$\rho \quad = \quad 2297 \text{ kg/m}^3 \text{ (material: impermeable plastic)}.$$

Specific drop tests with respect to the structural integrity of the Xbloc armour unit showed that the noses and legs from the armour units are the most vulnerable parts with respect to breakage (Hakenberg et al. 2004). One nose or leg was therefore cut off from every model Xbloc unit that simulated a broken unit.

To place the broken units, the detached nose or leg of the unit was glued back on the unit with a sugar/water solution. When this solution dried the sugar crystallized again and the broken parts were attached to each other. After placement of these units in the armour layer the water in the wave flume dissolved the sugar, simulating the broken units in reality as close as possible.
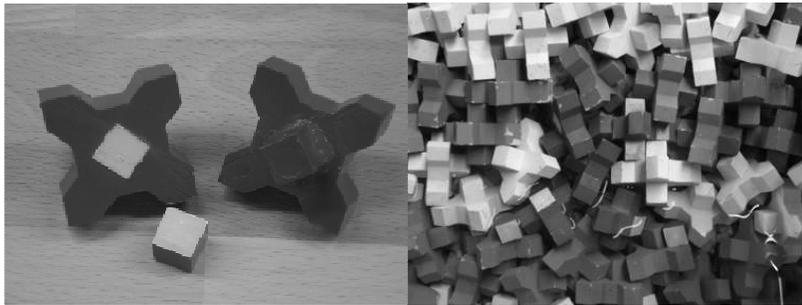

Figure 2. Broken Xbloc armour units used for the test series.

Testing Set-up

A Jonswap spectrum was used to simulate the irregular waves of a young sea state. To limit wave overtopping and minimize breaking of waves on the foreshore the water depth was stated at 0.55 m. The local wave steepness s at the wave generator was held constant during the test series. Typical wave steepness' for wind waves are between s = 0.02 and s = 0.06. A wave steepness s of 0.045 was used during the test series to cover the band of wave steepness'.

The design wave height H_d for the Xbloc armour units used in the model tests is 10 cm. For every test series the significant wave height H_s was increased from 80% up till 190% of the design wave height until failure of the armour layer occurred.

For the stability of a Xbloc armour layer the following is given in the Xbloc guidelines (Bakker et al. 2006):

1. Start of damage occurs at wave heights ≥ 120% of the design wave height.
2. Failure occurs at wave heights ≥ 150% of the design wave height.

For this research start of damage is defined as displacement of 1 or more Xbloc units (in the order of 4 units) from the armour layer. Failure is defined as displacement of several units from the armour layer (in the order of 25 units) leading to exposure of the first underlayer and displacements of stones out of the first underlayer.

Figure 3. Failure of the armour layer and exposure of the first underlayer.

The damaged units were positioned in the armour layer over a total height of two times H_d around the still water level. This is the area with the highest wave loads and where the greatest influence of the damaged units can be expected (Schiereck 2001).

It is not known where the units will break in reality, with respect to the position in the armour layer and whether they break in clusters or individual. Different configurations of the broken units were therefore tested.

To get a high sensitivity in the test series and to get quick results a large number of broken Xbloc units was used. In total 7.5% or 15% of the units in the area around the still water line over a height of $2H_d$ was broken during the test series. The damaged units were placed in clusters of 5 broken units or individual. The position of the units was varied with respect to the still water line.

Reference test series were performed with no broken Xblocs in the armour layer to compare the stability of the armour layer with and without broken units. These tests were also used to compare the stability of the model to the required stability of an Xbloc armour layer given in the Xbloc guidelines.

EXPERIMENTAL RESULTS

In Figure 4 all the data are used with respect to start of damage and failure determined for the different configurations during the test series.
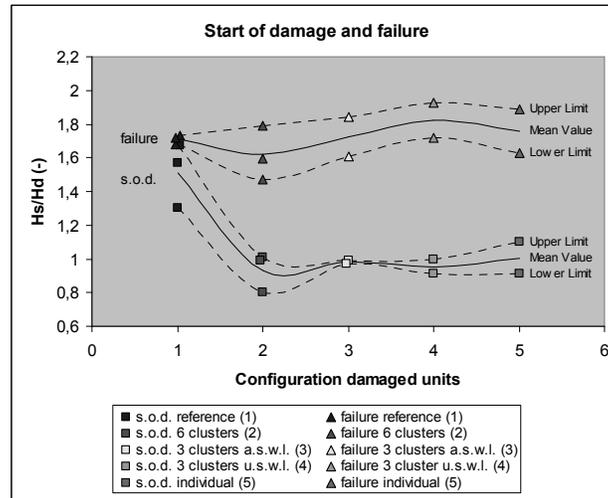

Figure 4. Start of damaged and failure for the different tested configurations with lower limits, mean values and upper limits.

Figure 4 shows clearly that the broken Xbloc units have a significant negative effect on start of damage. Start of damage occurs at significant lower values of H_s/H_d compared to the reference tests with no damaged units in the armour layer.

Failure however occurs at approximately the same values of H_s/H_d for all configurations including the reference test series.

During start of damage it is observed that in most cases non-damaged units surrounding broken units were displaced. These units do not have a loss of mass due to breakage. The negative influence of damaged armour units on the start of damage is therefore not caused by the decrease of mass of the damaged armour units. The negative influence of the damaged units is primarily an interlocking problem. The decrease in interlocking capacity of the damaged units affects the armour layer as an integral system. The local effects are limited as only a few damaged armour units are displaced during the test series.

At failure relatively the same amount of broken and non-broken units were displaced from the area around still water level. The decrease of interlocking capacity and mass of the damaged units do therefore not significantly influence failure of the armour layer.

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Figure 4 shows that one configuration is more favourable compared to another with respect to start of damage and failure of the armour layer.

To compare the different configurations with damaged units figures are used with the data of start of damage and failure from the test series representing a certain configuration.

In these figures a lower limit, mean value and upper limit for both start of damage and failure are used to show the spreading of the measured data.

For comparison of the different configurations only the lower limit is used. This is done to be conservative as for prototype breakwaters large safety factors are used with respect to the design.

There are some differences between the different configurations with damaged units and one may look more favourable than another. However one must be careful interpreting the outcomes of the different configurations compared to each other due to the large spreading of the data and limited performed tests.

Start of Damage and Failure with Different Percentages of Damaged Units

In Figure 5 the data from the reference tests and the test series with 3 clusters above and under the still water line are respectively used for the data of 0% and 7.5% broken units. The test series with 6 clusters and individual placed broken units are used for the data of 15% damaged units.
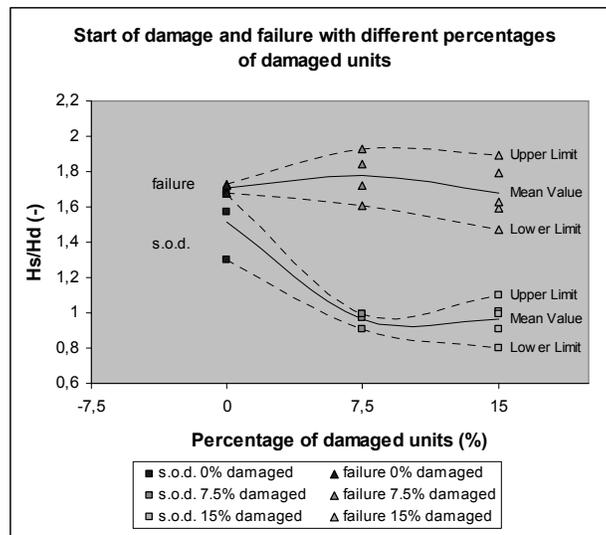

Figure 5. Start of damage and failure with different percentages of damaged units with lower limits, mean values and upper limits.

Figure 5 shows that increasing the percentage of broken units in the armour layer from 0% to 7.5% gives a significant negative effect on start of damage of the armour layer. Further increasing the percentage of damaged units from 7.5% to 15% does not give a significant additional negative effect on start of damage.

The increase of the percentage of damaged units from 0% to 15% leads to a constant minor increase of the negative effect on failure of the armour layer.

Start of Damage and Failure with Different Numbers of Damaged Units Clustered

In Figure 6 the data from all test series are used, except for the series with 3 clusters of damaged units. The data are sorted at no damaged units (reference tests), individual placed damaged units and units placed in 6 clusters of 5 damaged units around the still water line.
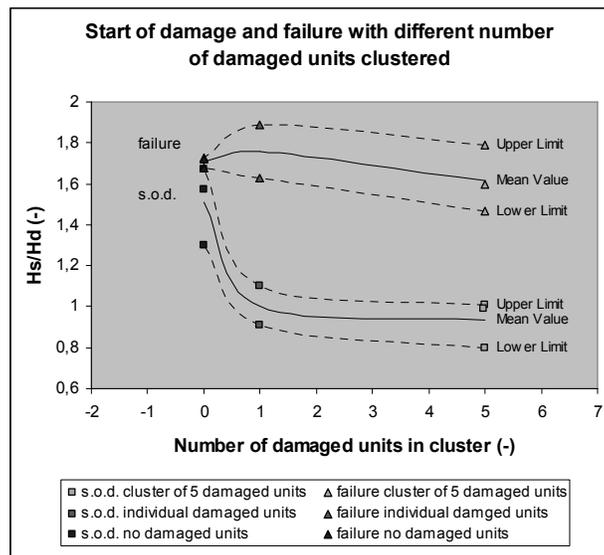

Figure 6. Start of damage and failure with different numbers of damaged units clustered with lower limits, mean values and upper limits.

Increasing the number of damaged units in a cluster from 0 to 1 has a significant negative effect on start of damage of the armour layer. Further increasing the number of damaged units in a cluster from 1 to 5 units gives no significant additional increase of the negative effect on start of damage.

The increase of the number of damaged units from 0 to 5 leads to a constant minor increase of the negative effect on failure of the armour layer.

Start of Damage and Failure with Different Positions of Damaged Units

    The data from the test series with 3 clusters above and under the still water line are given in Figure 7.
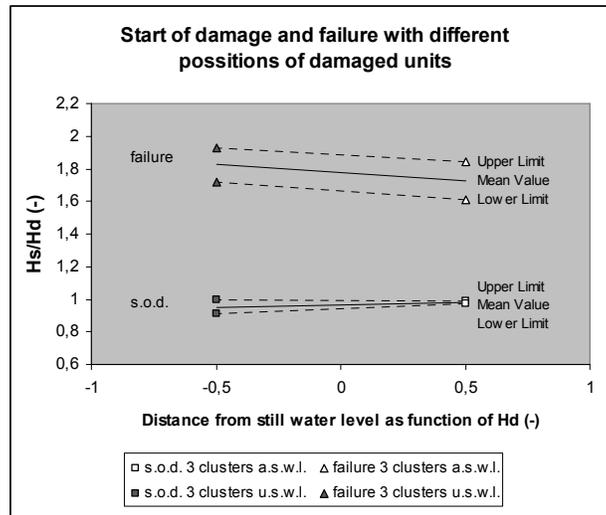

Figure 7. Start of damage and failure with different positions of damaged units with lower limits, mean values and upper limits.

    The clusters above and under the still water line are respectively positioned between still water level and one H_d above still water level and still water level and one H_d under still water level.

    For Figure 7 the average distance from the clusters of both configurations to the still water line is used. The mean position from the 3 clusters above the still water line with respect to the still water line is $0.5H_d$. The 3 clusters under the still water line have a mean position of $-0.5H_d$ with respect to the still water line.

    Figure 7 shows that there is a minor difference between start of damage and failure for both configurations. Start of damage occurs at lower values of H_s/H_d for clusters under the still water line compared to clusters above the still water line. Failure occurs at lower values of H_s/H_d for clusters above the still water line compared to clusters under the still water line.

    These differences are however very small (in the order of 5%) and can be neglected. The position of the damaged units between one H_d under and above the still water line gives therefore no difference in influence of the broken units on start of damage and failure.

EVALUATION START OF DAMAGE AND FAILURE

The lowest value of start of damage and failure from the reference tests and the tests with broken units are shown in Figure 8. The tests with 6 clusters of 5 damaged units around the still water line have the lowest values with respect to start of damage and failure for an armour layer with broken units. These values are therefore used in Figure 8. In this figure also the required values for the stability of an Xbloc armour layer according to the Xbloc guidelines are shown.
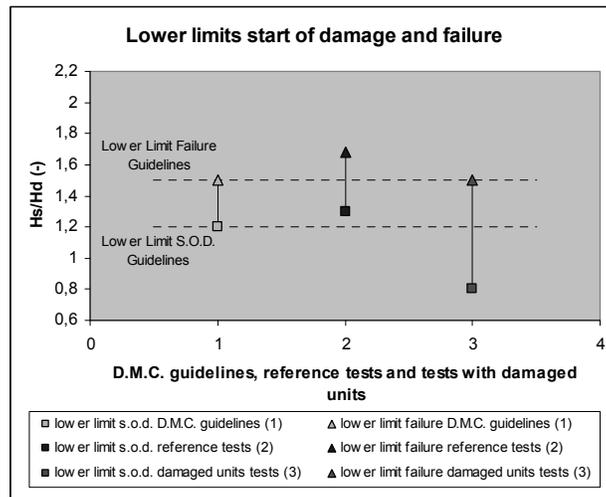

Figure 8. Lower limits start of damage and failure for the Xbloc guidelines, reference tests and tests with damaged units.

Start of damage of the test series with damaged units occurs for the lowest observed value of H_s/H_d at an approximately 40% lower value compared to the Xbloc guidelines and at an approximately 50% lower value compared to the reference tests.

Failure of the test series with damaged units occurs for the lowest observed value of H_s/H_d at the same value of H_s/H_d as for the Xbloc guidelines and at a 20% lower value of H_s/H_d compared to the reference tests.

Damaged units in the armour layer have a significant negative effect on start of damage compared to both the Xbloc guidelines and the reference test series. Compared to the Xbloc guidelines the damaged units have no effect on failure of the armour layer and compared to the reference tests the damaged units have some effect on failure of the armour layer but not as significant as was expected. Even in the most negative case failure of an armour layer with damaged units occurs at wave heights of approximately 50% above the design wave height.

DAMAGE PROGRESSION

Start of damage occurs at a significant lower level of H_s/H_d for an armour layer with damaged units compared to an armour layer without damaged units. This is primarily caused by a decreased interlocking capacity of the damaged units. With further damage progression the negative influence of the decreased interlocking capacity on the stability of the armour layer decreases. Failure occurs generally at the same values of H_s/H_d for an armour layer with damaged units compared to an armour layer without damaged units. The negative influence of the decreased interlocking capacity has therefore decreased to zero at failure.

This behaviour leads to a longer and more gradual damage progression of an armour layer with broken units than was generally assumed, see Figure 9.
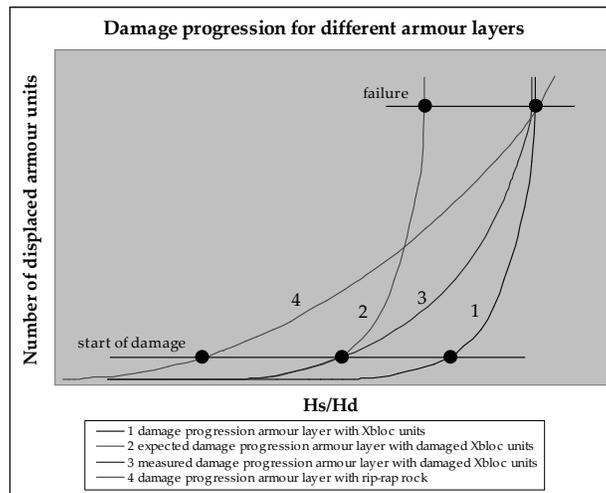

Figure 9. General damage progression for different types of armour layer.

This type of damage progression looks more like the damage progression of an armour layer consisting of rip-rap rock. Due to the lower interlocking capacity of the Xbloc units their behaviour becomes more like an armour stone (rip-rap rock) with no interlocking capacity.

However the Xbloc units still have a large part of their interlocking capacity left. The behaviour of the damage progression of the armour layer therefore lies in between the damage progression of an armour layer consisting of rip-rap rock and an armour layer with no damaged Xbloc armour units (see Figure 9).

BEHAVIOUR DETACHED NOSES AND LEGS

During the test series the displacements of the detached noses and legs were monitored. The total amount of detached parts depends on the test configuration that was used (7.5% or 15% of broken units). In total 15 or 30 noses and legs were detached during the test series. Figure 10 shows how many noses and legs were displaced during each test series.

The majority of the detached noses and legs showed little to no movement and stayed in the armour layer or even tended to dig themselves in the first underlayer. On the average only 2 or 3 detached parts showed displacement for each test series (see Figure 10). After this displacement these parts settled again in the armour layer. It is therefore unlikely that the broken parts damage other units as only a few detached parts showed displacement during the test series.
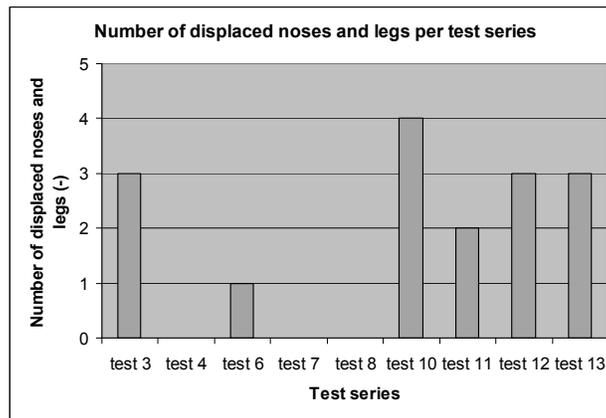

Figure 10. Number of displaced detached noses and legs observed during each test series with broken units.

CONCLUSIONS

The conclusions are based on the results from the performed physical model tests with broken single layer interlocking armour units. It must be noted that these conclusions are based on the specific test configuration with Xbloc units used for this research. The conclusions do therefore not automatically apply for all types of rubble mound breakwaters with single layer interlocking armour units.

Stability Armour Layer with Damaged Single Layer Interlocking Armour Units

It was generally assumed that damaged single layer interlocking armour units have a significant negative effect on the stability of the armour layer. The start of damage and failure of the armour layer would occur at significant lower wave heights as in comparison to an armour layer with no damaged units.

This hypothesis is true for the start of damage of an armour layer with broken Xbloc armour units. Start of damage occurs at significant lower wave heights for an armour layer with damaged units compared to an armour layer with no damaged units.

This hypothesis is rejected for failure of an armour layer with broken Xbloc armour units. Failure occurs for an armour layer with damaged units at approximately the same wave heights as for an armour layer with no damaged units.

This damage behaviour leads to a longer and more gradual damage progression than was generally assumed. This kind of damage progression looks more like the damage progression of an armour layer of rip-rap rock. So the damage progression of an armour layer with damaged units does not resemble the damage progression of an armour layer with no damaged units shifted to significant lower wave heights as was generally assumed.

The negative influence of the damaged armour units on start of damage is not caused by the decrease of mass of the damaged armour units. The decrease in interlocking capacity of the damaged units affects the armour layer as an integral system. The local effects are limited as only a few damaged units are displaced during the test series.

Further increasing the percentage of damaged units around the still water level or number of damaged units in a cluster has only a minor additional negative influence on start of damage and failure of the armour layer.

The position of the damaged units between one H_d under and one H_d above the still water line gives no difference in the influence of damaged units on start of damage and failure of the armour layer.

Behaviour Broken Parts of Damaged Single Layer Interlocking Armour Units

It was also generally assumed that the broken parts of the damaged single layer armour units would act like projectiles. The waves would "throw" these broken parts back and forth to the armour layer during run-up and run-down. More armour units would break due to the impact of these broken parts leading to rapid damage progression of the armour layer and finally to failure of the total construction.

In contradiction to this assumption the majority of the detached noses and legs showed little to no movement during the test series and stayed in the armour layer or even tended to dig themselves in the first underlayer. It is therefore unlikely that rapid damage progression occurs due to broken parts damaging other units as only a few detached parts showed displacement during the test series.

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