Preface

This is the final report of my Master thesis titled “Breakwater stability with damaged single layer armour units”. This research was carried out as the final thesis of the study of Civil Engineering at the Faculty Civil Engineering and Geosciences of Delft University of Technology.

The research was carried out in cooperation with Delta Marine Consultants bv.

Therefore I want to thank above-mentioned cooperation for making it possible for me to fulfil this research.

During this thesis I received great support from a number of people whom I like to thank. First of all I would like to thank the members of my thesis committee for their contribution to my thesis, Prof. dr. ir. M.J.F. Stive (TU Delft), Ir. H.J. Verhagen (TU Delft), Dr. ir. W.S.J. Uijttewaal (TU Delft) and Ir. A. van den Berge (Delta Marine Consultants).

Next I want to thank Dr. Ir. M. Muttray and Ir. J.S. Reedijk from Delta Marine Consultants for their additional input to my thesis and the employees of the Fluid Mechanics Laboratory at the Faculty Civil Engineering and Geosciences of Delft University of Technology for assisting me during the experiments.

And last I would like to thank my parents for all the support during my study.

Richard de Rover,

Gouda, october 2007

picture cover: Broken Accropode armour units at the damaged seawall of Scarborough, UK

In this report the following types of single layer interlocking armour units are mentioned:

-	Accropode:	registered trademark of Sogreah;
-	Core-Loc:	registered trademark of the US Army Corps of Engineers;
-	A-Jack:	registered trademark of Armortec;
-	Xbloc:	registered trademark of Delta Marine Consultants bv.

Some differences are treated between different types of units, however Delft University of Technology does not imply that one type of unit performs better than another.

Abstract

At breakwater and seawall projects at Port St Francis and Scarborough breakage of single layer interlocking armour units was observed. It is generally assumed that breakage of single layer armour units has a significant negative effect on the hydraulic stability of a rubble mound breakwater. The significant decrease of interlocking capacity and mass of the broken units would lead to displacement of these units and surrounding units. The broken parts of the damaged units would act like projectiles. The waves would “throw” these broken parts back and forth to the armour layer. 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. This damage behaviour has however never been confirmed.

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

A 2-dimensional model of a rubble mound breakwater with typical cross section was tested with individual and clustered positioned broken Xbloc armour units around the still water line. The residual stability of the armour layer was determined. The armour unit displacement and damage progression was assessed.

It is concluded that breakage of single layer armour units has a significant negative effect on start of damage of the armour layer. Breakage of single layer armour units has no significant effect on failure of the armour layer.

This damage behaviour leads to a long and gradual damage progression. This type of damage progression looks more like the damage progression of an armour layer consisting of rip-rap rock.

The majority of the broken parts show little to no movement. It is therefore unlikely that rapid damage progression occurs due to broken parts damaging other units.

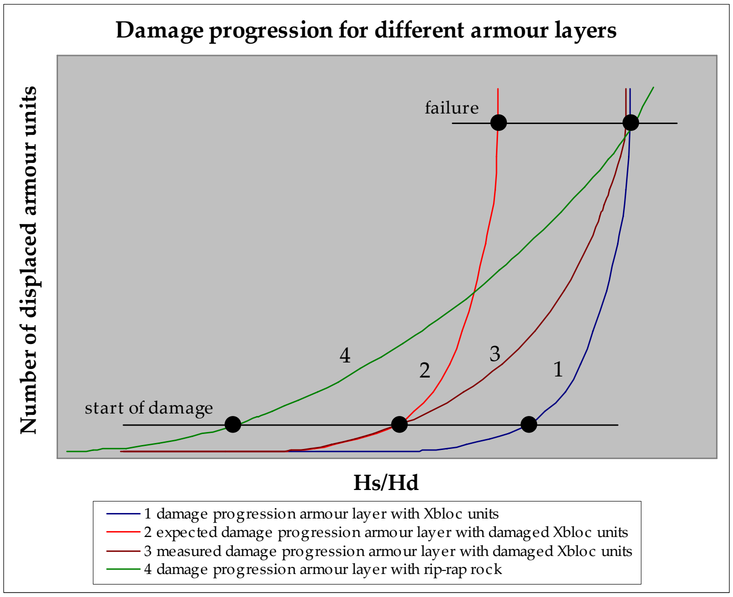

figure top of page: Broken Accropode armour units at the damaged seawall of Scarborough, UK
figure bottom of page: General damage progression for different types of armour layer

Executive summary

At breakwater projects at the coast of Sines and Scarborough severe damage to concrete armour units was observed at wave conditions lower than the design conditions. For double layer armour units several physical model tests were performed with Tetrapods and Dolosse to determine the influence of damaged armour units on the stability of a breakwater.
These researches and breakwater projects like the one at the coast of Sines show that breakage of double layer armour units has a significant negative effect on the hydraulic stability of a breakwater. The significant decrease of interlocking capacity and mass of the broken units leads to displacement of these units and surrounding units. The broken parts of the damaged units act like projectiles. The waves "throw" these broken 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.

It is generally assumed that breakage of single layer armour units has the same effect on the hydraulic stability of a breakwater as breakage of double layer armour units. This behaviour has however never been confirmed.

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.

To come to an answer of the objective a 2-dimensional physical model of a scaled rubble mound breakwater is constructed in a wave flume of Delft University of Technology. This model has a front slope of 3:4 and a foreshore of 1:30, which represents a foreshore in reality. The armour layer consists of Xbloc armour units with a nominal diameter D_n of 2.77cm and a design wave height H_d of 10cm.

From every model Xbloc unit that simulates a damaged Xbloc unit one nose or leg is cut off. To place the broken units, the detached nose or leg of the unit is glued back on the unit with a sugar/water solution. After placement of these units in the armour layer the water in the wave flume will dissolve the sugar again. Simulating the broken units in reality as close as possible.

In total 15% or 7.5% of the units in the area around still water level over a height of $2H_d$ is damaged during the test series. Different configurations of the damaged units are tested. The damaged units are placed in clusters of 5 damaged units or random (individual). The position of the units is varied with respect to the still water line. Reference test series are performed with no broken Xblocs in the armour layer to compare the stability of the armour layer with and without broken units. These tests are also used to compare the stability of the model to the required stability of an Xbloc armour layer prescribed in the Xbloc guidelines.

For the test series irregular waves with a Jonswap-spectrum are used to simulate a young sea state in front of the model breakwater. During the test series the wave height is varied over a range of 80% to 190% of the design wave height at a constant water depth of 0.55cm and wave steepness of 0.045.

From the performed test series it is observed that damaged single layer armour units have a significant negative effect on the start of damage of the armour layer compared to both the Xbloc guidelines and the reference test series. Compared to the Xbloc guidelines the damaged units have no effect on the failure of the armour layer and compared to the reference tests the damaged units have some effect on the failure of the armour layer but not as dramatic as was expected. Even in the most negative case of 6 clusters of 5 damaged units around the still water line failure still occurs at wave heights of approximately 50% above the design wave height.

Start of damage mostly occurs at approximately one H_d under the still water line (between -0.5 H_d and -1.5 H_d). This is generally a non-damaged unit in the surroundings of damaged units. The negative influence of damaged units on start of damage is therefore primarily an interlocking problem. Apparently the area between 0.5 and 1.5 H_d under still water level is the most vulnerable place in the armour layer for displacement of armour units.
During the damage progression only in the order of 2 damaged armour units are displaced from the armour layer. The majority of the displaced units during the test series are therefore non-damaged Xbloc units. Most of the displaced Xbloc armour units are displaced under the still water line.

Increasing the percentage of damaged units or number of damaged units in a cluster has only a minor additional negative influence on start of damage and failure. The position of the damaged units between one H_d under and one H_d above the still water line gives no difference in influence of the damaged units on start of damage and failure.

The damage progression of an armour layer with damaged units has a longer and more gradual damage progression compared to the damage progression of an armour layer with no damaged armour units. This type of damage progression looks more like the damage progression of an armour layer consisting of rip-rap rock. This is a contradiction to what is generally assumed.

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer. This is a contradiction to the hypothesis that under influence of the waves the broken parts would act like projectiles damaging other units. This is highly unlikely to occur as only a few detached parts showed displacement during the test series. The detached parts above the still water line have a smaller chance on displacement compared to detached parts under the still water line as buoyancy increases the chance of displacement of the last mentioned detached parts.

So the general assumed hypothesises that breakage of single layer armour units has a significant negative effect on the hydraulic stability of a breakwater and that the broken parts would act like projectiles are rejected by the outcomes of this research.

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Chapter 1 Problem analysis

1.1 Introduction

Breakwaters are designed to reduce the influence of waves in the area behind the breakwater. They are used for instance at harbour entrances to reduce the influence of the waves inside the harbour entrance and basin (see figure 1.1). This way the ships calling on the port can safely enter the port and be handled at the quays.
Another application of breakwaters is to protect the shoreline of being eroded by waves by reducing these waves.

There are two major types of breakwaters, rubble mound breakwaters and monolithic breakwaters.

Rubble mound breakwaters are made of a core constructed out of rock (quarry run). To protect this core from being “washed away” as a result from wave attack a top layer of large rock stones or concrete units called armour units is used.

figure 1.1: Dana point harbour rubble mound breakwater, US

Before 1950 armour layers of breakwaters were only built with rock or concrete cubes. These types of armour units derive their stability against the waves from their weight.

After 1950 a new type of armour units was designed. These units have the ability to interlock with the surrounding units. Due to this interlocking mechanism the units not only use their own weight as stability against the waves but also the weight of the surrounding units.
Because of their slender shapes less concrete is needed compared to cubes and the porosity of the armour layer is much larger leading to a higher hydraulic stability.

Tetrapods were the first units designed with this interlocking capacity. After that a large variety of this type of armour unit were designed for instance the Tripod and the Dolos.

All these units are double layer interlocking armour units placed randomly. The second layer is necessary to create interlocking. The units of this layer however tend to rock leading to breakage of these units [23].

As more of this type of units were designed they became more slender increasing the interlocking capacity. This way they gained more hydraulic stability and less concrete was needed. The best example of this is the Dolos.

However due to the slenderness the structural strength of these units decreased significantly. This became very clear when breakwaters at the coast of Sines (1978) and Tripoli (1974 and 1984) were destroyed due to breakage of these armour units.

As a result of this a new type of armour unit the Accropode was introduced in 1980. The Accropode is a single layer interlocking armour unit that is significantly more robust then a Dolos. These units are placed randomly in a grid with predefined position and orientation. For these units only one layer of armour units is needed. As a result these units show less rocking compared to double layer interlocking armour units [23]. Due to the higher structural stability and decrease of rocking the change of breakage of units is significantly reduced.

After the Accropode other types of single layer interlocking armour units are designed. These are the A-Jack, Core-Loc and Xbloc. The difference between the Xbloc and the other types of units is that Xblocs do not have to be placed with a predefined orientation.

Despite the improved design of this type of units several cases are known of damaged breakwaters and seawalls like projects at Scarborough (2004) and Port St Francis (1996). At these projects breakage of Accropode and Core-Loc units was observed leading to damage of the armour layer.

For double layer interlocking armour units physical model tests have been performed [16] to determine the influence of damaged armour units on the hydraulic stability of a breakwater. These tests and breakwater projects like Sines [1 and 2] show that damaged double layer interlocking armour units are of great influence on the hydraulic stability of a rubble mound breakwater in a negative way.

It is generally assumed that the same is true for single layer interlocking armour units. The influence of damaged armour units on the stability of a rubble mound breakwater with single layer armour units has however never been assessed in physical model tests.

This research is performed to assess the influence of damaged single layer interlocking armour units on the hydraulic stability of a rubble mound breakwater with physical model tests.

A typical feature of Accropode and Core-Loc armour units is that they have three different faces (the anchor, the face with two legs and the face with one leg). Each unit within the armour layer is in contact with four other units. Therefore the interface and consequently the interlocking between an individual unit and the surrounding units may vary significantly. The Xbloc unit has only two different faces reducing the possible interfaces between armour units.

For this research Xbloc armour units are used to reduce the possible interfaces between the armour units. The reduction of possible interfaces reduces the variability in interfaces of the damaged units with other units.

1.2 Problem description

Single layer interlocking armour units are mostly applied with relatively large safety margins with regard to hydraulic stability. The armour layer should be able to survive a significant exceedence of design conditions without major damage. It is generally agreed that a minor damage to a single layer armouring will result in rapid damage progression. The margin between start of damage and failure of the armour layer is consequently small.

Hydraulic model tests with Xbloc armour units indicated that an initial damage to the armour layer is mostly not associated with damage progression [3]. When individual Xbloc armour units are extracted from the armour layer the neighbouring units will be rearranged. Settlements are typically observed in the vicinity of the displaced units. The armour layer stabilises and can subsequently withstand even larger wave loads without additional damage. This mechanism is called self-repairing capacity of Xbloc armouring.

The interlocking capacity and the self-repairing capacity of Xbloc armouring may be reduced when armour units start breaking. Breakage of armour units is mostly not considered in hydraulic model tests as the structural strength of armour units is not properly scaled.

1.3 Problem definition

The problem definition that is posed in this master thesis is:

What is the effect of single layer armour unit breakage on the hydraulic armour layer stability and potential damage progression?

1.4 Research objective

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

Sub objectives

To come to the research objective the following sub objectives are completed:

First a literature study is performed, to get more theoretical insight into the subject of the objective.

A breakwater model is designed, taking into account the scaling effects, using the proper scaling rules.

After finishing the design, a schedule for the test series is made. The test series are performed in a wave flume of the Fluid Mechanics Laboratory at the Faculty Civil Engineering and Geosciences of Delft University of Technology.

During these test series the configuration and position of broken Xbloc armour units varies for several test series. For each test series the wave height varies as a percentage of the design wave height for the given Xbloc armour units that are used during the tests.
For each configuration and positioning of the broken units several test series are performed with a constant wave steepness and water depth.
The tests results are documented and analyzed to evaluate the test outcomes and when necessary to adapt the testing programme to come to useful and valuable results.

With the wave height as well as the configuration and position of the damaged units as varying input parameters the influence on the stability of the armour layer by these parameters is determined.

With the test results and the information from the literature study the objective is answered, after which the conclusions and recommendations are made.

1.5 Outline Master Thesis report

The outline of this report is as follows:

In chapter 2 the concept of a Xbloc armour unit is treated. The literature with respect to breakage of double and single layer interlocking armour units and their relevance to this research is treated also in chapter 2. A rubble mound breakwater with typical cross section was tested with individual and clustered positioned broken units around the still water line. In chapter 3 the set-up of the performed experiment is treated. In chapter 4 the residual stability of the armour layer is determined and the armour unit displacement and damage progression is assessed. These results are further discussed in chapter 5. The conclusions and recommendations with respect to the effect of single layer armour unit breakage on the hydraulic armour layer stability and potential damage progression are made in chapter 6. These conclusions and recommendations are based on the literature treated in chapter 2 and the discussion of chapter 5.

Chapter 2 Damaged interlocking armour units

2.1 Introduction

In this chapter the research with respect to damaged interlocking armour units will be treated. First the concept of the Xbloc armour unit will be treated. The available research performed for damaged double layer interlocking armour units will be analysed with respect to their relevancy to this research. After which the available research on damaged single layer interlocking armour units will be treated.

2.2 Concept Xbloc armour unit

After extensive research Delta Marine Consultants introduced the Xbloc armour unit in 2003. The Xbloc armour unit is a single layer interlocking armour unit, which can be used for breakwaters and revetments along the coast.
The unit was first applied on a small shore protection in 2004 and secondly on a breakwater at Port Oriel, Ireland in 2005.

The unit has four spiky parts (the legs) and two cubic shaped parts (the noses), which give the unit its interlocking capacity (see figure 2.1). These parts give the unit two faces instead of three like Accropods and Core-Locs reducing the possible interfaces between armour units.

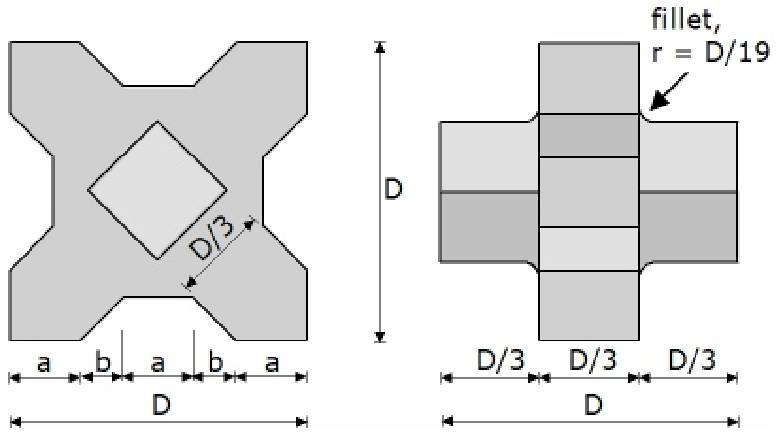

figure 2.1: Xbloc unit showing the two faces with four legs and two noses of the unit

Hydraulic model tests showed that the Xbloc unit has the same hydraulic stability as the Accropode unit and the Core-Loc unit [4]. The structural stability of the unit is the same as the Accropode and greater as the Core-Loc [17].

The units have to be placed in a grid with a predefined position. A great advantage of the Xbloc unit to Accropode and Core-Loc units is that the units do not have to be placed with a predefined orientation and are therefore easy to place. As the unit has only two faces it can easily find a stable position in the armour layer after placement.

2.3 Damaged double layer interlocking armour units

A lot of research has been done with respect to broken Tetrapods and Dolosse. Research on the structural stability as well as the influence of broken units on the hydraulic stability has been performed [9,10,11,13,16 and 23]. For breakwater projects like the one at Sines detailed research has been performed with respect to the cause of failure of the breakwater [1 and 2].

These researches show that due to rocking the armour units tend to break. When they break a large piece of the unit is broken off or the unit is even broken in half (Dolos).

For Dolosse this is caused by the slenderness of the unit. After breakage the unit looses most of its interlocking capacity and a large part of its weight. As a result the broken parts are displaced and tend to move under influence of the waves. By moving over the armour layer other units can be damaged and the broken parts themselves further disintegrate. These parts are thrown back and forth to the armour layer, which could damage other units.
The significant decrease of interlocking capacity of the broken units leads to displacement of the surrounding units. This behaviour finally leads to rapid damage progression of the armour layer leading to failure of the breakwater.

The behaviour of Xbloc armour units with respect to double layer interlocking armour units is however very different with respect to the structural integrity and rocking.

Tests with respect to the structural integrity show that Xbloc armour units are less vulnerable to breakage compared to Tetrapods and Dolosse [17]. When a Xbloc armour unit breaks only a small part is broken off. This is different compared to Tetrapods and Dolosse where a large part is broken off which leads to a significant decrease of the interlocking capacity and mass. Especially Dolosse have a lower structural integrity due to the slender body of the unit.

For double layer armour the units of the second layer tend to rock leading to breakage of these units. Single layer armour units show less rocking than in a double layer armour and therefore have a lower risk of impact loads and breakage [23].

The findings of these researches can therefore not be used as comparison for the test results of this research.

2.4 Damaged single layer interlocking armour units

Several cases are known of breakwaters and seawalls with breakage of single layer interlocking armour units (see table 2.1).

Breakwater site	Year of damage	Armour type	Probable cause of damage
Port St Francis, South Africa	1996/97	Core-Loc	Breakage of armour units during construction
Argeles, France	1999	Accropode	Breakage of armour units, cause uncertain
Scarborough, UK	2004	Accropode	Breakage of armour units in service

table 2.1: Cases of damaged breakwaters and seawalls with breakage of single layer interlocking armour units [21]

figure 2.2: Broken Accropode unit at the damaged seawall of Scarborough, UK

Very little information is known about these projects. The information that is known is very general and does not give any technical information with respect to the damage due to breakage. With this kind of information an in depth technical literature study cannot be performed.

However it is 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.

The following damage progression of an armour layer with damaged single layer interlocking armour units is generally assumed to occur (see figure 2.3).

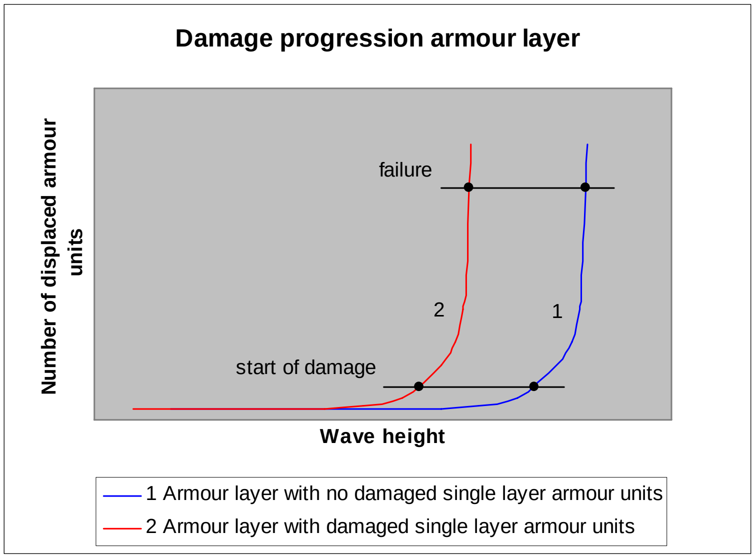

figure 2.3: Expected damage progression of an armour layer with damaged single layer armour units with respect to the damage progression of an armour layer with no damaged single layer armour units

This behaviour would be caused by the dramatic decrease of mass and interlocking capacity of the armour units. These units would be displaced at significantly lower wave heights due to this negative change in properties of the units. The displacement of these damaged units decreases the interlocking capacity of the surrounding units leading to rapid damage progression of the armour layer.

It is also generally assumed that the broken parts of these damaged units will act like projectiles. It is generally assumed that this is due to the dramatic decrease of the mass and interlocking capacity of these broken parts.
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 more projectiles, which can damage other units. This would cause rapid damage progression of the armour layer and finally failure of the total construction.

These hypothesises have however never been confirmed with observations or hydraulic model tests.

2.5 Summary

A lot of research has been done with respect to broken Tetrapods and Dolosse. The behaviour of Xbloc armour units with respect to double layer interlocking armour units is however very different with respect to the structural integrity and rocking.
The findings of these researches can therefore not be used as comparison for the test results of this research.
Several cases are known of breakwaters and seawalls with breakage of single layer interlocking armour units. However very little information is known about these projects.

It is 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. The significant decrease of interlocking capacity and mass of the broken units leads to displacement of these units and surrounding units. The broken parts of these damaged 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.

Chapter 3 Experimental set-up

3.1 Introduction

A 2-dimensional model of a rubble mound breakwater and a slope in front of the model representing the foreshore in reality is used for the hydraulic model tests.
The cross section of the breakwater model, the materials to be used and the testing set-up will be determined in this chapter.

3.2 Wave flume

For the experiments a wave flume of the Fluid Mechanics Laboratory of the faculty Civil Engineering and Geosciences at Delft University of Technology is used. This wave flume has a length of approximately 38m, a width of 0.80m and a depth of 1.0m, with a restriction of the depth to 0.90m to ensure that no waves will overtop the sidewalls of the flume.
At the beginning of the wave flume the wave board, with a wave reflection compensator, is positioned, which generates the desired waves. At the end of the wave flume a wave dissipative slope is positioned.
The model of the breakwater is positioned in front of this slope, with three wave gauges positioned in front of the toe construction. These wave gauges are used to measure the incoming wave heights and wave periods. Between the wave board and the foreshore of the breakwater model another three wave gauges are positioned to measure the wave heights and wave periods, which are generated by the wave board.

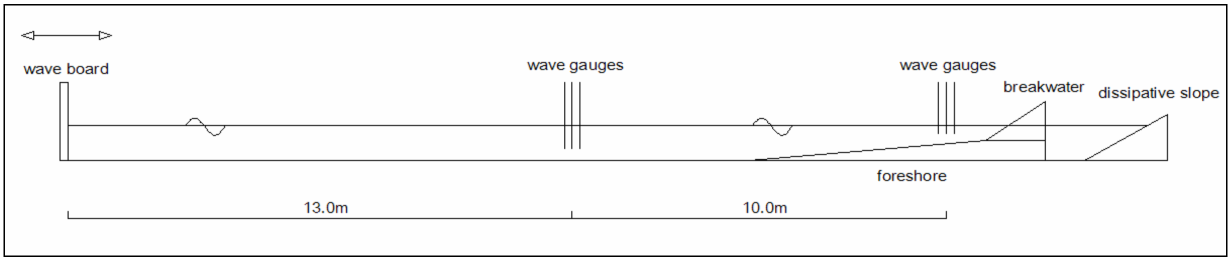

figure 3.1: Wave flume

3.3 Breakwater model

3.3.1 Scaling rules

To get useful results from the hydraulic model tests it is of great importance that the model dimensions and input parameters for the variables are scaled properly. If that is not the case then the results from the tests cannot be related to cases in reality and become therefore useless.

The scale is defined by scale factor N. The scale factor is the ratio of the value of a parameter in the prototype to the value of the same parameter in the model. When these scale factors are not used properly scale effects will occur, leading to inaccurate or even unrealistic results of the model tests. Therefore scaling rules are developed to overcome this problem.

Complete similarity in models is obtained when the values of all relevant dimensionless parameters in the prototype are maintained in the model. For complete similarity the following similarity classifications can be used:

- Geometrical similarity
- Kinematical similarity
- Dynamic similarity

It would be beyond the scope of this research to go into detail for all classifications, for more detailed information about scaling laws, one is referred to Hughes [20].

For practically all experiments in coastal engineering the most important scaling laws are the geometrical similarity as well as the Froude- and the Reynolds-scaling laws. These will be elaborated here.

Geometric similarity

To get geometric similarity for the prototype and the scale model the following requirement must be met:

$$N = \frac{x_p}{x_m} = \frac{y_p}{y_m} = \frac{z_p}{z_m} \qquad (3.1)$$

This means that every length of the scale model must be scaled with the same scale factor with respect to the prototype to avoid geometric distortions in the scale model.

Froude scaling-law

The Froude number expresses the relative influence of inertial and gravity forces in a hydraulic flow by the square root of the ratio of inertial to gravity forces. For this scaling law it is required that the Froude number is the same for the prototype and the scale model. This gives:

$$Fr = \left(\frac{U}{\sqrt{gL}}\right)_p = \left(\frac{U}{\sqrt{gL}}\right)_m \qquad (3.2)$$

with:

Fr	=	Froude number	(-)
U	=	velocity	(m/s)
g	=	gravitational acceleration	(m/s^2)
L	=	length	(m)
p	=	prototype	
m	=	model	

The gravitational acceleration g is the same for the prototype and the model. When g taken as a constant we get:

$$Fr = \left(\frac{U}{\sqrt{L}}\right)_p = \left(\frac{U}{\sqrt{L}}\right)_m \tag{3.3}$$

which can be rewritten as:

$$\sqrt{\frac{L_m}{L_p}} = \frac{U_m}{U_p} \tag{3.4}$$

stating that $\sqrt{N_L} = N_U$ must hold for similarity, with U=L/T this becomes:

$$N_T = \sqrt{N_L} \tag{3.5}$$

This implies that the scale factor of the time has to be equal with the square root of the length scale factor.

Reynolds scaling-law

The Reynolds number represents the ratio of inertial to viscous forces in a hydraulic flow. For this scaling law it is required that the Reynolds number is the same for the prototype and the scale model. This gives:

$$\mathrm{Re} = \left(\frac{UL}{\upsilon}\right)_p = \left(\frac{UL}{\upsilon}\right)_m \tag{3.6}$$

with:

υ = viscosity (m²/s)

with $N_u = \frac{U_m}{U_p}$, $N_L = \frac{L_m}{L_p}$ and because the modelling is done with water, the small viscosity difference between the salt water for the prototype and the fresh water for the model can be neglected, the following holds $N_\upsilon = \frac{\upsilon_m}{\upsilon_p} = 1$.

This gives eventually:

$N_U = \frac{1}{N_L}$, and finally with U=L/T this becomes:

$$N_T = N_L^2 \tag{3.7}$$

This implies that the scale factor of time has to be equal with the square of the length scale factor.

Scale effects

The requirements of the Froude scaling-law and the Reynolds scaling-law cannot be met at the same time. However in free-surface flow, gravity is considered dominant over viscosity. Therefore for experiments with wave flumes the Froude scaling-law is mostly used.
The use of the Froude scaling-law however, causes incorrectly scaling of the viscosity, elasticity and surface tension, causing scale effects. The linear geometric scaling of material diameters, which follows from Froude scaling, may lead to too large viscous forces in relation to inertial forces corresponding to too small Reynolds numbers, especially in under-layers and core of small-scale models. The related increase in flow resistance reduces the flow in and out of under-layers and core. This causes the flow to be laminar instead of turbulent, which will be the case with a prototype breakwater.
As a result wave reflection inside the model would occur and pressure will build up under the armour layer, which will lead to a lower stability of the armour layer. In order to avoid this problem it is required to create a similar flow field for the prototype and the model.
When designing a small-scale breakwater model one has to take these effects into account for the under-layers and core of the model.

3.3.2 Dimensions

3.3.2.1 Foreshore

In front of the breakwater model a foreshore with a slope of 1:30 is used to represent a foreshore in reality. This foreshore has a height of 0.20m, which leads with a slope of 1:30 to a length of 6.0m.

3.3.2.2 Slope

For the front side of the breakwater a slope of 3:4 is chosen. In most other hydraulic model tests on armour layer stability with Xbloc armour units this slope was used [3], so to compare the test results with the test results of these tests, it is necessary to have the same slope.

3.3.2.3 Crest

To minimize wave breaking on the foreshore a water depth of 0.55m is used. Wave overtopping reduces the forces of the waves on the armour layer. The objective of this research is to determine the stability of this armour layer. To get the full impact of the waves on the armour layer the overtopping is reduced to a minimum by using a freeboard of 0.30m.
With a water depth of 0.55m and a freeboard of 0.30m the crest of the model breakwater is positioned at 0.85m above the bottom of the wave flume. The crest width is dimensioned at 0.18m.
For the crest of the breakwater model the same Xblocs are used as for the slope. The Xblocs on the crest however are fixed with a steel net on top of it. This is to ensure that the slope of the breakwater model will not become unstable as a result of instability of the crest. In this way the damage observation can purely be focussed on the slope of the breakwater model.

3.3.2.4 Backside of the model

To ensure that no failure of the breakwater model will occur due to instability of the rear slope of the model caused by overtopping, the rear slope is replaced by a vertical frame at the end of the crest.
This vertical frame is permeable to ensure that the permeability of the model breakwater will not be lowered by its presence. Due to the permeability of the vertical frame there will be no extra wave reflection inside the model, which would cause extra instability of the armour layer.

figure 3.2: Permeable backside of the model

3.3.2.5 Cross-section

With the dimensions determined the cross-section of the model breakwater to be used for the tests is as follows:

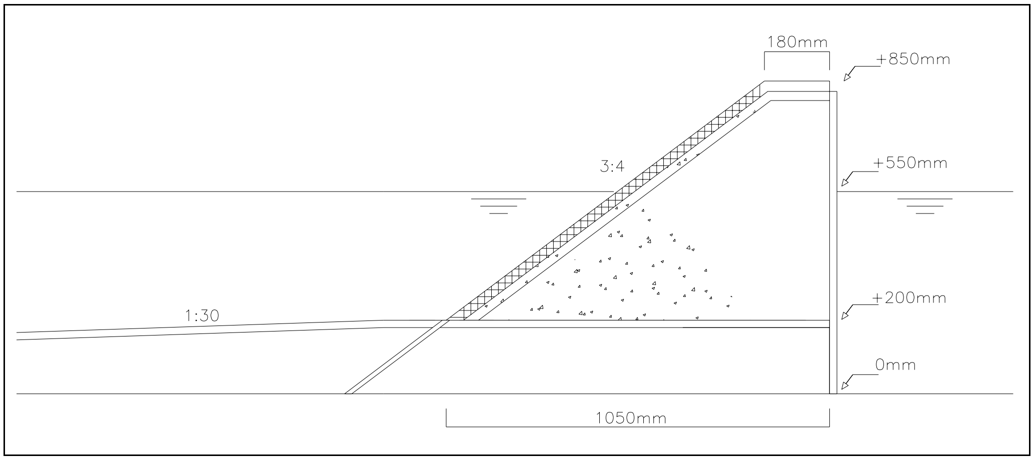

figure 3.3: Cross-section breakwater model

3.3.3 Xbloc armour units

For the armour layer of the breakwater model Xbloc armour units are used with the following parameters:

D = 40 mm;
D_n = 27.7 mm;
W = 49 gram;
ρ = 2297 kg/m³ (material: impermeable plastic);

with:

D = characteristic diameter of the Xbloc unit;
D_n = nominal diameter of the Xbloc unit;
W = weight of the Xbloc unit;
P = density of the Xbloc unit.

3.3.3.1 Non-broken Xbloc armour units

The non-broken Xblocs are coloured green or white to separate the different rows of the armour layer. With this colour difference one can better observe the settlement and displacement of the Xblocs individually after the armour layer has been damaged due to the waves.

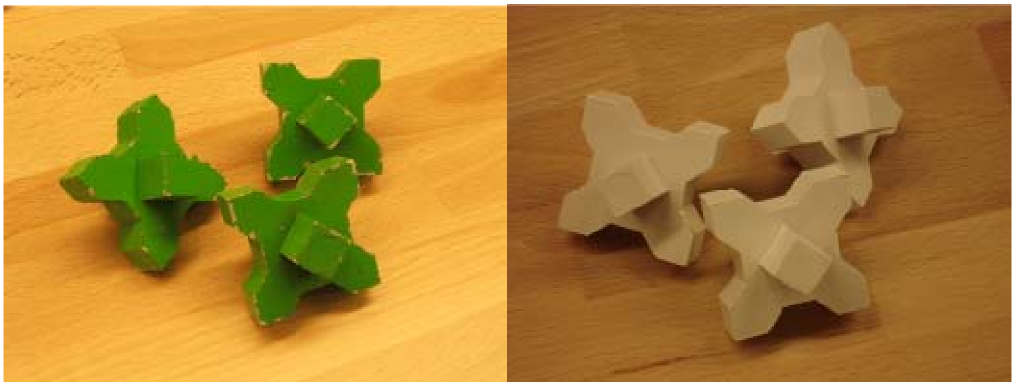

figure 3.4: Xbloc units

3.3.3.2 Broken Xbloc armour units

Specific model tests with respect to the structural strength of the Xbloc armour unit show that the noses and legs from the armour units are the most vulnerable parts of the Xbloc with respect to breakage [17]. Therefore it is assumed for this research that the noses and legs from the Xbloc units have the highest probability of breakage. From every model Xbloc unit that simulates a damaged Xbloc unit one nose or leg is cut off.

To distinguish the broken Xbloc armour units from the normal Xblocs, the broken units are coloured red.
With this colour difference the broken Xblocs can easily be observed during the tests so one can distinguish their behaviour in comparison to the non-broken units and whether there is more damage in the surroundings of the broken units compared to the non-broken units.

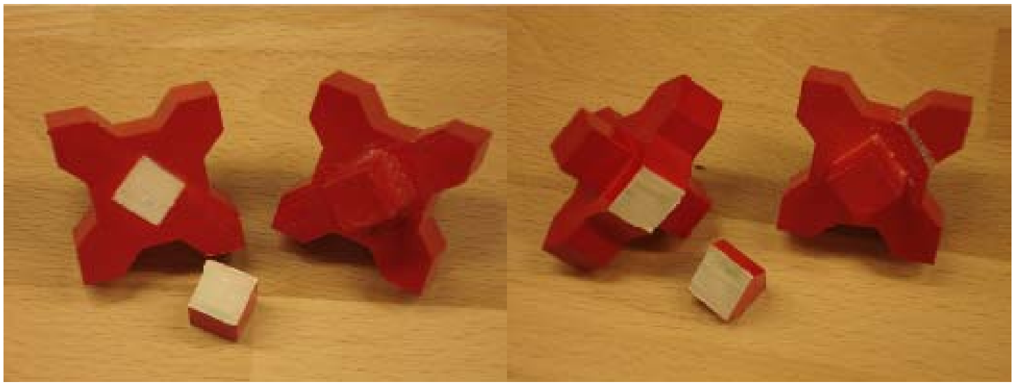

figure 3.5: Broken Xblocs, left with a broken nose and right with a broken leg

To place the broken units, the detached nose or leg of the unit is glued back on the unit with a sugar/water solution. When this solution dries the sugar crystallizes again and the broken parts are attached to each other. After placement of these units in the armour layer the water in the wave flume will dissolve the sugar again. This leads to the broken Xbloc armour units in the armour layer of the breakwater with the broken parts still between the non-broken units, simulating the broken units in reality as close as possible.
The influence of the dissolved sugar on the wave measurements is determined in appendix A. The measurements from appendix A show that the dissolved sugar has no influence on the wave measurements.

figure 3.6: Cluster of damaged Xbloc units after dissolving of the sugar

3.3.3.3 Packing density

For the design packing density and the distances between the Xbloc armour units the following requirements are given [5]:

Unit size	Packing density (-/m²)
$V \leq 5m^3$	$1.20/D^2$
$5m^3 < V \leq 12m^3$	$1.15/D^2$
$V > 12m^3$	$1.10/D^2$

table 3.1: Design packing density for different sizes of Xbloc
(D is the characteristic height of the Xbloc)

Unit size	Δx (along the slope in m)	Δy (up the slope in m)
$V \leq 5m^3$	$1.30 \cdot D$	$0.64 \cdot D$
$5m^3 < V \leq 12m^3$	$1.33 \cdot D$	$0.655 \cdot D$
$V > 12m^3$	$1.36 \cdot D$	$0.67 \cdot D$

table 3.2: Distances between Xblocs (D is the characteristic height of the Xbloc)

For hydraulic model experiments with Xbloc armour units Delta Marine Consultants prescribes a packing density of $1.20 / D^2$-/m² and distances between the Xblocs of $\Delta x = 1.30 \cdot D$ and $\Delta y = 0.64 \cdot D$.

To guarantee the stability of the Xbloc armour layer two additional requirements are made with respect to the placements of the units on the slope:

- The packing density on the slope (number of units per m²) shall be between 98% and 102% of the theoretical required packing density $1.2 / D^2$ with D as the characteristic height of the Xbloc (40mm);

- Each Xbloc shall be secured by two other Xblocs in the row above and beneath and by contact with the under-layer.

To meet these requirements the Xblocs have to be placed in a staggered grid, with along the slope a distance between the centres of the Xblocs of $1.3 \cdot D = 52mm$ and with up the slope a distance between the centres of the Xblocs of $0.64 \cdot D = 25.6mm$. This leads to the following theoretical grid:

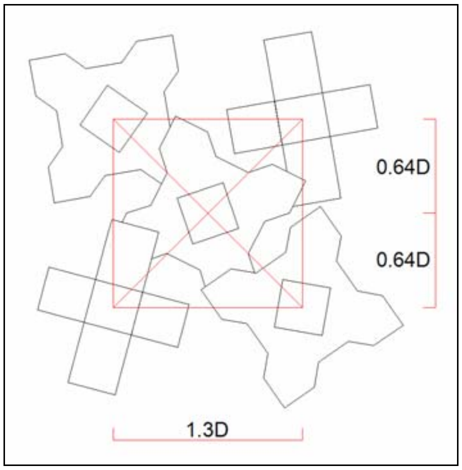

figure 3.7: Position Xblocs

At the walls of the wave flume the Xbloc armour units can only partially interlock with the other Xblocs. Due the fact that one side of the unit can not interlock with another unit the stability of these Xblocs will decrease and the chance of displacement will be higher.

figure 3.8: Xbloc armour layer with clusters of damaged units

3.3.4 Xbase units

For the toe construction special toe units called Xbase units are used. These Xbase units are in fact Xbloc units with one nose removed from the unit to give the unit a flat base. This increases the placement accuracy and stability of the toe construction. For the Xbase units the same Xbloc units as for the armour layer are used.
Although project specific test results show that this toe construction is very stable [7], it is chosen to fix the toe units with glue at the bottom. This is done to ensure that the breakwater model will not fail due to failure of the toe construction.

figure 3.9: Xbase units

For the Xbase units the following requirements have to be met with respect to the placement:

- The horizontal distance between the centers of the Xbase units must be $1.3 \cdot D = 52mm$;
- The horizontal distance between the centre of the Xbase unit and the plane parallel to the first under-layer must be at least $\frac{1}{2}\sqrt{2} \cdot D = 28.3mm$.

The orientation in the horizontal plane can be random, as in reality it may be difficult to place the Xbase units under water with the same orientation.

figure 3.10: Toe construction with Xbase units

3.3.5 First under-layer

With the parameters of the Xbloc armour units known the stones to be used for the first under-layer can be determined.

For the first under-layer the filter rules for rubble mound breakwaters are used [15], these state that the W_{50} of the stones for the first under-layer must be 1/10 – 1/15 of the W_{50} of the armour units. With 1/10 of the W_{50} of the Xbloc used in this model we get a W_{50} for the stones used in the first under-layer of 4.95 gram. With a mass density of the stones of $2690 kg/m^3$, this gives a required D_{n50} of 12.3 mm.

Delta Marine Consultants recommends the use of standard gradings as specified in CUR/CIRIA C683 [14] and listed in the Xbloc design guidelines [5].

If the use of these standard gradings is not desired or can not be applied as is the case in our model, the following requirements apply:

- the W_{15} of the first under-layer rock grading shall be larger than or equal to $W_{Xbloc}/15$;
- the W_{50} of the first under-layer rock grading shall be between $W_{Xbloc}/9$ and $W_{Xbloc}/11$;
- the W_{85} of the first under-layer rock grading shall be smaller than or equal to $W_{Xbloc}/7$;

in which:

W_{Xbloc} = the weight of the Xbloc;
W_{15} = the stone mass for which 15% of the total sample mass is of lighter stones;
W_{50} = the stone mass for which 50% of the total sample mass is of lighter stones;
W_{85} = the stone mass for which 85% of the total sample mass is of lighter stones.

With these requirements the following must hold for the stones in the first under-layer with respect to the Xbloc units to be used in the model tests:

given $W_{Xbloc} = 49$ gram;

$$W_{15} \geq 3.27\,gram;$$
$$4.45\,gram \leq W_{50} \leq 5.44\,gram;$$
$$W_{85} \leq 7\,gram.$$

With the following formula [22] we can determine the required grading:

$$\text{grading} = \sqrt[3]{\frac{W_{85}}{W_{15}}} \tag{3.8}$$

the required grading for the stones in the first under-layer then becomes:

$$\text{grading } \leq 1.29.$$

After sieving and weighing the stones a grading of the stones of 1.23 is obtained, which indicates a narrow grading (a narrow grading holds for 1.2 – 1.5) and meets the above mentioned requirement. The W_{15}, W_{50} and W_{85} are respectively 3.64 gram, 4.95 gram and 6.78 gram which also meet the requirements as stated above.

figure 3.11: First under-layer

For the first under-layer a thickness of $2 \cdot D_{n50}$ is recommended, with W_{50} = 4.95 gram and a mass density of the stones of $2690 kg/m^3$, we get $D_{n50} = 12.3mm$. This leads to a thickness of approximately 25 mm.

To see the difference between the first under-layer and the core of the model, the stones in the first under-layer are coloured blue.

3.3.6 Core

For the core the filter rules cannot be applied. When using these rules we would get core material with the size of sand grains. With this material the core would become impermeable for waves. This causes scale effects as stated in paragraph 3.3.1 leading to wave reflection inside the model which will lead to a lower stability of the armour layer. In order to avoid this problem it is required to create a similar flow field for the prototype and the model.
To come to this similarity the method of H.F. Burcharth et al. [12] is used. This method describes how to scale the core material of a prototype rubble mound breakwater to the core material needed for the model of that breakwater (see appendix B).

To use the method of Burcharth et al. a prototype breakwater is needed, as the objective of this research is not to investigate a specific breakwater prototype, any realistic scale for the breakwater model can be used.

Assuming a scale of 1:45 we get, with D_n = 2.77cm for the model Xblocs, a D_n of 1.25m for the prototype Xbloc. From the guidelines for design using Xbloc armour units we can see that the prototype Xbloc which matches this D_n closest is the Xbloc with D_n = 1.26m. So for the Xbloc armour units of the prototype breakwater a D_n of 1.26m is chosen, which has a D of 1.82m and a design wave height H_d of 4.65m.

To determine the model wave height the following similarity between the stability numbers of the Xbloc units is used:

$$N_s = \frac{H_{s,m}}{\Delta_m D_{n,m}} = \frac{H_{s,p}}{\Delta_p D_{n,p}} \tag{3.9}$$

This stability number N_s is developed by Van der Meer [15], it is an approach to measure the stability of the armour layer of a rubble mound breakwater. He defined a value N_s, which is the number of units displaced from one strip of the breakwater with a width of D_{n50}.
For studies with respect to the stability of armour layers consisting of concrete units, this stability number N_s is often used. For Xbloc armour units this number N_s is also used to determine the stability of the armour layer [4].

For geometrical similarity the following must hold:

$$N_L = \frac{H_{s,p}}{H_{s,m}} = \frac{\Delta_p D_{n,p}}{\Delta_m D_{n,m}} \tag{3.10}$$

which can be written as:

$$N_L = \frac{H_{s,p}}{H_{s,m}} = \frac{\left(\frac{\rho_{Xbloc} - \rho_w}{\rho_w}\right)_p D_{n,p}}{\left(\frac{\rho_{Xbloc} - \rho_w}{\rho_w}\right)_m D_{n,m}} \tag{3.11}$$

with:

N_s	=	stability number	(-)
H_s	=	significant wave height	(m)
Δ	=	relative density $= \frac{\rho_{Xbloc} - \rho_w}{\rho_w}$	(-)
ρ_{Xbloc}	=	Xbloc density	(kg/m^3)
ρ_w	=	water density	(kg/m^3)
D_n	=	nominal diameter of the Xbloc armour unit	(m)
p	=	prototype	
m	=	model	

This leads to a wave height of 10cm for the model with the scale of 1:45 between the prototype breakwater and the model of the breakwater.

For the method of Burcharth et al. also a wave period T_s is needed. Wind waves have wave periods varying between 1s – 15s, as a representative wave period for the range of wave periods a wave period T_s of 9s is chosen.

With this prototype breakwater, the design wave height and a wave period of 9 seconds, the pressure gradients at different points according to figure B1 can be calculated at different times of the wave period. The following parameters are used for this calculation:

Scale 1:45	Proto type breakwater	Model breakwater
D_n (of the Xbloc units)	1.26 m	0.0277 m
D_{n50} (of the core material)	0.21 m	unknown
H_s	4.65 m	0.10 m
ρ_{Xbloc}	2400 kg/m³	2297 kg/m³
ρ_w	1030 kg/m³	1000 kg/m³
T_s	9 s	1.34 s

table 3.3: Parameters prototype and model breakwater

With the method of Forchheimer the pore velocities can be calculated at these points in time. The characteristic pore velocity in the prototype is now given by the average of all calculated pore velocities.

With a D_{n50} of 0.21m for the core material of the prototype, calculated with the filter rules [15], the characteristic pore velocity in the prototype becomes $\bar{U}^{p} = 0.0686$ m/s.

With this characteristic pore velocity and the Froude scale rule the required characteristic pore velocity in the model can be calculated, this states that $\bar{U}^{m} = \bar{U}^{p} / \sqrt{45} = 0.01023$ m/s.

With the same procedure as for the prototype breakwater the core material of the model breakwater can be determined. The only difference now is that the D_{n50} of the core material is the unknown variable and the required characteristic pore velocity in the core of the model is known.

After trial and error with the D_{n50} of the core material of the model as input variable we get D_{n50} = 10.8 mm, which complies with the required characteristic pore velocity in the model.

Because the method of H.F. Burcharth et al. is inaccurate, with respect to the α and β coefficients which cannot be determined precisely, a somewhat larger D_{n50} for the core material is used to ensure that the model is permeable enough leading to turbulent flow inside the model as it would be with a prototype breakwater.
For the core material of the model a D_{n50} of 11.5 mm is used with a grading of 1.49 which is a narrow grading.

This wider grading with respect to the first under-layer is chosen to represent the use of "quarry run" in prototype breakwaters for the core material. This "quarry run" material for the core in prototype breakwaters has a very wide grading, which is cheaper than stones with a narrow grading.

figure 3.12: Core

3.4 Testing set-up

3.4.1 Wave spectrum

To model reality as close as possible irregular waves are used during the test series. There are various spectra to model the irregular waves of a sea state, for instance the Jonswap spectrum for young sea states and the Pierson-Moskowitz spectrum for fully developed sea states.
Because a fully developed sea state hardly ever occurs along the coast where breakwaters are located, because of the limited fetch and duration of a storm the Pierson-Moskowitz spectrum is not a very realistic spectrum for coastal areas.
Therefore a Jonswap spectrum is chosen for the variance density spectrum to simulate the waves of a young sea state.

The variance density spectrum of the Jonswap spectrum is given by [19]:

$$E_{JONSWAP}\left(f\right)=\alpha g^{2}\left(2\pi\right)^{-4} f^{-5} \exp\left\{-\frac{5}{4}\left(\frac{f}{f_{peak}}\right)^{-4}\right\}\cdot\gamma^{\exp\left[-\frac{1}{2}\left(\frac{f/f_{peak}-1}{\sigma}\right)^{2}\right]} \tag{3.12}$$

with:

E = variance density (m²/Hz)
f = frequency (Hz)
f_{peak} = peak frequency (Hz)
g = gravitational acceleration (m/s²)
α = scaling parameter (Pierson-Moskowitz) (-)
γ = scaling parameter (Jonswap peak-enhancement factor) (-)
σ = scaling parameter (Jonswap peak-enhancement factor) (-)

$\sigma=\sigma_a$ for $f \le f_{peak}$ and $\sigma=\sigma_b$ for $f > f_{peak}$

For the standard Jonswap spectrum the following holds:

σ_a = 0.07
σ_b = 0.09
γ = 3.3

This standard Jonswap spectrum is used for the test series.

From the spectrum the significant wave height can be retrieved with:

$$H_s \approx H_{m_0} = 4\sqrt{m_0} \tag{3.13}$$

with $m_0=\int_0^{+\infty} E\left(f\right)df$, which is the area underneath the spectrum.

3.4.2 Testing parameters

During the test series the wave height is varied at a constant water depth and wave steepness.

Water depth

To limit wave overtopping (see paragraph 3.3.2.3) and minimize breaking of waves on the foreshore the water depth is stated at 0.55m.

Wave steepness

The local wave steepness s at the wave generator is held constant during the test series. Typical wave steepness's for wind waves are between s = 0.02 and s = 0.06. For the wave steepness used during the test series a wave steepness of s = 0.045 is chosen to cover the band of wave steepness'.

Wave height and period

The design wave height for Xbloc armour units used in the model tests is determined with the stability number formula:

$$N_s = H_s / \Delta D_n \tag{3.14}$$

For the Xbloc units used for the tests a design stability number of 2.77 is given, with the other parameters known this leads to a design wave height H_d of 10cm, which is the same wave height as used for the method of Burcharth et al.

For every test series the wave height is varied over a range of 80% to 190% of the design wave height. The wave height is increased until failure of the armour layer occurs. With the design wave height of 10cm for the given Xbloc units this gives the following wave heights H_s (significant wave height):

percentage	80%	100%	110%	120%	130%	140%	150%	160%	170%	180%	190%
Hs (cm)	8.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0

table 3.4: Wave heights H_s as percentage of the design wave height

With the wave steepness s = 0.045 and the given wave heights the wave lengths can be determined with:

$$s = \frac{H}{L} \tag{3.15}$$

with:

s = wave steepness (-)
H = wave height (m)
L = wave length (m)

This leads to the following wave lengths:

Hs (cm)	8.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0
L (cm)	178	222	244	267	289	311	333	356	378	400	422

table 3.5: Wave lengths test series

To get the desired wave steepness for the given wave heights at the given water depth in the wave flume, the wave periods have to be determined. With the wave lengths known these wave periods can be determined with the linear wave theory [6]:

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi h}{L}\right) \qquad (3.16)$$

with:

T = wave period (s)
h = water depth (m)

With $T \approx 0.9T_p$ (T_p is the peak period of the Jonswap spectrum) [19], the design wave height of 10cm for the given Xbloc units, the given wave lengths and water depth of 0.55m during every test series this leads to the following parameters used for each test series:

Hs (cm)	8.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0
Tp (s)	1.21	1.39	1.47	1.56	1.66	1.75	1.84	1.94	2.03	2.13	2.23

table 3.6: Significant wave heights and peak periods used during the test series

The significant wave heights and peak periods are the desired values for the test series as the wave generator cannot produce exactly these values. As the wave generator cannot reproduce the same values for the significant wave height and peak period for every test series again these values vary around the desired values during the test series.

Because of the limited time available for the test series 1000 waves are used for every wave height of a test series. With an average peak period of 1.7s for al tests this leads to a duration of approximately 30 minutes for a test with one wave height.

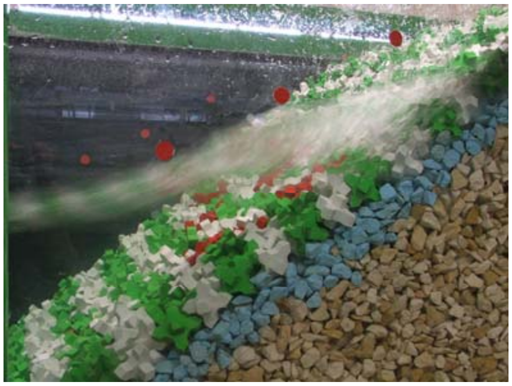

figure 3.13: Wave attack on armour layer with damaged Xbloc units

3.4.3 Configuration of broken Xbloc armour units

To asses the influence of damaged armour units on the hydraulic stability of the model test series are performed with no damaged units and with damaged units in the armour layer of the breakwater model.

The damaged units are positioned in the armour layer over a total height of two times H_d, which is the area with the highest wave loads and where the greatest influence of the damaged units can be expected [22].

As we do not know how the units will break in reality, with respect to the position and whether they break in clusters or individual, different configurations are tested.

To get a high sensitivity in the test series and to get quick results a large number of damaged Xbloc units is used. In total 15% or 7.5% of the units in the area around the still water level over a height of $2H_d$ is damaged during the test series.

The total height of this area is vertical 0.2m, with a slope of 3:4 and the width of the wave flume of 0.8m this leads to a total area of 0.267m² around the still water level. The packing density of the Xbloc units in the armour layer is $1.20/D^2$ units/m² (see table 3.1). With D = 0.04m for the Xblocs this leads to 750 units/m².
The total amount of Xblocs in the area around still water level then becomes 200 units, with 15% damaged this leads to 30 damaged units positioned in this area and with 7.5% damaged to 15 damaged units.

These units are divided in 1/3 of the total units with detached noses and 2/3 of the total units with detached legs. This ratio is chosen because the number of noses and legs on a Xbloc has the same ratio.

The damaged units are positioned 3 units away from the wave flume walls to rule out the influence of these walls on the test results (see paragraph 3.3.3.3).

Different configurations of the damaged units are tested. The damaged units are placed in clusters of 5 damaged units or random (individual). The position of the units is varied with respect to the still water line in the area of $2H_d$ around the still water line.
The following configurations are tested:

	Total series	Clusters of 5 units	Random units	Percentage
Reference tests	3	-	-	0% damaged
Clusters around s.w.l.	3	6	-	15% damaged
Clusters above s.w.l.	2	3	-	7.5% damaged
Clusters under s.w.l.	2	3	-	7.5% damaged
Random around s.w.l.	2	-	30	15% damaged

table 3.7: Different configurations tested

Reference test series

Three reference test series are performed with no broken Xblocs in the armour layer. These series are used to determine the stability of the armour layer of this specific scale model of a breakwater, which is used to compare the stability of the armour layer with and without broken units. These tests are also used to compare the stability of the model to the required stability of a Xbloc armour layer prescribed in the Xbloc guidelines.

Test series with 6 clusters of damaged units around still water level

Three test series are performed with 6 clusters of 5 damaged units, these clusters are evenly positioned over the total height of two times H_d. This way the position around the still water line, which is most sensitive to the damaged units with respect to the stability, can be determined.
The position of the clusters is as far away from each other as possible to minimize the influence of the clusters on each other.

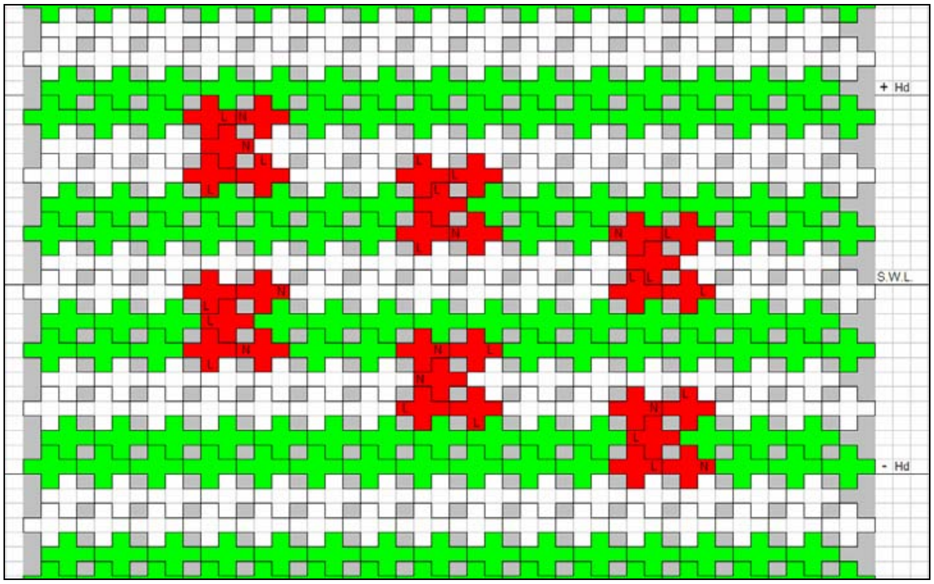

figure 3.14: 6 clusters of damaged armour units around still water level

Test series with 3 clusters of damaged units above still water level

Two test series with 3 clusters of 5 damaged units above still water level are performed to determine the difference on the stability of the armour layer between damaged units only positioned above still water level and only underneath still water level.

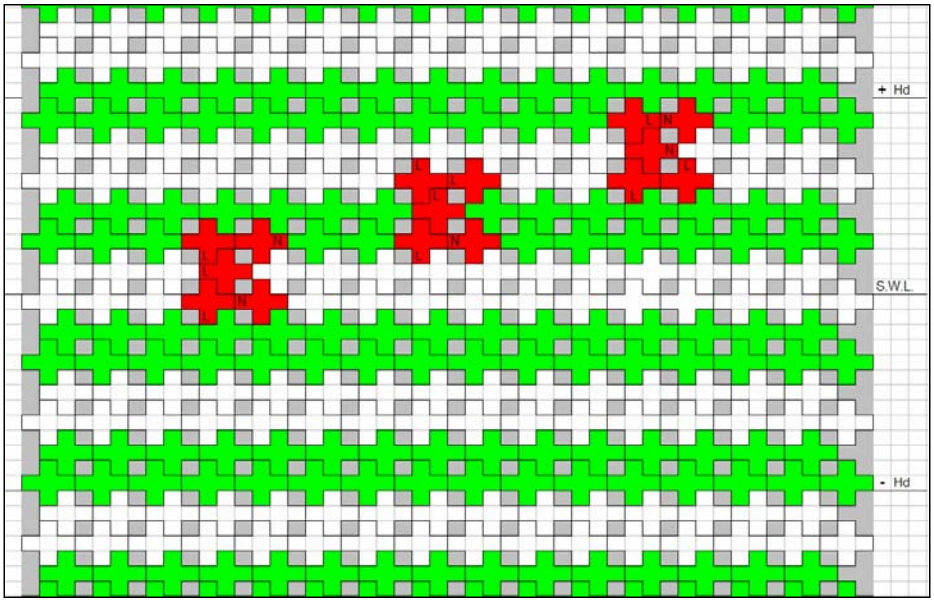

figure 3.15: 3 clusters of damaged armour units above still water level

Test series with 3 clusters of damaged units under still water level

Two test series with 3 clusters underneath still water level are performed with the same reason as for the test series with 3 clusters above still water level.

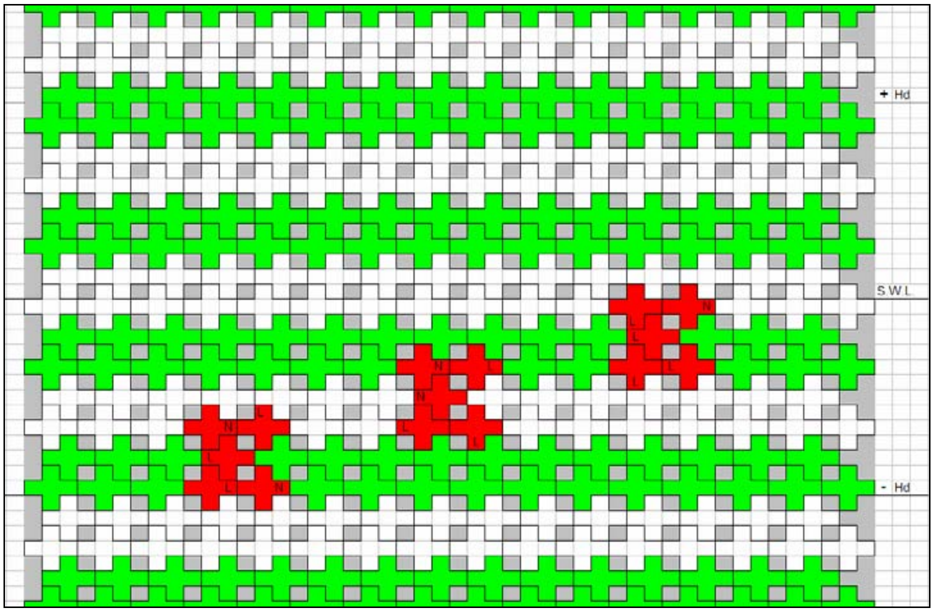

figure 3.16: 3 clusters of damaged armour units under still water level

Test series with individual random positioned damaged units

To determine the difference in influence on the stability of the armour layer between clusters and individual positioned damaged units two test series were performed with individual randomly placed damaged units.
These units are positioned as far away from each other as possible to minimize the influence on each other.

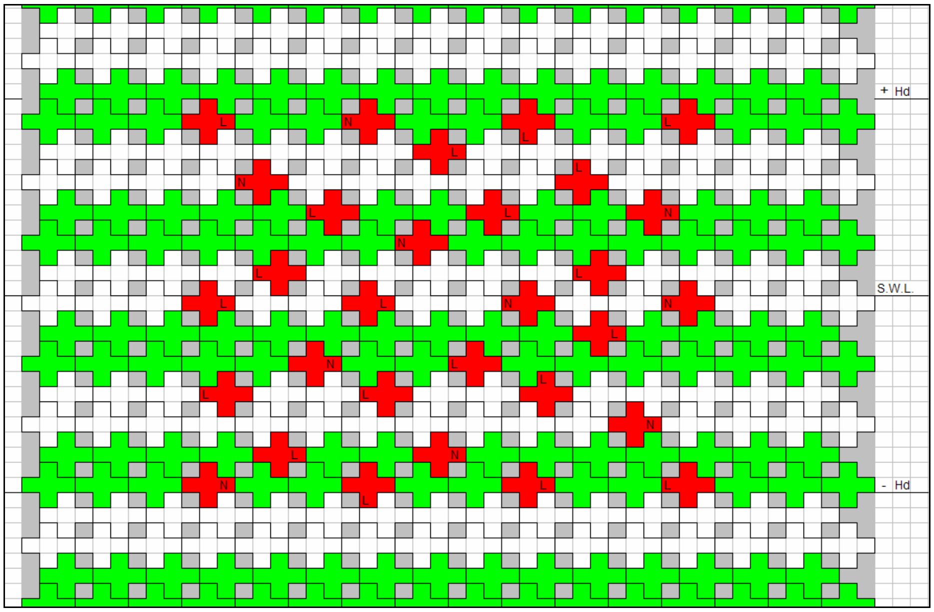

figure 3.17: Individual and random placed damaged armour units

3.4.4 Measuring and documenting test series

Measuring waves

To measure the wave heights and wave periods wave gauges are used as mentioned in paragraph 3.2. To analyse the signals from these wave gauges the program Dasylab is used. To convert these data into the desired Jonswap spectrum, wave heights and wave periods the Matlab program Decomp is used. This program separates the incoming waves and reflected waves for irregular waves and gives the desired Jonswap spectrum, wave heights (H_{m0}) and peak periods (T_p).

Displacement armour units

For measuring the damage progression of the armour layer photos are made after every test with one wave height. These photos are made with a photo camera positioned on a fixed frame above the wave flume, to ensure that every photo is made from exactly the same position. This is done to ensure the similarity between the photos with respect to the distance and angle with the breakwater model.
The position of the photo camera is rectangular to the slope of the model breakwater. This way the displacement of the Xblocs can be observed best without distortion of the

dimensions and the difference in damage of the armour layer between the different wave heights can be assessed exactly.

Displacement of an armour unit is defined as total removal of a unit from the armour layer leading to no contribution of this unit to the protection of the first under-layer.

figure 3.18: Photo's damage progression armour layer

The position of the broken Xblocs is determined before the test series, with a spreadsheet showing all positions of the Xblocs in the armour layer. The broken Xblocs are coloured red in these spreadsheets as they are in the armour layer of the model breakwater. For every test series with the same configuration, the position of the broken Xblocs is held the same to ensure uniformity in these test series, so the difference with respect to damage due to the configurations can be assessed.

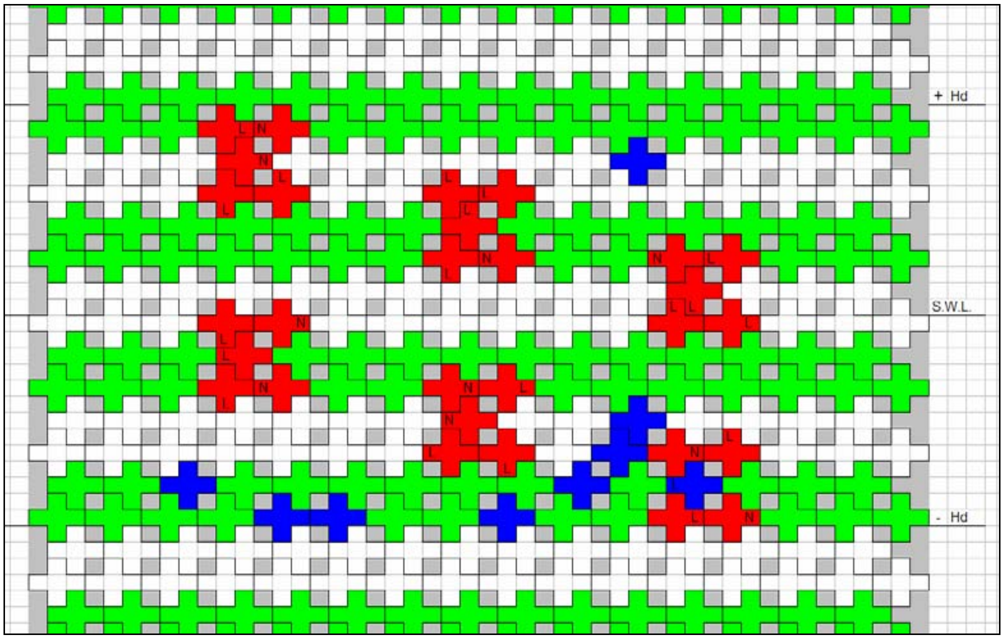

figure 3.19: Spreadsheet with damaged Xbloc units clustered positioned around still water level and displaced units represented by blue units

On these spreadsheets the displacements of the broken Xbloc units is documented. For every wave height a separate spreadsheet is used where the displaced Xblocs are represented by blue Xblocs. This way the damage progression from the test series can be assessed easily.
In the broken Xbloc units on the spreadsheet the letter N or L corresponds to respectively a broken nose or leg. The position of the broken nose or leg is presented by the place of the letter N or L in the broken Xblocs units of the spreadsheet.

Damage progression

For each test series the damage is observed. To determine whether the armour layer meets the required stability the Xbloc guidelines are used [4].

For the desired stability of the armour layer the following was observed during the tests of the Xbloc guidelines:

- start of damage occurs at $3.3 \le N_s \le 5.5$;
- failure occurs at $3.7 \le N_s \le 6.0$.

These are rather vague criteria, therefore for model tests Delta Marine Consultants states the following:

- start of damage occurs at wave heights ≥ 120% of the design wave height;

- failure occurs at wave heights ≥ 150% of the design wave height.

These criteria are used for the reference tests.

Start of damage is defined as displacement of 1 or more Xbloc units (in the order of 4 units) from the armour layer and failure is defined as displacement of several units from the armour layer (in the order of 25 units) leading to exposure of the first under layer and displacements of stones out of the first under-layer.

figure 3.20: Failure of the armour layer and exposure of the first under-layer

3.5 Summary

For the experiments a wave flume of the Fluid Mechanics Laboratory of the faculty Civil Engineering and Geosciences at Delft University of Technology is used. A 2-dimensional model of a rubble mound breakwater with a slope of 3:4 and a foreshore with a slope of 1:30 is used for the hydraulic model tests. For the armour layer of the breakwater model Xbloc armour units are used with D_n = 27.7 mm, W = 49 gram and a design wave height H_d of 10 cm.

From every model Xbloc unit that simulates a damaged Xbloc unit one nose or leg is cut off. To place the broken units, the detached nose or leg of the unit is glued back on the unit with a sugar/water solution. After placement of these units in the armour layer the water in the wave flume dissolves the sugar again. Simulating the broken units in reality as close as possible.

To model reality as close as possible irregular waves are used during the test series. A Jonswap spectrum is chosen for the variance density spectrum to simulate the waves of a young sea state. During the test series the wave height is varied over a range of 80% to 190% of the design wave height at a constant water depth of 0.55cm and a wave steepness of 0.045.

In total 15% or 7.5% of the units in the area around the still water level over a height of $2H_d$ is damaged during the test series. Different configurations of the damaged units are tested. The damaged units are placed in clusters of 5 damaged units or random (individual). The position of the units is varied with respect to the still water line.

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

Chapter 4 Experimental results

4.1 Introduction

For every test series the results are displayed in a figure with the start of damage and failure and a figure with the damage progression.

In the figures of start of damage and failure two levels of damage are used to separate the start of damage and failure. Start of damage is represented by the value 0.5 and failure by 1.0 on the y-axis. On the x-axis a dimensionless wave height is used. The significant wave height H_s ($\approx H_{m0}$) measured during the test series is divided by the design wave height H_d of 10cm. By making the wave height dimensionless the figure becomes more general and can more easily be used when other values for H_s and H_d are used.

In the figures of damage progression the cumulative number of displaced units for each wave height during the test series is given on the y-axis. This way the damage progression for every configuration can easily be observed. On the x-axis the dimensionless wave height is presented by H_s/H_d for the same reason as with the figures for start of damage and failure.

The wave heights H_s used in the figures are the wave heights measured at section 1 (between the wave generator and the foreshore). This is done to ensure that the wave steepness s is kept constant for all wave heights used during the test series.
The higher waves in the test series are subjected to breakage at the toe of the breakwater model (section 2). Therefore the waves at this section do not give a constant wave steepness during the test series.

First the test results of the reference tests will be treated. These results will also be used in the figures for the configurations with damaged units. This way the difference in start of damage, failure and damage progression between an armour layer without damaged units and an armour layer with damaged units can easily be observed.

The measured wave heights and peak periods for each test series can be found in appendix D. In appendix E the spreadsheets with the position of the displaced Xbloc units can be found. The pictures taken of the armour layer after each test with a wave height can be found in appendix F.

4.2 Reference test series

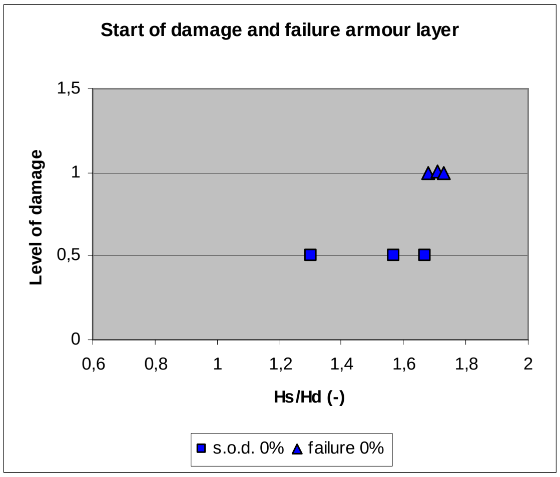

figure 4.1: Start of damage (0.5) (s.o.d.) and failure (1) of the reference tests

0% damaged		s.o.d.	failure
		Hs/Hd	Hs/Hd
	Testserie 1	1,57	1,68
	Testserie 5	1,67	1,73
	Testserie 9	1,3	1,72

table 4.1: Start of damage (s.o.d.) and failure of the reference tests

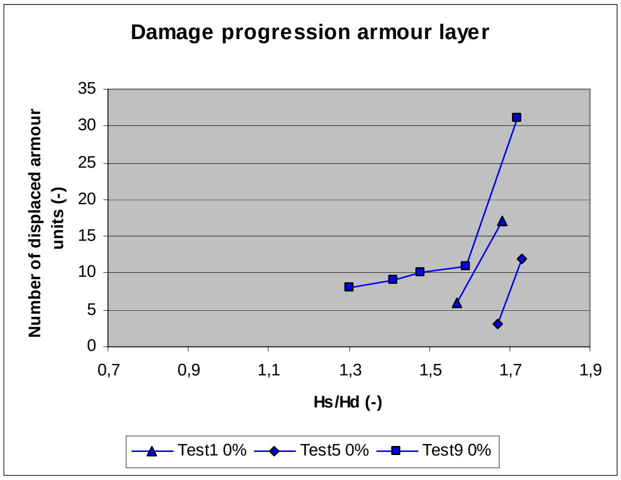

figure 4.2: Damage progression armour layer reference tests

	Test 1		Test 5		Test 9	
	Hs/Hd	units (-)	Hs/Hd	units (-)	Hs/Hd	units (-)
s.o.d.	1,57	6	1,67	3	1,3	8
					1,41	9
					1,48	10
					1,59	11
failure	1,68	17	1,73	12	1,72	31

table 4.2: Damage progression armour layer reference tests

4.2.1 Observations

At a wave height H_s of approximately 8.0cm settlement occurs under the still water line. Additional settlement is observed at higher wave heights. Due to this settlement the packing density above the still water line becomes smaller. Most of the units that are subjected to rocking are observed in this area between the still water line and one H_d above the still water line.

Start of damage occurs at approximately one H_d under the still water line. During test series 1 and 5 also failure occurs at approximately one H_d under the still water line. Failure during test series 9 occurs above the still water level.

Most of the displaced Xbloc armour units are displaced under the still water line. During run-up these units are slightly lifted up and during run-down displaced from the armour layer. This mostly occurs at high and long waves.

4.2.2 Start of damage and failure

For an armour layer with no damaged Xblocs the following must hold (see paragraph 3.4.4):

- start of damage occurs at values of $H_s/H_d \geq 1.2$;
- failure occurs at values of $H_s/H_d \geq 1.5$.

When we look at figure 4.1 we can see that the values for start of damage and failure from the reference test series represent the design guidelines for Xbloc armour units very well with an even greater stability.

4.2.3 Damage progression armour layer

When we look at the damage progression in figure 4.2 we can see two different patterns, two test series with a very fast damage progression (Test 1 and 5) and a test series (Test 9) where the damage progression goes more gradually. This is due to the fact that in the first case the damage is very concentrated, which leads to a big hole in the armour layer exposing the first under-layer very fast. In the second case the displacement of the armour units is more divided over the armour layer giving the other units the chance to resettle and fill in the holes left open by the displaced units. Eventually a big hole exposing the first under-layer also appears in this type of more gradual damage progression.

4.3 Test series with 6 clusters of damaged units around still water level

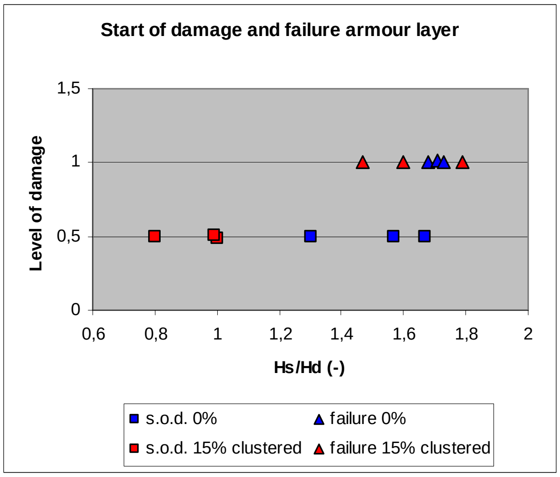

figure 4.3: Start of damage (0.5) (s.o.d.) and failure (1) with six clusters of damaged units around still water level

15% damaged	6 clusters	s.o.d.	failure
		Hs/Hd	Hs/Hd
	Testserie 3	0,8	1,79
	Testserie 4	1,01	1,47
	Testserie 6	0,99	1,6

table 4.3: Start of damage (s.o.d.) and failure with six clusters of damaged units around still water level

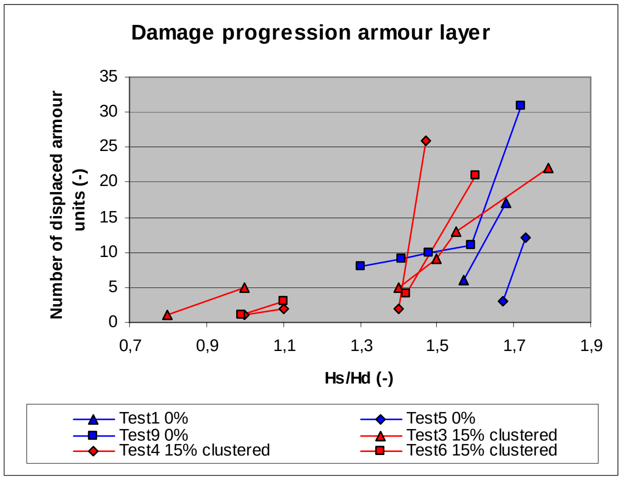

figure 4.4: Damage progression armour layer with six clusters of damaged units around still water level

	Test 3		Test 4		Test 6	
	Hs/Hd	units (-)	Hs/Hd	units (-)	Hs/Hd	units (-)
s.o.d.	0,8	1	1	1	0,99	1
	1	5	1,1	2	1,1	3
	1,5	9			1,42	4
	1,55	13				
failure	1,79	22	1,47	26	1,6	21

table 4.4: Damage progression armour layer with six clusters of damaged units around still water level

4.3.1 Observations

At a wave height H_s of approximately 8.0cm settlement occurs under the still water line. Additional settlement is observed at higher wave heights. Due to this settlement the packing density above the still water line becomes smaller.
This smaller packing density is concentrated between and slightly above the clusters. This is the area between the still water level and one H_d above the still water level. The smaller packing density leads to small gaps in the armour layer in this area. The clusters under the still water line are compressed and the clusters above the still water line widened due to the settlement.

Most of the units that are subjected to rocking are observed in the area between the still water line and one H_d above the still water line where the packing density is smaller.

The start of damage occurs under the still water line and is for two test series a damaged armour unit and for one test series a non-damaged unit in the surroundings of a cluster (see table 4.5). During all three test series the start of damage occurs at approximately one H_d under the still water level (between 0.5 and 1.5 H_d under the still water level).

start of damage	displaced units	
	damaged units	non-damaged units
test 3	1	0
test 4	1	0
test 6	0	1

table 4.5: Displaced armour units at start of damage

Failure occurs under the still water line. Therefore most of the displaced Xbloc armour units are displaced under the still water line. During run-up these units are slightly pushed up the slope and lifted from the first under-layer to be displaced from the armour layer during run-down. This mostly occurs at high and long waves.

During the damage progression of the three test series only 1 or 2 damaged armour units are displaced from the armour layer for each test series. So the majority of the displaced units during the test series are non-damaged Xbloc units. These units are generally positioned around the clusters with damaged units.

When we look at the percentage of displaced damaged and non-damaged armour units we see no significant difference (see table 4.6). For this comparison the units in the area between $-H_d$ and $+H_d$ are used. This is the area where the damaged units are positioned. In this area the damaged units and the non-damaged units are subjected to the same wave forces. This way we can better determine whether damaged units are relatively displaced more easily during the test series. The damaged units were placed 3 units away from the glass walls of the wave flume to rule out the negative influence of these walls on the units (see paragraph 3.4.3). Therefore these units at the walls are not taken in to account, as they might be more unstable then normal non-damaged units. To compare the damaged units with the non-damaged the average number of displaced units during the test series is divided by the total of each type of unit used in the area between $-H_d$ and $+H_d$.

failure	displaced units	
	damaged units	non-damaged units
test 3	2	15
test 4	2	2
test 6	1	4
average per test serie	1.7	7
total positioned in the area	30	94
percentage displaced	5.6%	7.5%

table 4.6: Displaced armour units at failure as percentage of the total of these units used in the area between –Hd and +Hd

When we look at the difference between the amount of displaced units with a nose or a leg detached we see no significant difference during the tests series (see Appendix C).

Looking at the orientation of the detached parts we see that no units with the detached parts pointing upwards are displaced during the test series. The other orientations (detached part pointing left, right or down) show no significant difference in the relative amount of displaced units (see Appendix C).

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer.
Only a few parts (order 2) show displacement (displacement is defined as movement of the detached part over a distance of more than the D_n of a Xbloc unit). After this displacement these parts settle again in the armour layer.

4.3.2 Start of damage and failure

When we look at figure 4.3 we can see a significant difference between the start of damage of the reference test series (0% damaged) and the test series with 6 damaged clusters (15% damaged). The start of damage for the test series with 6 clusters starts at significant lower wave heights compared to the reference test series. On the other hand when we look at failure for both configurations we see that failure occurs at approximately the same values.

To investigate whether the start of damage can occur at lower wave heights than a wave height of 8cm, wave heights of 6 and 7 cm were added to the testing program of test series 6. Because the start of damage of test series 3 and 4 were at respectively wave heights of 8 and 10cm also a wave height of 9cm was added to the test series to determine the value of the wave height at which start of damage occurs more accurate.
As start of damage of test series 6 occurred at a wave height of 10cm the wave heights of 6 and 7cm were removed from the testing program. The wave height of 9cm was kept in the testing programme to determine the start of damage of the test series more accurate.

4.3.3 Damage progression armour layer

From figure 4.4 it can be seen that the damage progression for both configurations differs significantly. The damage with 6 clusters of damaged units in the armour layer starts at significantly lower wave heights with respect to the reference tests with no damaged units in the armour layer. However after the start of damage the armour layer stabilizes again and further damage and failure occurs at approximately the same values of respectively start of damage and failure of the reference test series. So after start of damage the armour layer with damaged units stabilizes again and continues to behave more like an armour layer with no damaged Xbloc units.

4.4 Test series with 3 clusters of damaged units above still water level

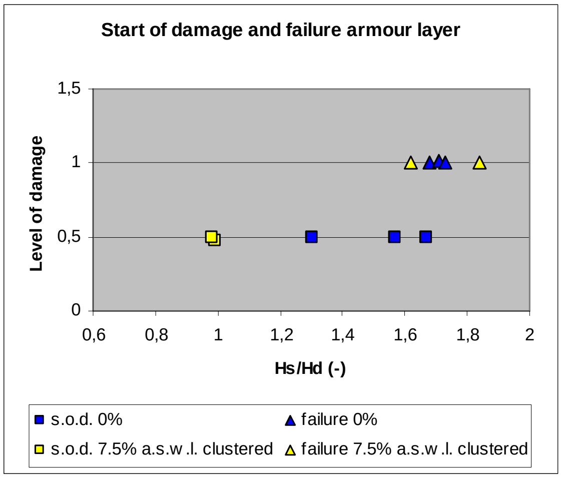

figure 4.5: Start of damage (0.5) (s.o.d.) and failure (1) with three clusters of damaged units above still water level

7.5% damaged 3 clusters	above s.w.l.	s.o.d.	failure
		Hs/Hd	Hs/Hd
	Testserie 7	0,99	1,84
	Testserie 8	0,99	1,61

table 4.7: Start of damage (s.o.d.) and failure with three clusters of damaged units above still water level

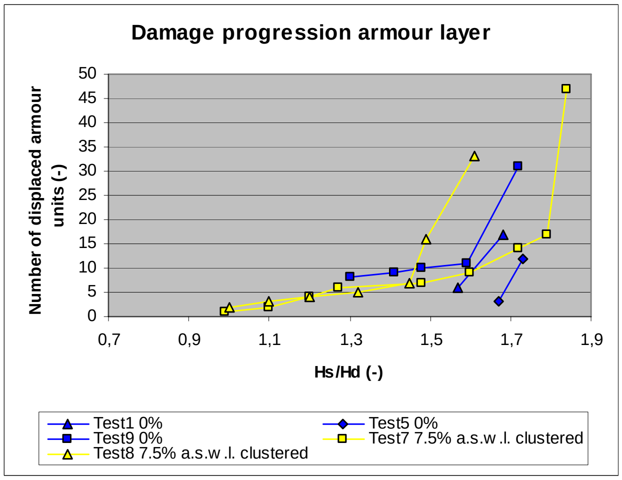

figure 4.6: Damage progression armour layer with three clusters of damaged units above still water level

	Test 7		Test 8	
	Hs/Hd	units (-)	Hs/Hd	units (-)
s.o.d.	0,99	1	1	2
	1,1	2	1,1	3
	1,2	4	1,2	4
	1,27	6	1,32	5
	1,48	7	1,45	7
	1,6	9	1,49	16
	1,72	14		
	1,79	17		
failure	1,84	47	1,61	33

table 4.8: Damage progression armour layer with three clusters of damaged units above still water level

4.4.1 Observations

At a wave height H_s of approximately 8.0cm settlement occurs under the still water line. Additional settlement is observed at higher wave heights. Due to this settlement the packing density above the still water line becomes smaller.
This smaller packing density is concentrated around the clusters. This is the area between the still water level and one H_d above the still water level. The smaller packing density leads to small gaps in the armour layer in this area. The clusters are widened due to this settlement.

Most of the units that are subjected to rocking are observed in this area between the still water line and one H_d above the still water line where the packing density is smaller.

During start of damage 1 or 2 non-damaged armour units are displaced (see table 4.9). The start of damage occurs at approximately one H_d under the still water level (between 0.5 and 1.5 H_d under the still water level) where no damaged armour units are positioned.

start of damage	displaced units	
	damaged units	non-damaged units
test 7	0	1
test 8	0	2

table 4.9: Displaced armour units at start of damage

Also failure occurs under the still water line. Therefore most of the displaced Xbloc armour units are displaced under the still water line. During run-up these units are slightly pushed up the slope and lifted from the first under-layer to be displaced from the armour layer during run-down. This mostly occurs at high and long waves.

During the damage progression of the two test series 0 or only 2 damaged armour units are displaced from the armour layer. The majority of the displaced units during the test series are non-damaged Xbloc units.

When we look at the percentage of displaced damaged and non-damaged armour units we see that relatively almost twice as much non-damaged armour units are displaced during the test series compared to the relative amount of displaced damaged units (see table 4.10). For this comparison the units in the area between still water level and $+H_d$ are used.

failure	displaced units	
	damaged units	non-damaged units
test 7	2	10
test 8	0	3
average per test serie	1	6.5
total positioned in the area	15	52
percentage displaced	6.7%	12.5%

table 4.10: Displaced armour units at failure as percentage of the total of these units used in the area between still water level and +Hd

When we look at the difference between the amount of displaced units with a nose or a leg detached we see that no units with a detached nose are displaced during the tests series (see Appendix C).

Looking at the orientation of the detached parts we see that no units with the detached parts pointing left or right are displaced during the test series. The other orientations (detached part pointing up or down) show no significant difference in the relative amount of displaced units (see Appendix C).

All of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer.
Figure 4.7 shows that every detached nose or leg is still on the first under-layer in the place where the damaged clusters were and some of the parts lie deep in between the stones of the first under-layer.

4.4.2 Start of damage and failure

When we look at figure 4.5 we can see a significant difference between the start of damage of the reference test series (0% damaged) and the test series with 3 damaged clusters (7.5% damaged) above still water level. The start of damage for the test series with 3 clusters above still water level starts at significant lower wave heights compared to the reference test series. Failure occurs at approximately the same values for both configurations.

4.4.3 Damage progression armour layer

From figure 4.6 it can be seen that the damage progression for both configurations differs significantly. The damage progression with 3 clusters of damaged units in the armour layer above still water level starts at significantly lower wave heights with respect to the reference tests with no damaged units in the armour layer. After start of damage the damage progression continues until failure occurs. The values of the wave height at which failure occurs is approximately the same as for the reference test series.

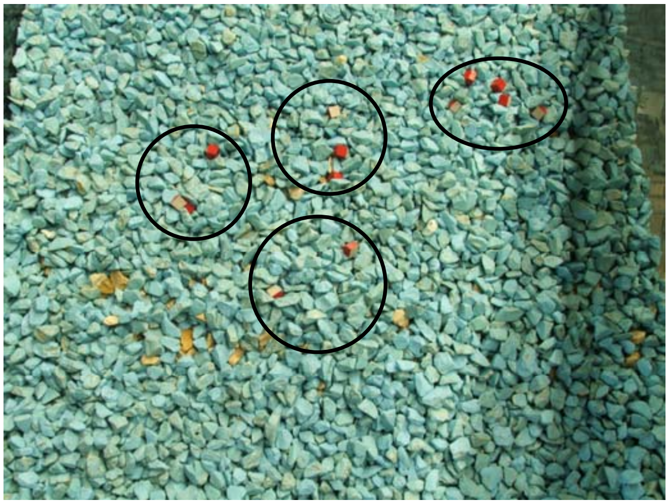

figure 4.7: Legs and noses in and on the first under-layer after removal of the armour layer still at the position where the damaged clusters were positioned

4.5 Test series with 3 clusters of damaged units under still water level

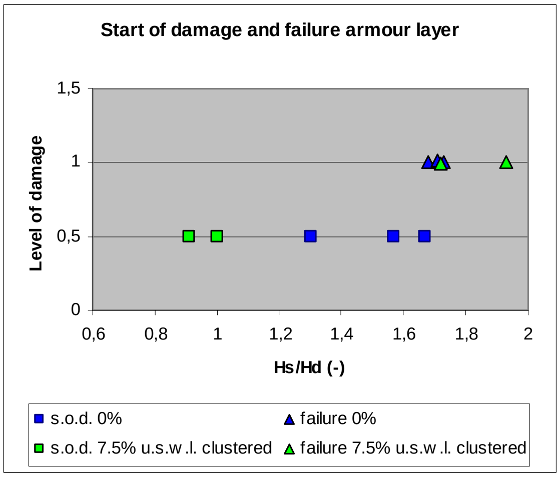

figure 4.8: Start of damage (0.5) (s.o.d.) and failure (1) with three clusters of damaged units under still water level

7.5% damaged 3 clusters	under s.w.l.	s.o.d.	failure
		Hs/Hd	Hs/Hd
	Testserie 10	1,0	1,93
	Testserie 11	0,91	1,72

table 4.11: Start of damage (s.o.d.) and failure with three clusters of damaged units under still water level

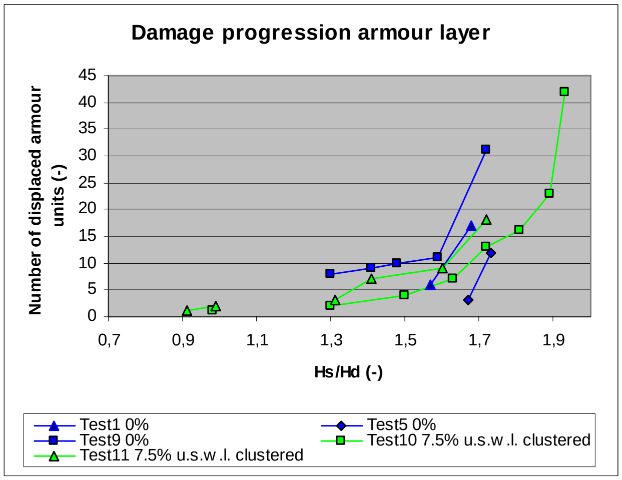

figure 4.9: Damage progression armour layer with three clusters of damaged units under still water level

	Test 10		Test 11	
	Hs/Hd	units (-)	Hs/Hd	units (-)
s.o.d.	0,98	1	0,91	1
	1,3	2	0,99	2
	1,5	4	1,31	3
	1,63	7	1,41	7
	1,72	13	1,6	9
	1,81	16		
	1,89	23		
failure	1,93	42	1,72	18

table 4.12: Damage progression armour layer with three clusters of damaged units under still water level

4.5.1 Observations

At a wave height H_s of approximately 8.0cm settlement occurs under the still water line. Additional settlement is observed at higher wave heights. Due to this settlement the packing density above the still water line becomes smaller.
This is the area between the still water level and one H_d above the still water level. The smaller packing density leads to small gaps in the armour layer in this area. The clusters are compressed due to this settlement.

Most units that are subjected to rocking are observed in the area between the still water line and one H_d above the still water line where the packing density is smaller.

Start of damage occurs at approximately between still water level and one H_d under the still water level. For both test series this is a non-damaged unit in the surroundings of a cluster of damaged units (see table 4.13).

start of damage	displaced units	
	damaged units	non-damaged units
test 10	0	1
test 11	0	1

table 4.13: Displaced armour units at start of damage

During test series 10 failure occurs above the still water level in the area between the still water level and one H_d above the still water level. During test series 11 failure occurs under the still water level in the area between the still water level and one H_d under the still water level.
During run-up the displaced units under the still water level are slightly pushed up the slope and lifted from the first under-layer to be displaced from the armour layer during run-down. This mostly occurs at high and long waves.

Only 2 damaged units were displaced during the test series so the majority of the displaced units during the test series are non-damaged Xbloc units.

When we look at the percentage of displaced damaged and non-damaged armour units we see no significant difference (see table 4.14). For this comparison the units in the area between $-H_d$ and still water level are used.

failure	displaced units	
	damaged units	non-damaged units
test 10	2	9
test 11	2	9
average per test serie	2	9
total positioned in the area	15	52
percentage displaced	13.3%	17.3%

table 4.14: Displaced armour units at failure with percentage from the total of these units used in the area between –Hd and still water level

When we look at the difference between the amount of displaced units with a nose or a leg detached we see no significant difference during the tests series (see Appendix C).

Looking at the orientation of the detached parts we see that no units with the detached parts pointing upwards are displaced during the test series. The other orientations (detached part pointing left, right or down) show no significant difference in the relative amount of displaced units (see Appendix C).

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer.
Only a few parts (order 3) show displacement. After this displacement these parts settle again in the armour layer.

4.5.2 Start of damage and failure

When we look at figure 4.8 we can see a significant difference between the start of damage of the reference test series (0% damaged) and the test series with 3 damaged clusters (7.5% damaged) under the still water line. The start of damage for the test series with 3 clusters under still water level starts at significant lower wave heights compared to the reference test series. On the other hand when we look at failure for both configurations we see that failure occurs at approximately the same values.

4.5.3 Damage progression armour layer

From figure 4.9 it can be seen that the damage progression for both configurations differs significantly. The damage with 3 clusters of damaged units in the armour layer starts at significantly lower wave heights with respect to the reference tests with no damaged units in the armour layer. After the start of damage the armour layer stabilizes again and further damage and failure occurs at approximately the same values of respectively start of damage and failure of the reference test series. So after start of damage the armour layer with damaged units stabilizes again and continues to behave more like an armour layer with no damaged Xbloc units.

4.6 Test series with individual random positioned damaged units

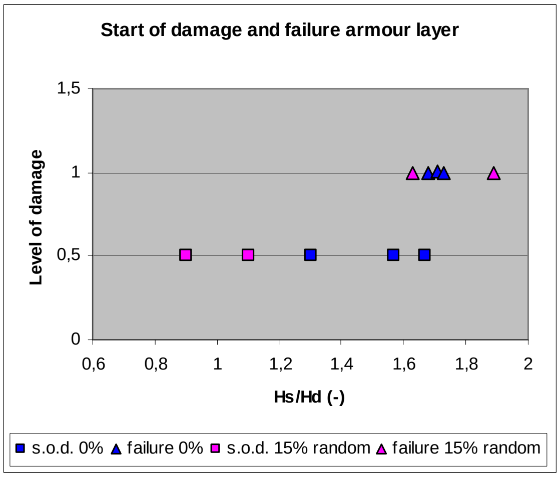

figure 4.10: Start of damage (0.5) (s.o.d.) and failure (1) with individual random positioned damaged units

15% damaged random	individual	s.o.d.	failure
		Hs/Hd	Hs/Hd
	Testserie 12	1,1	1,89
	Testserie 13	0,91	1,63

table 4.15: Start of damage (s.o.d.) and failure with individual random positioned damaged units

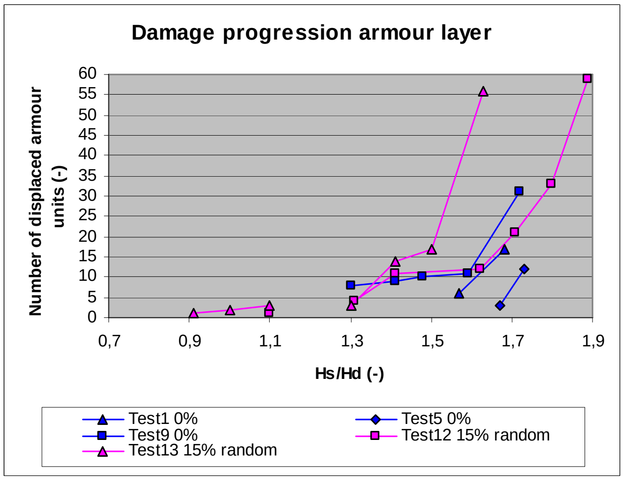

figure 4.11: Damage progression armour layer with individual random positioned damaged units

	Test 12		Test 13	
	Hs/Hd	units (-)	Hs/Hd	units (-)
s.o.d.	1,1	1	0,91	1
	1,31	4	1	2
	1,41	11	1,1	3
	1,62	12	1,41	14
	1,71	21	1,5	17
	1,8	33		
failure	1,89	59	1,63	56

table 4.16: Damage progression armour layer with individual random positioned damaged units

4.6.1 Observations

At a wave height H_s of approximately 8.0cm settlement occurs under the still water line. Additional settlement is observed at higher wave heights. Due to this settlement the packing density above the still water line becomes smaller.
This is the area between the still water level and one H_d above the still water level. The smaller packing density leads to small gaps in the armour layer in this area. Under the still water line the area with damaged units is compressed and above the still water line the area with damaged units is widened due to the settlement.

Most units that are subjected to rocking are observed in the area between the still water line and one H_d above the still water line where the packing density is smaller.

The start of damage at test series 12 occurs at approximately one H_d above the still water level. The start of damage at test series 13 occurs at approximately one H_d under the still water level. For both test series this is a non-damaged unit in the surroundings of a damaged unit (see table 4.17).

start of damage	displaced units	
	damaged units	non-damaged units
test 12	0	1
test 13	0	1

table 4.17: Displaced armour units at start of damage

During test series 12 failure occurs around the still water level in the area between one H_d under the still water level and one H_d above the still water level. During test series 13 failure occurs above the still water level in the area between the still water level and one H_d above the still water level.
During run-up the displaced units under the still water level are slightly pushed up the slope and lifted from the first under-layer to be displaced from the armour layer during run-down.

Most of the displaced units are non-damaged units. For each test series 5 damaged units were displaced from the armour layer.

When we look at the percentage of displaced damaged and non-damaged armour units we see no significant difference (see table 4.18). For this comparison the units in the area between $-H_d$ and $+H_d$ are used.

failure	displaced units	
	damaged units	non-damaged units
test 12	5	19
test 13	5	13
average per test serie	5	16
total positioned in the area	30	94
percentage displaced	16.7%	17%

table 4.18: Displaced armour units at failure with percentage from the total of these units used in the area between –Hd and +Hd

When we look at the difference between the amount of displaced units with a nose or a leg detached we see no significant difference during the tests series (see Appendix C).

Looking at the orientation of the detached parts we see that no units with the detached parts pointing up wards are displaced during the test series. The other orientations (detached part pointing left, right or down) show no significant difference in the relative amount of displaced units (see Appendix C).

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer.
Only a few parts (order 3) show displacement. After this displacement these parts settle again in the armour layer.

4.6.2 Start of damage and failure

When we look at figure 4.10 we can see a significant difference between the start of damage of the reference test series (0% damaged) and the test series with the individual randomly placed damaged units (15% damaged). The start of damage for the test series with the individual randomly placed damaged units starts at significant lower wave heights compared to the reference test series. On the other hand when we look at failure for both configurations we see that failure occurs at approximately the same values.

4.6.3 Damage progression armour layer

From figure 4.11 it can be seen that the damage progression for both configurations differs significantly. The damage with the individual randomly placed damaged units in the armour layer starts at significantly lower wave heights with respect to the reference tests with no damaged units in the armour layer.
After the start of damage the armour layer stabilizes again and further damage and failure occurs at approximately the same values of respectively start of damage and failure of the reference test series. So after start of damage the armour layer with damaged units stabilizes again and continues to behave more like an armour layer with no damaged Xbloc units.

4.7 Summary

For all test series with damaged units start of damage occurs at significant lower wave heights compared to the reference test series. Failure occurs at approximately the same wave heights for both test series with and without damaged units in the armour layer. Start of damage mostly occurs at approximately one H_d under the still water line (between -0.5 H_d and -1.5 H_d). This is generally a non-damaged unit in the surroundings of damaged units.

After start of damage for the configuration with 3 clusters of 5 damaged units above still water level the damage progression continues until failure occurs
For the other configurations with damaged units the armour layer stabilizes again after start of damage and further damage and failure occurs at approximately the same values of respectively start of damage and failure of the reference test series.

During the damage progression only in the order of 2 damaged armour units are displaced from the armour layer. The majority of the displaced units during the test series are therefore non-damaged Xbloc units. Most of the displaced Xbloc armour units are displaced under the still water line.

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer.
Only a few parts (order 3) show displacement. After this displacement these parts settle again in the armour layer.

Chapter 5 Discussion of results

5.1 Introduction

In this chapter the measurements and observations of the test series with respect to start of damage and failure, damage progression and the behaviour of the detached noses and legs will be further discussed.
The different configurations with damaged units will be compared with each other and with the reference tests with respect to the start of damage and failure and damage progression.
The behaviour of the detached parts for the different configurations with damaged units will be compared with each other.
First the general observations will be discussed.

5.2 Discussion general observations

Greater stability reference tests compared to required stability of Xbloc guidelines

In paragraph 4.2 we saw that the reference test series have a greater stability compared to the required stability of the Xbloc guidelines. This might be caused by the permeable backside of the model. Normally a breakwater has a rear slope through which the waves also have to propagate. This rear slope is replaced by the permeable backside. Therefore the waves have to propagate through only half of the normal breakwater. This leads to a decrease of wave induced pore pressure inside the model. This could lead to a more stable armour layer compared to a normal breakwater with a rear slope used for the tests to determine the requirements of the Xbloc guidelines.

Early settlement

During every test series early settlement was observed at a wave height of approximately H_s = 8.0cm. This might be caused by the relatively long slope of the model. Due to this long slope approximately 40 rows of Xbloc armour units were needed for the armour layer on the slope. Normally a breakwater only needs approximately 15 to 20 rows. So twice the number of rows is used compared to a normal breakwater. Therefore more settlement can be expected and at an earlier stage.

Vulnerable area for displacement

During start of damage generally most of the displaced armour units are displaced in the area between 0.5 and 1.5 H_d under the still water level. Apparently this is the most vulnerable area for displacement of armour units. Start of damage occurs at significantly lower levels than required generally due to damaged armour units in this area.

Rocking

Most units that are subjected to rocking are observed in the area between the still water line and one H_d above the still water line where the packing density is smaller due to settlement under still water level. As the packing density becomes smaller the interlocking capacity decreases. Therefore the Xbloc units become more vulnerable to rocking. Under the still water line the packing density becomes larger as settlement occurs in this area. This leads to an increased interlocking capacity of the units. Therefore the units in this area are less vulnerable to rocking and less rocking is observed.
It is therefore unlikely that a large amount of armour units are damaged in the area between $0.5\,H_d$ and $1.5\,H_d$ under the still water line due to rocking, which is the most vulnerable area for displacement of armour units during start of damage.
It must be noted that this behaviour of rocking can be caused by the settlement due to the long slope used for the model.

Difference displacement between units with detached nose or leg and their orientation

During the test series generally no significant difference is observed between the relative amount of displaced armour units with a detached nose or leg. Apparently breaking of a nose or a leg has the same effect on the decrease of the stability of a Xbloc armour unit. This could be expected as both nose and leg have approximately the same shape and mass.

Generally the units with a detached part pointing upwards are not displaced. Apparently breakage of parts pointing upwards does not lead to a higher vulnerability of displacement.

This would mean that these parts contribute to a lesser extend to the interlocking capacity of a Xbloc armour unit.
However the two units positioned above this unit are partially secured by the part pointing upwards of this unit. Breaking of this part leads to a lower interlocking capacity of the two units positioned above of the damaged unit.
Also it must be noted that only a few of these kind of Xbloc units were used compared to the units with other orientations of the detached parts. The chance that a unit with a detached part pointing upwards is displaced is therefore smaller.

The relative amount of displaced units with detached parts orientated in the other directions (left, right and up) show no significant differences. Apparently the other orientations of the detached parts have no influence on the displacement of a damaged unit.

5.3 Start of damage and failure of different configurations with damaged units

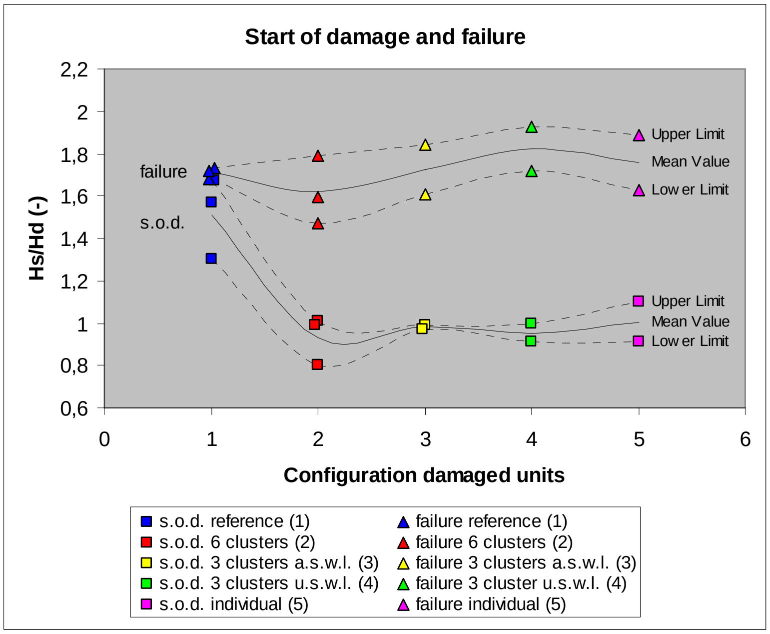

figure 5.1: Start of damaged and failure for the different tested configurations with lower limits, mean values and upper limits

For figure 5.1 all data with respect to start of damage and failure for the different configurations determined during the test series are used. Figure 5.1 shows clearly that the damaged Xbloc units have a significant negative effect on the start of damage. The 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 occurs at approximately the same values of H_s/H_d for all configurations including the reference test series. The decrease of interlocking capacity and mass of the damaged units apparently do not significantly influence the failure of the armour layer.

Comparing the different configurations with damaged units we see that the values of H_s/H_d of start of damage and failure are a little more favourable for one configuration compared to another. The differences between the configurations will be elaborated in the next paragraphs.

During start of damage it is observed that in most cases non-damaged units adjacent to damaged units are 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 apparently primarily an interlocking problem and is not caused by the decrease of mass of the damaged armour units.

There is little known about the interlocking capacity of armour units and its behaviour is not fully understood. Delta Marine Consultants has done research on the interlocking capacity of the Xbloc [21]. The probability of occurrence and exceedence of the relative pullout force F/G (with pullout force F and unit weight G) is shown in figure 5.2. To pull out a non-damaged Xbloc unit from the armour layer a mean pull out force of approximately 7 times the weight of the Xbloc unit was needed (see figure 5.2 and table 5.1). In this research the results of pullout experiments with rock are used for comparison [18]. Figure 5.2 and table 5.1 show that the average pullout force for rock is about 1.8G. So the force needed to pull out an armour unit of rock is approximately 2 times the weight of the armour unit.

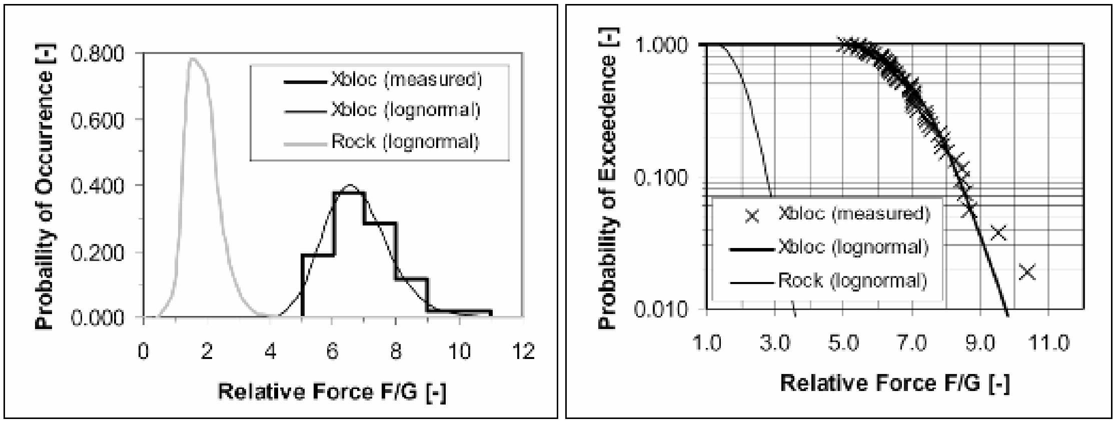

figure 5.2: Results of Xbloc pull out tests [21]

Type of armour	Estimated lognormal parameters			Relative pullout force			
	μ	σ	R^2	$F_{10\%}/G$	$F_{50\%}/G$	$F_{90\%}/G$	F_{mean}/G
Rock	0.6	0.26	0.97	2.6	1.8	1.3	1.8
Xbloc	1.9	0.15	0.99	8.4	6.7	5.7	6.9

table 5.1: Pullout tests force distribution for Xbloc and rock armour [21]

In total only a small amount of damaged armour units were displaced during the test series. Therefore it can be stated that damaged units with broken noses or legs show minor decrease of their interlocking capacity compared with non-damaged units.

Due to the observed minor decrease of the interlocking capacity of the damaged Xbloc armour units the mean pullout force of damaged Xbloc armour units is assumed to be in the order of 6G.

This would mean that by removing a nose or leg from the unit the force needed to remove the unit from the armour layer decreases with one times the weight of a unit. By breaking off a leg or nose the total weight of the unit only reduces with approximately 10%. The force needed to displace the weight of the unit decreases therefore with only 10% of the unit weight. The displaced units adjacent to the damaged units do not have a loss of mass. They however do suffer from the same decrease of interlocking capacity as the damaged units. Therefore it can be stated that the negative influence of damaged armour units on the start of damage is primarily an interlocking problem and is not caused by the decrease of mass of the damaged armour units.

5.4 Comparison start of damage and failure of different configurations

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 comparing 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 of a breakwater.

It must be noted that the spreading of the values of start of damage and failure is rather large and the amount of tests performed for every configuration very limited. There are some differences between the different configurations with damaged units and one configuration may look more positive than another. However one must be very careful interpreting the outcomes of the different configurations compared to each other due to the large spreading and limited performed tests.

The amount of tests done for a specific configuration is too small to use statistics for the comparison of the configurations. The outcomes of these statistics would be too unreliable.

Also the use of calculated differences between the configurations would suggest a false accuracy due to the limited amount of tests performed. Therefore only the behaviour of the differences is treated. Occasionally a difference is quantified as an indication.

5.4.1 Start of damage and failure with different percentages of damaged units

In figure 5.3 the data from the reference tests and the data from the test series with 3 clusters above and under the still water line are respectively used for the data of 0% and 7.5% damaged units. The test series with 6 clusters and individual random placed units are used for the data of 15% damaged units.

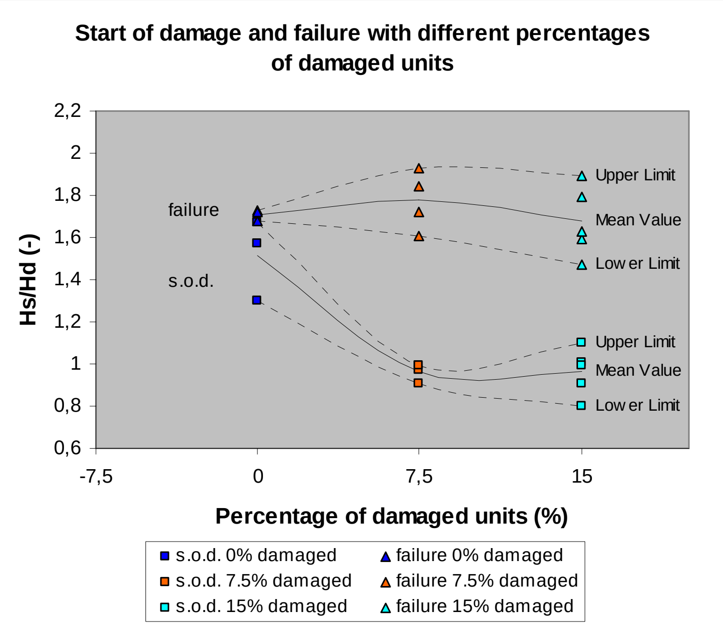

figure 5.3: Start of damage and failure with different percentages of damaged units with lower limits, mean values and upper limits

Looking at the lower limits figure 5.3 shows that with an increasing percentage of damaged units that the start of damage and failure occur at lower values of H_s/H_d. The decrease of H_s/H_d at start of damage is significantly between 0% and 7.5% damaged units. Between 7.5% and 15% damaged units the rate at which H_s/H_d decreases becomes smaller. The decrease of H_s/H_d for failure occurs at a more or less constant rate. This rate of decrease is however small compared to the rate of decrease of start of damaged observed between 0% and 7.5% damaged units.

Apparently increasing the percentage of damaged units in the armour layer from 0% to 7.5% increases the negative influence of damaged units on start of damage significantly. Increasing the percentage of damaged units in the armour layer from 7.5% to 15% does not give a significant additional increase of the negative influence of damaged units on start of damage.
For failure the increase of damaged units from 0% to 15% leads to a constant minor increase of the negative influence.

No tests have been done with percentages between 0% and 7.5% damaged units. Tests with lower percentages of damaged units may also have a significant influence on start of damage leading to a different curve between 0% and 7.5% damaged units.

5.4.2 Start of damage and failure with different numbers of damaged units clustered

In figure 5.4 the data from all test series, except for the series with 3 clusters of damaged units, were used and 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.

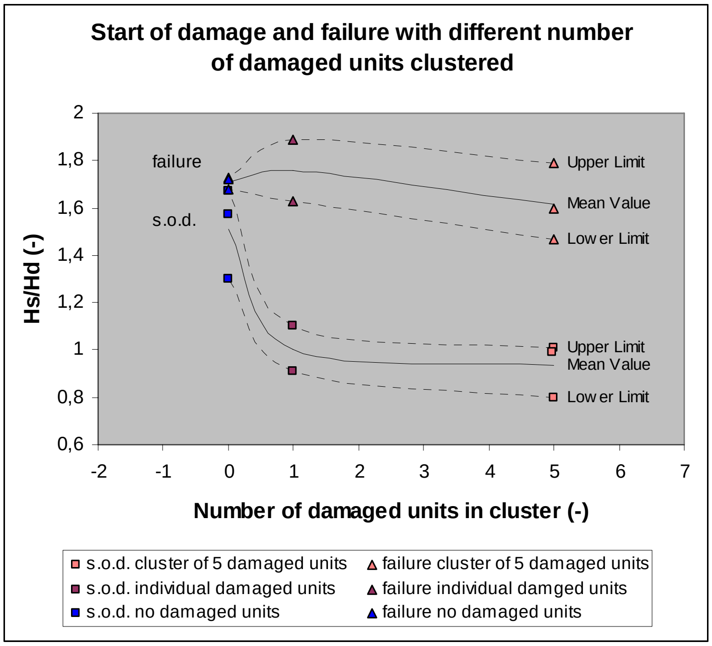

figure 5.4: Start of damage and failure with different numbers of damaged units clustered with lower limits, mean values and upper limits

The lower limits in figure 5.4 show that with an increasing number of damaged units in a cluster that the start of damage and failure occurs at lower values of H_s/H_d. The decrease of H_s/H_d at start of damage is significantly between 0 damaged units and damaged units placed individual. Between 1 damaged unit and 5 damaged units in a cluster the rate at which H_s/H_d decreases becomes significantly smaller. The decrease of H_s/H_d for failure occurs at a more or less constant rate. This rate of decrease is however small compared to the rate of decrease of start of damaged observed between 0 damaged units and individual damaged units.

Apparently increasing the number of damaged units in a cluster from 0 to 1 has a significant influence on the start of damage.
Increasing the number of damaged units in a cluster from 1 to 5 units gives no significant additional increase of the influence on start of damage. Clusters with 2, 3 or 4 damaged units probably give the same behaviour as for individual placed units and clusters of 5 units with respect to start of damage.

Increasing the number of damaged units in a cluster from 0 to 5 gives a constant small increase of the negative influence on failure. Clusters with 2, 3 or 4 damaged units probably give a behaviour on the line between individual placed units and clusters of 5 units with respect to failure. This behaviour would be almost similar to the behaviour of 1 and 5 damaged units in a cluster.

5.4.3 Start of damage and failure with different positions of damaged units

In figure 5.5 the data from the test series with 3 clusters above and under the still water line are used. 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 5.5 the average distance from the clusters of each configuration 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 $0.5\,H_d$ and the mean position from the 3 clusters under the still water line with respect to the still water line is $-0.5\,H_d$.

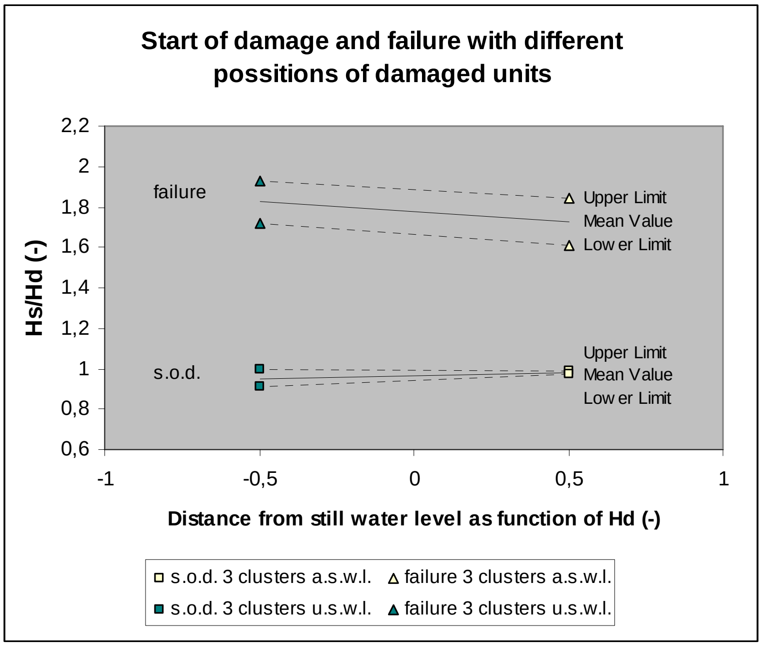

figure 5.5: Start of damage and failure with different positions of damaged units with lower limits, mean values and upper limits

Looking at the lower limits figure 5.5 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%). Only two tests series were performed for each configuration. Therefore these differences can be neglected. Apparently the position of the damaged units between one Hd under and one Hd above the still water line gives no difference on the influence of the damaged units on start of damage and failure.

At start of damage with 3 clusters above the still water line non-damaged Xbloc units were displaced under the still water line. The interlocking mechanism of Xbloc units does not reach that far downwards. These units should therefore not be aware of the fact that there are damaged units above the still water line as the distance is too large.

The porosity of the armour layer is already very large with no damaged units in the armour layer. The increase of the armour layer porosity due to damaged units is therefore negligible and could therefore not increase the flow through the armour layer and is therefore not the cause of the increased instability of the armour units under the still water line.

There is no physical explanation for the observed phenomenon. Every experiment gives some false results and only two test series with 3 clusters of damaged units above the still water line are performed. It could therefore be possible that the outcomes of these test series are errors in the experiment.

5.4.4 Evaluation start of damage and failure

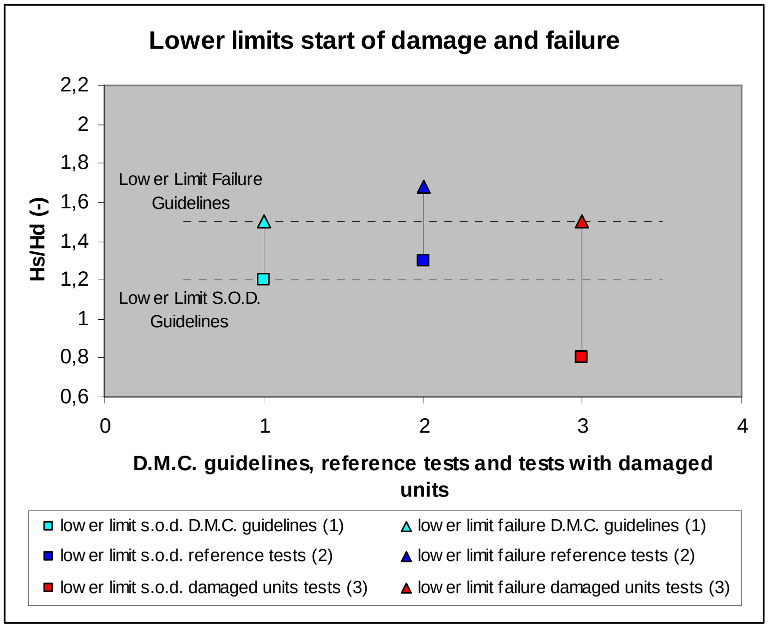

figure 5.6: Lower limits start of damage and failure for the Xbloc guidelines, reference tests and tests with damaged units

In figure 5.6 the lowest value of start of damage and failure of the reference tests and of the tests with damaged units are used. For the tests with damaged units 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. These values are used for figure 5.6. In this figure also the required values for stability of a Xbloc armour layer from the Xbloc guidelines are shown (see paragraph 3.4.4).

Start of damage and failure for the reference test series occur at higher values of H_s/H_d then for start of damage and failure from the Xbloc guidelines. This might be due to the positive influence on the armour layer stability of the permeable vertical frame used behind the breakwater model.

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

The 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.

It must be noted that only 3 reference test series are performed and 9 test series with damaged units. As a consequence the chance on lower values of H_s/H_d is higher for the test series with damaged units compared to the reference tests.

So damaged units in the armour layer have a significant negative effect on the 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 the failure of the armour layer and compared to the reference tests the damaged units have some effect on the failure of the armour layer but not as dramatic as was expected. Even in the most negative case failure still occurs at wave heights of approximately 50% above the design wave height for an armour layer with damaged units.

5.5 Behaviour damage progression armour layer

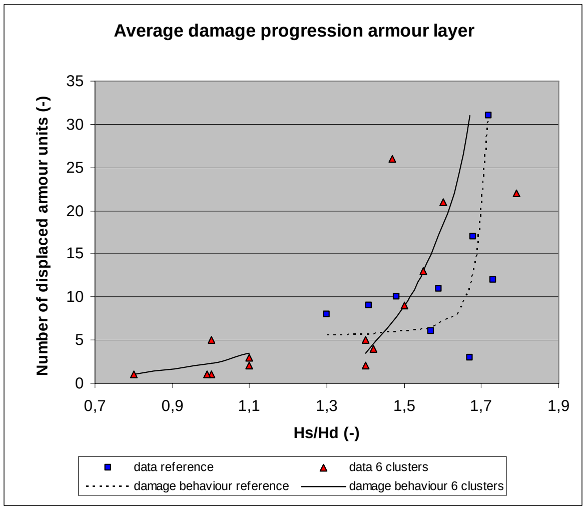

figure 5.7: Average behaviour damage progression of 6 clusters of damaged units around still water level and reference tests

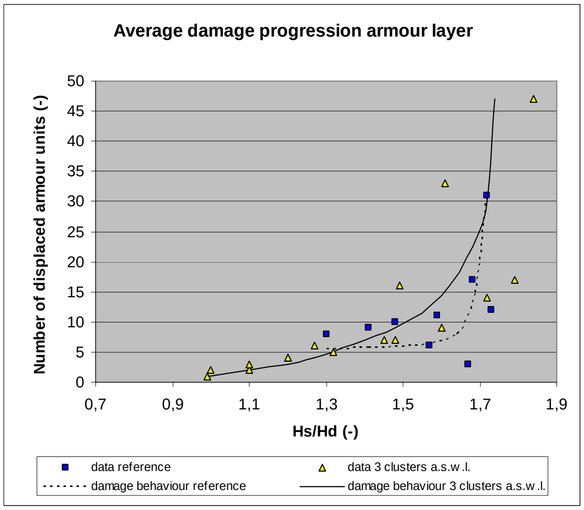

figure 5.8: Average behaviour damage progression of 3 clusters of damaged units above still water level and reference tests

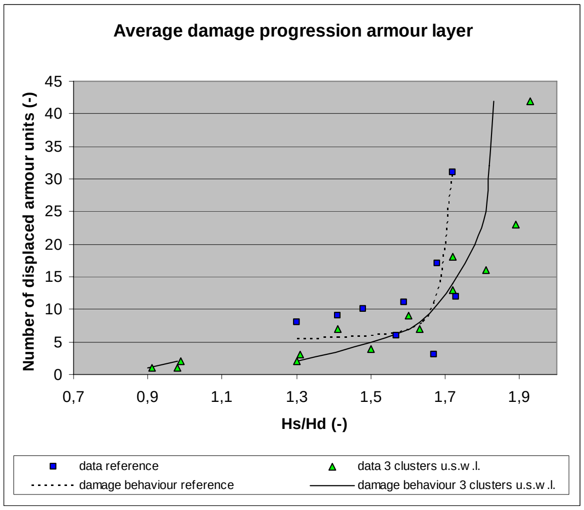

figure 5.9: Average behaviour damage progression of 3 clusters of damaged units under still water level and reference tests

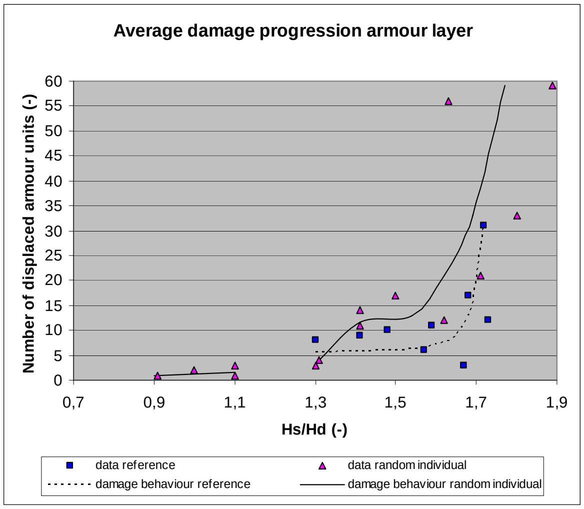

figure 5.10: Average behaviour damage progression of individual random placed damaged units around still water level and reference tests

In the figures 5.7 – 5.10 the average behaviour of damage progression for the different configurations is treated. In these figures the average behaviour of damage progression for the reference tests is shown for comparison. All the data from every test for each configuration is used. A line representing the average of all the data shows the average behaviour of the damage progression.

Start of damage for the reference tests occurs at a value of 1.3 for H_s/H_d. The damage continues with the same rate to increase significantly around a value of 1.7 for H_s/H_d until failure occurs.

Looking at figures 5.7 – 5.10 we can see that all configurations with damaged units have a start of damage at significantly lower values of H_s/H_d compared to the reference tests. The damage progression generally continues with at a more or less constant rate to increase significantly for values of H_s/H_d between 1.5 and 1.7 until failure occurs.

Figures 5.7 – 5.10 show two types of damage progression for the configurations with damaged units. The configurations with 6 clusters, 3 clusters under the still water line and individually random placed damaged units show a discontinuity in the damage progression. After start of damage the damage progression stops to continue at a higher value of H_s/H_d . These configurations all have damaged units positioned under the still water line.
The configuration with 3 clusters of damaged units above the still water line show a continues damage behaviour. This configuration has no damaged units under the still water line.

It assumed that due to damaged units positioned under the still water line extra settlement occurs, which increases the packing density in this area. With this increased packing density the interlocking capacity increases. The armour layer under the still water line becomes more stable. The displaced units during start of damage were positioned in this area. As the stability in this area increases, no more units can be displaced and the damage progression stops to continue at higher values of H_s/H_d until failure occurs.
With 3 damaged clusters positioned above the still water line no damaged units are positioned under the still water line. As there are no damaged units under the still water line no extra settlement occurs, leading to continues damage progression of the armour layer until failure occurs.

It could also be stated that the stop of damage progression is due to the self-repairing capacity of the Xbloc units. This however would not explain the continues damage progression with no damaged units under the water line. The self-repairing mechanism should also apply for this case as it would for an armour layer with damaged units under the still water line.

Therefore it is assumed that the stop of damage progression after start of damage is caused by extra settlement due to the damaged armour units under the still water line.

The damage progression of an armour layer with damaged units has a longer and more gradual damage progression. This type of damage progression looks more like the damage progression of an armour layer consisting of rip-rap rock.
This is actually very obvious as the lower level of H_s/H_d for start of damage is primarily caused by a decrease of interlocking capacity. 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 5.11).

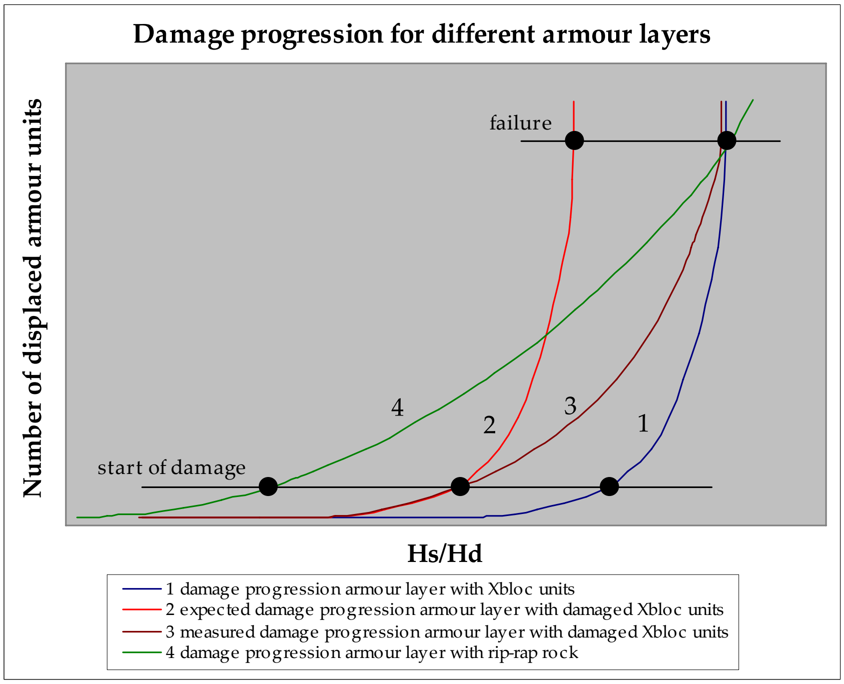

figure 5.11: General damage progression for different types of armour layer

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 leads to the damage behaviour showed in figure 5.11.

In chapter 6 it was shown that at failure relatively the same amount of damaged units were displaced as non-damaged units in the same area. Apparently damaged and non-damaged units in the same area suffer from the same behaviour of interlocking capacity during damage progression of the armour layer.

5.6 Behaviour detached legs and noses

During every test series the displacements of the detached noses and legs were monitored. Figure 5.12 shows how many noses and legs were displaced during each test series.

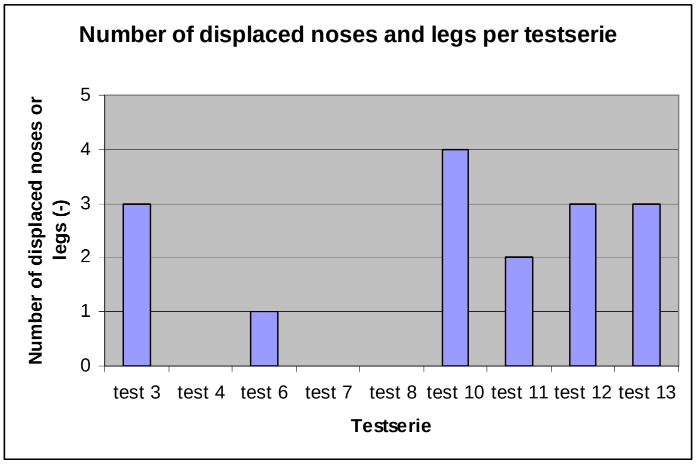

figure 5.12: Number of displaced detached noses and legs observed during each test series

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer. On the average only 2 or 3 detached parts showed displacement for each test series (see figure 5.12). After this displacement these parts settle again in the armour layer. It is therefore highly unlikely that the broken parts damage other units as only a few detached parts showed displacement during the test series.

For the configuration with only 3 clusters of damaged units above still water level the detached noses and legs show no displacement (see figure 5.12, test 7 and 8). Apparently detached parts above the still water line have a smaller chance on displacement.
This is probably caused by the fact that wave action during run-up and run-down are the only forces acting on these parts. The detached noses and legs under the still water line of the other configurations are also subjected to buoyancy as addition to the wave forces during run-up and run-down.
Apparently buoyancy increases the chance of displacement of the detached parts. This is however very obvious as buoyancy decreases the force needed to displace the detached parts with approximately 44%. This is calculated with:

$$\left(1-\left(\frac{2297kg/m^3-1000kg/m^3}{2297kg/m^3}\right)\right)100\%$$

with:

2297 kg/m^3 as density detached parts;
1000 kg/m^3 as density water.

5.7 Summary

Damaged units in the armour layer have a significant negative effect on the 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 the failure of the armour layer and compared to the reference tests the damaged units have some effect on the failure of the armour layer but not as dramatic as was expected. Even in the most negative case of 6 clusters of 5 damaged units around the still water line failure still occurs at wave heights of approximately 50% above the design wave height.

The area between 0.5 and 1.5 H_d under still water level is the most vulnerable place in the armour layer for displacement of armour units at start of damage. Generally a non-damaged unit in the surroundings of damaged units is displaced during start of damage. Therefore it can be stated that the significant negative influence of damaged units on start of damage is primarily an interlocking problem.

Increasing the percentage of damaged units or number of damaged units in a cluster has only a minor additional negative influence on start of damage and failure.
The position of the damaged units between one H_d under and one H_d above the still water line gives no difference in influence of the damaged units on start of damage and failure.

The damage progression of an armour layer with damaged units has a longer and more gradual damage progression compared to the damage progression of an armour layer with no damaged armour units. This type of damage progression looks more like the damage progression of an armour layer consisting of rip-rap rock.

The majority of the detached noses and legs show little to no movement and stay in the armour layer or even tend to dig themselves in the first under-layer. It is therefore highly unlikely that the broken parts damage other units as only a few detached parts showed displacement during the test series. The detached parts above the still water line have a smaller chance on displacement compared to detached parts under the still water line as buoyancy increases the chance of displacements of the last mentioned detached parts.

Chapter 6 Conclusions and recommendations

6.1 Conclusions

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

6.1.1 Main conclusions

Stability armour layer with damaged single layer interlocking armour units

It is 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.

For failure this hypothesis is rejected. 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 compared to an armour layer with no damaged armour units. 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 lower wave heights as was generally assumed.

Behaviour broken parts of damaged single layer interlocking armour units

It is 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 of what is generally assumed the majority of the detached noses and legs show little to no movement during the test series and stay in the armour layer or even tend to dig themselves in the first under-layer. It is therefore highly 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.

6.1.2 Additional conclusions

Start of damage and failure

- During start of damage generally most of the displaced armour units are displaced in the area between 0.5 and 1.5 H_d under the still water level. This is the most vulnerable area for displacement of armour units during start of damage. It must be noted that this holds for this test configuration. A shorter slope may give a different pattern of displacement.

- The negative influence of damaged armour units on the 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 armour units are displaced during the test series. The mechanism behind this behaviour is unclear.

- Increasing the percentage of damaged units or number of damaged units in a cluster has only a minor additional negative influence on start of damage and failure.

- 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.

Damage progression armour layer

- With further damage progression the negative influence of the decreased interlocking capacity of damaged units and adjacent units on the stability of the armour layer decreases and becomes zero at failure.

- The discontinuity in the damage progression of an armour layer with damaged units positioned under the still water line is assumed to be caused by the extra settlement due to the damaged units positioned under the still water line.

- Rocking is generally observed between the still water line and one H_d above the still water. Therefore it is unlikely that a large amount of armour units are damaged in the area between $0.5 H_d$ and $1.5 H_d$ under the still water line due to rocking, which is the most vulnerable area for displacement of armour units during start of damage.

- Units in the area between the still water line and one H_d above the still water line are more vulnerable to rocking, as the packing density is smaller due to settlement under still water level.

- Breaking off a nose or a leg has the same effect on the decrease of the stability of a Xbloc armour unit.

- Breakage of parts pointing upwards does not lead to a higher vulnerability of displacement of a damaged unit compared to a non-damaged unit.

- Breaking off parts pointing upwards leads to a lower interlocking capacity of the two units positioned above of the damaged unit.

- The orientations left, right and down of the detached parts give no difference on the influence of the displacement of a damaged unit.

Behaviour detached noses and legs

- The detached parts above the still water line have a smaller chance on displacement compared to detached parts under the still water line as buoyancy increases the chance of displacements of the last mentioned detached parts.

6.2 Recommendations

Based on the conclusions recommendations are made in this paragraph.

6.2.1 Practical recommendations

This research is hypothetic as Xbloc armour units are designed and proven to be structural stable even when the design wave height is exceeded. Therefore breakage of these units during the construction lifetime is highly unlikely. The research is performed to assess what would happen to the hydraulic stability of a breakwater if against all odds armour units would break. The following recommendations are therefore focussed on what could be done when armour units unexpectedly break.

- When only a small amount of units is broken in the armour layer (in the order of 2%) it is not necessary to take measures with respect to repair of the armour layer. These units are not expected to have a significant negative effect on the stability of the armour layer. It is however advisable to monitor the structure for increase of the amount of broken units.

- When the number of broken units increases to a total in the order of 7.5% or more of the number of units used between one H_d under and one H_d above the still water line one has to consider whether the damage progression found in this research is desired or not. Although failure occurs at wave heights comparable to an armour layer with no broken units it is still advisable to repair the armour layer. This would be more like maintenance of the structure to expand its lifetime.

When cases of broken Xbloc units unexpectedly occur in the future the following is opted as modification in the design:

- Stricter requirements can be used for the placement of Xbloc units between one H_d above the still water line and one H_d under the still water line reducing the chance on rocking and therefore breakage of armour units in this area.

6.2.2 Recommendations for further research

- Very little is known about the behaviour of interlocking of armour units. Therefore an assumption is made with respect to the interlocking capacity of a damaged Xbloc unit. Research on the topic of the interlocking capacity of armour units is recommended to better understand its behaviour.

- No tests have been done with percentages between 0% and 7.5% damaged units in an armour layer. Tests with lower percentages of damaged units may also have a significant influence on start of damage leading to a different curve between 0% and 7.5% damaged units. Therefore tests have to be performed with lower percentages of damaged units in an armour layer.

- Clusters with 2, 3 or 4 damaged units probably give approximately the same behaviour as for individual placed units and clusters of 5 units with respect to start of damage and failure. As these sizes of clusters are not tested it is advised to perform tests with these sizes of clusters to confirm this assumption.

- Increasing the percentage of damaged units or number of damaged units in a cluster has only a minor additional negative influence on start of damage and failure. This statement is however based on a small amount of test series for different configurations of damaged Xbloc units. As the measurements show a rather large variation additional tests are recommended to confirm or reject this statement.

- With 3 clusters of 5 damaged units above the still water level start of damage occurred under the still water line where no damaged units were positioned. There is no physical explanation for the observed phenomenon. It could be possible that the outcomes of these test series are errors in the experiment.
  This phenomenon has to be further investigated to determine whether the test results were errors in the experiment and if not what the cause of the displaced armour units under the still water line is.

- Rocking is generally observed between the still water line and one H_d above the still water line. This could be caused by the settlement due to the long slope used for the experiments. Tests series with a shorter slope are advised to determine the area, which is most vulnerable to rocking.

- During the test series the area between one H_d above the still water line and one H_d under the still water line is used for the position of the broken units. The area where units generally break is however not known. Further research is therefore needed to determine the position in the armour layer where breakage of armour units is most likely to occur.

- Technical information about projects with broken single layer interlocking armour units was not available during this research. When this information is available in the future it is recommended to compare the results of these projects with the findings of this research with respect to the damage behaviour of the armour layer with damaged units.

- For this research only Xbloc armour units are used. The findings of this research therefore do not necessarily have to apply for other types of single layer interlocking armour units. Additional research with the other types of single layer interlocking armour units has to be performed to determine whether the findings of this research are generally applicable for single layer interlocking armour units.

- For the test configuration a breakwater model with a long slope is used. A shorter slope may lead to less settlement and less easily re-arrangement of the armour units. This possibly causes more effect of the damaged units on the armour layer stability. Testing with a shorter slope is therefore recommended as prototype breakwaters have shorter a slope than used for this research.

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Appendix A

List of symbols

Roman characters

b = core width (m)

D =
1. coefficient to account for seepage length as a result of the deviation of the flow path caused by the grains (-)
2. characteristic diameter of the Xbloc unit (m)

D_n = nominal diameter of the Xbloc armour unit (m)

E = variance density (m²/Hz)

f = frequency (Hz)

f_{peak} = peak frequency (Hz)

g = gravitational acceleration (m/s²)

Fr = Froude number (-)

h = water depth (m)

H = wave height (m)

H_d = design wave height (m)

H_{m0} = zero-th order moment wave height (m)

H_s = significant wave height (m)

L =
1. length (m)
2. length of the incident wave (m)
3. wave length (m)

L' = wave length in the core (m)

m = model

$m0$ = area of the wave spectrum (m²)

n = porosity (-)

N = scale factor (-)

N_s = stability number (-)

p = prototype

P = density of the Xbloc unit (kg/m³)

Re = Reynolds number (-)

s = wave steepness (-)

T = wave period (s)

T_p = peak period (s)

U =
1. velocity (m/s)
2. pore velocity (m/s)

V = volume Xbloc (m³)

W = weight of the Xbloc unit (kg)

W_{Xbloc} = the weight of the Xbloc (kg)

W_{15} = the stone mass for which 15% of the total sample mass is of lighter stones (kg)

W_{50} = the stone mass for which 50% of the total sample mass is of lighter stones (kg)

W_{85} = the stone mass for which 85% of the total sample mass is of lighter stones (kg)

Greek characters

α = 1. coefficient dependent on the Reynolds number and the grain shape and grading (-)
2. scaling parameter (Pierson-Moskowitz) (-)

β = coefficient dependent on the Reynolds number and the grain shape and grading (-)

δ = damping coefficient (-)

Δ = relative density (-)

γ = scaling parameter (Jonswap peak-enhancement factor) (-)

ρ_{Xbloc} = Xbloc density (kg/m³)

ρ_w = water density (kg/m³)

σ = scaling parameter (Jonswap peak-enhancement factor) (-)

υ = kinematic viscosity (m²/s)

Appendices

Appendix A: The influence of sugar on wave measurements

The problem with minerals suspended in water is that they can influence the outcome of the wave gauges used for measuring the wave heights and periods. These wave gauges use electricity and the resistance of the water to determine the wave height. By adding minerals to the water this resistance will change.

To determine whether sugar in suspension influences the outcome of the wave gauges, tests have been performed. A wave gauge was set in 10 litres of water and different amounts of sugar where dropped between the two poles of the wave gauge.

A difference of 20 Volt on the measuring device stands for a difference in water level of 10cm. This leads to a difference in water level of 0.5cm for a difference of 1 Volt. The following measurements were taken:

sugar (gram)	0	0.08	0.57	1.81
voltage (V)	+3.94	+3.94	+4.44	+5.04

table A.1: Influence of sugar on wave gauge measurements

Table A.1 and figure A.1 show that 1.81 gram of sugar gives a difference in voltage of 1.1V, which stands for an overestimation of the water level with 0.55cm. During the test series this would lead to an overestimation of the waves.

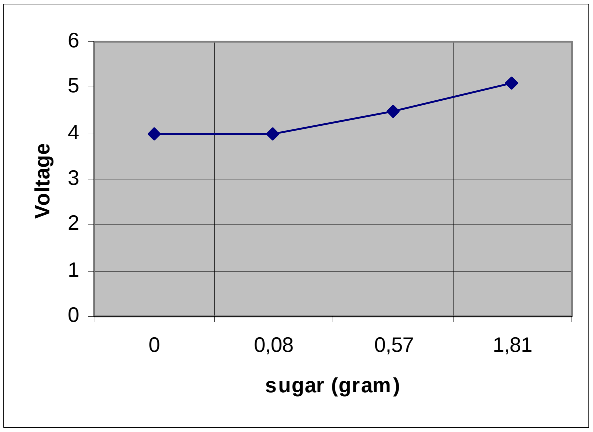

figure A.1: Influence of sugar in suspension

It turns out that large amounts of sugar can influence the outcomes of the wave gauge significantly, see figure A.1.

However when the water is mixed and the sugar better suspended the difference reduces to zero.

So during the test series no influence of the sugar solution is expected, because the waves in the wave flume will mix the sugar rapidly over the water in the flume.

Only small amounts of sugar are used for the broken Xbloc units, in the order of 10 gram, with respect to the large amount of water contained in the wave flume in front of the breakwater model. However one must be aware that a very small chance exists that a small cloud of sugar in suspension may pass the wave gauge, which may affect the outcomes of the wave gauge only for a short period of time.

Appendix B: Scaling of core material in rubble mound breakwater tests [12]

The permeability of the core material influences armour stability, wave run-up and wave overtopping. The main problem related to the scaling of core materials in models is that the hydraulic gradient and the pore velocity are varying in space and time. This makes it impossible to arrive at a fully correct scaling.

The method of Burcharth et al. presents an empirical formula for the estimation of the wave induced pressure gradient in the core, based on measurements in models and prototype. The formula, together with the Forchheimer equation can be used for the estimation of pore velocities in cores.

$$I_x = -\frac{\pi H_s}{L'} e^{-\delta \frac{2\pi}{L'} x} \left[\delta \cos\left(\frac{2\pi}{L'}x + \frac{2\pi}{T_p}t\right) + \sin\left(\frac{2\pi}{L'}x + \frac{2\pi}{T_p}t\right) \right]$$

Burcharth et al.

with:

δ = damping coefficient which is given by $\delta = 0.0141\frac{n^{1/2}L_p^2}{H_s b}$

Hs = significant wave height

b = core width

Tp = wave period

L’ = wave length in the core. L’ = $L/\sqrt{D}$ valid for h/L < 0.5, where h is the water depth in front of the breakwater

L = length of the incident wave

D = coefficient to account for seepage length as a result of the deviation of the flow path caused by the grains. Le Mehaute (1957) gives the empirical value 1.4 for quarry rock material. Biesel (1950) found the theoretical value 1.5.

$$I_x = \alpha \left(\frac{1-n}{n}\right)^2 \frac{\nu}{g d_{50}^2}\left(\frac{U}{n}\right) + \beta \frac{1-n}{n}\frac{1}{g d_{50}}\left(\frac{U}{n}\right)^2$$

Forchheimer equation

with:

n = porosity

ν = kinematic viscosity taken as $1.1 \cdot 10^{-6} m^2/s$

U = pore velocity

α and β are coefficients dependent on the Reynolds number $\mathrm{Re} = \frac{U d_{50}}{\nu}$ and the grain shape and grading. Values of α and β can be found in Burcharth et al. 1995 [8].

The method of Burcharth et al. proposes that the diameter of the core material in models is chosen in such a way that the Froude scale law holds for a characteristic pore velocity. The characteristic pore velocity is chosen as the average velocity of the 6 points shown in figure B1. Note that the characteristic pore velocity is averaged with respect to time (one wave period) and space (6 points).

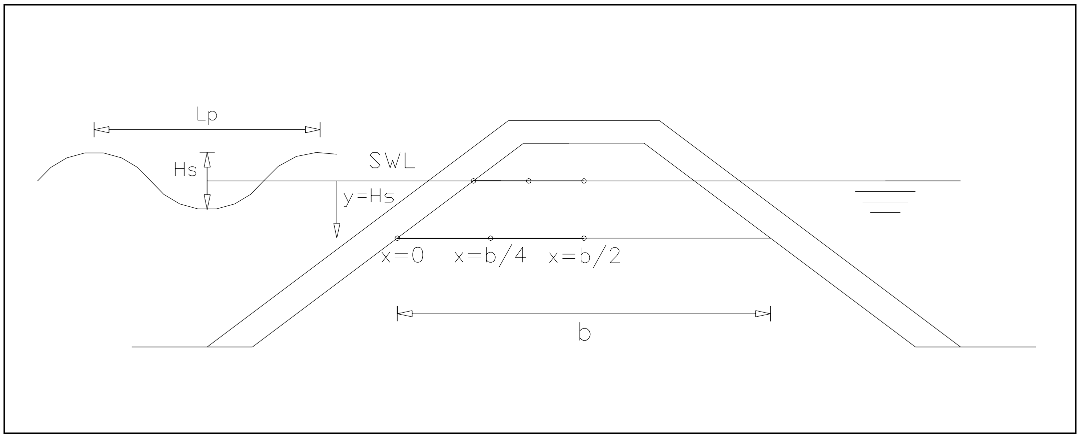

figure B.1: Location for characteristic pore velocity in the core

Appendix C: Total displaced damaged armour units with orientation

displaced	damaged	detached	part		orientation	detached	part
units at	failure	leg	nose	left	right	up	down
test 3	2	1			1		
			1	1			
test 4	2	1			1		
			1		1		
test 6	1	1					1
average at	test series	1	0.67	0.33	1		0.33
total used		20	10	10	9	5	6
relative		0.05	0.067	0.033	0.11	0	0.055

displaced	damaged	detached	part		orientation	detached	part
units at	failure	leg	nose	left	right	up	down
test 7	2	2				1	1
test 8	0						
average at	test series	1	0	0	0	0.5	0.5
total used		10	5	5	3	3	4
relative		0.2	0	0	0	0.17	0.13

displaced	damaged	detached	part		orientation	detached	part
units at	failure	leg	nose	left	right	up	down
test 10	2	1			1		
			1		1		
test 11	2	2		1			1
average at	test series	1.5	0.5	0.5	1	0	0.5
total used		10	5	5	6	1	3
relative		0.3	0.2	0.1	0.17	0	0.17

displaced	damaged	detached	part		orientation	detached	part
units at	failure	leg	nose	left	right	up	down
test 12	5	4		1	2		1
			1	1			
test 13	5	2		1	1		
			3	3			
average at	test series	3	2	3	1.5	0	0.5
total used		10	5	13	13	2	2
relative		0.3	0.4	0.23	0.12	0	0.25

Appendix D: Measurements wave heights and wave periods

For every test series two sections are given with the measured wave heights, wave periods and wave steepness. For the local wave steepness the significant wave height $H_s \approx H_{m0}$ and the significant wave period $T_s \approx 0.9T_p$ are used.

The water depth at section 1 (between the wave board and the foreshore) is 0.55m and the water depth at section 2 (in front of the toe construction of the breakwater model) is 0.37m.

Test series 1

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	4,775	1,21	1,2115	0,027
10	6,104	1,39	1,3942	0,027
11	6,734	1,47	1,48	0,027
12	7,378	1,56	1,5596	0,028
13	8,171	1,66	1,6674	0,028
14	8,73	1,75	1,7392	0,028
15	9,442	1,84	1,8465	0,028
16	10,116	1,94	1,9671	0,028
17	10,846	2,03	2,0354	0,029
20	11,96	1,56	1,5588	0,045
21	12,719	1,66	1,6878	0,043
22	13,689	1,75	1,7888	0,043
24 S.O.D.	15,66	1,56	1,5615	0,059
25 Failure	16,803	1,66	1,7363	0,055

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	4,882	1,21	1,2112	0,03
10	6,174	1,39	1,3936	0,031
11	6,776	1,47	1,4652	0,031
12	7,381	1,56	1,5583	0,032
13	8,123	1,66	1,6884	0,031
14	8,616	1,75	1,7392	0,032
15	9,281	1,84	1,8465	0,032
16	9,884	1,94	1,9092	0,033
17	10,55	2,03	2,0342	0,033
20	11,954	1,56	1,5588	0,051
21	12,637	1,66	1,6872	0,049
22	13,505	1,75	1,7889	0,049
24 S.O.D.	15,607	1,56	1,5597	0,067
25 Failure	16,62	1,66	1,6902	0,064

Test series 3

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8 S.O.D.	7,984	1,21	1,2113	0,045
10	9,948	1,39	1,3801	0,045
11	10,965	1,47	1,479	0,045
12	11,908	1,56	1,578	0,044
13	12,923	1,66	1,6884	0,044
14	13,837	1,75	1,7876	0,043
15	15,022	1,84	1,791	0,047
16	15,469	1,94	1,962	0,043
17 Failure	17,89	2,03	2,0311	0,047

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8 S.O.D.	8,158	1,21	1,2004	0,05
10	10,058	1,39	1,3941	0,05
11	11,026	1,47	1,4638	0,051
12	11,905	1,56	1,5769	0,05
13	12,828	1,66	1,6877	0,05
14	13,65	1,75	1,7877	0,049
15	14,649	1,84	1,8438	0,051
16	15,09	1,94	1,9048	0,05
17 Failure	17,259	2,03	2,0311	0,054

Test series 4

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	7,999	1,21	1,2108	0,045
10 S.O.D.	10,046	1,39	1,3803	0,046
11	10,983	1,47	1,4793	0,045
12	11,884	1,56	1,5583	0,045
13	12,908	1,66	1,6878	0,044
14 Failure	14,702	1,75	1,7368	0,048

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,172	1,21	1,2105	0,05
10 S.O.D.	10,158	1,39	1,3798	0,051
11	11,045	1,47	1,464	0,051
12	11,88	1,56	1,557	0,051
13	12,815	1,66	1,6872	0,05
14 Failure	14,429	1,75	1,7368	0,054

Test series 5

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,031	1,21	1,2108	0,045
10	10,04	1,39	1,3782	0,046
11	10,992	1,47	1,4633	0,046
12	11,809	1,56	1,5777	0,044
13	12,93	1,66	1,6866	0,044
14	14,015	1,75	1,7879	0,044
15	15,061	1,84	1,7911	0,047
16	16,188	1,94	1,9634	0,045
17	16,634	2,03	2,0334	0,044
17 S.O.D.	16,67	2,03	2,0342	0,044
17 Failure	17,292	2,03	2,0342	0,046

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,205	1,21	1,2105	0,050
10	10,152	1,39	1,3785	0,051
11	11,055	1,47	1,4637	0,051
12	11,814	1,56	1,5766	0,05
13	12,838	1,66	1,6648	0,051
14	13,824	1,75	1,7628	0,051
15	14,69	1,84	1,8156	0,052
16	15,779	1,94	1,9046	0,053
17	16,105	2,03	2,0334	0,05
17 S.O.D.	16,157	2,03	2,0342	0,05
17 Failure	16,735	2,03	2,0342	0,052

Test series 6

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
6	5,706	1,03	1,0083	0,045
7	6,75	1,12	1,1018	0,045
8	8,048	1,21	1,1991	0,046
9	8,724	1,3	1,3021	0,043
10 S.O.D.	9,936	1,39	1,3809	0,044
11	10,964	1,47	1,4798	0,045
12	11,95	1,56	1,5603	0,045
13	12,866	1,66	1,644	0,045
14	14,164	1,75	1,7888	0,044
15	14,909	1,84	1,9053	0,043
16 Failure	15,96	1,94	1,9642	0,044

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
6	5,845	1,03	1,0085	0,048
7	6,9156	1,12	1,1019	0,049
8	8,222	1,21	1,1889	0,051
9	8,872	1,3	1,2896	0,049
10 S.O.D.	10,044	1,39	1,3803	0,051
11	11,027	1,47	1,4488	0,052
12	11,949	1,56	1,559	0,051
13	12,771	1,66	1,644	0,051
14	13,965	1,75	1,7888	0,05
15	14,563	1,84	1,9053	0,049
16 Failure	15,56	1,94	1,9051	0,052

Test series 7

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	7,972	1,21	1,2111	0,045
9	8,716	1,3	1,3024	0,043
10 S.O.D.	9,905	1,39	1,3789	0,045
11	10,932	1,47	1,4797	0,045
12	12,02	1,56	1,559	0,045
13	12,748	1,66	1,6872	0,043
14	13,554	1,75	1,7391	0,044
15	14,795	1,84	1,9046	0,043
16	15,994	1,94	1,9628	0,044
17	17,193	2,03	2,0333	0,045
18	17,899	2,13	2,1107	0,045
19 Failure	18,415	2,23	2,2668	0,043

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,147	1,21	1,2109	0,049
9	8,863	1,3	1,3019	0,048
10 S.O.D.	10,018	1,39	1,3931	0,05
11	10,995	1,47	1,4644	0,051
12	12,016	1,56	1,5578	0,052
13	12,66	1,66	1,6644	0,05
14	13,395	1,75	1,7371	0,05
15	14,482	1,84	1,9046	0,048
16	15,597	1,94	1,9047	0,052
17	16,632	2,03	2,0333	0,052
18	17,28	2,13	2,1816	0,049
19 Failure	17,715	2,23	2,2636	0,049

Test series 8

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,053	1,21	1,2107	0,045
9	9,124	1,3	1,3031	0,045
10 S.O.D.	9,912	1,39	1,3948	0,044
11	10,965	1,47	1,48	0,045
12	12,044	1,56	1,5777	0,045
13	13,187	1,66	1,6878	0,044
14	14,475	1,75	1,7391	0,047
15	14,922	1,84	1,9045	0,043
16 Failure	16,153	1,94	1,967	0,045

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,226	1,21	1,2104	0,05
9	9,276	1,3	1,3027	0,051
10 S.O.D.	10,026	1,39	1,394	0,05
11	11,033	1,47	1,4799	0,051
12	12,041	1,56	1,5765	0,051
13	13,088	1,66	1,6872	0,051
14	14,29	1,75	1,6935	0,055
15	14,604	1,84	1,9045	0,049
16 Failure	15,705	1,94	1,9641	0,051

Test series 9

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,069	1,21	1,2107	0,045
10	9,919	1,39	1,3799	0,045
11	10,919	1,47	1,4635	0,045
12	11,871	1,56	1,5973	0,043
13 S.O.D.	12,955	1,66	1,6665	0,044
14	14,122	1,75	1,7384	0,046
15	14,827	1,84	1,8485	0,044
16	15,915	1,94	1,9631	0,044
17 Failure	17,249	2,03	1,9693	0,047

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,245	1,21	1,2104	0,05
10	10,032	1,39	1,3794	0,051
11	10,983	1,47	1,4638	0,051
12	11,874	1,56	1,5773	0,05
13 S.O.D.	12,867	1,66	1,6669	0,051
14	13,947	1,75	1,7384	0,052
15	14,504	1,84	1,8506	0,05
16	15,518	1,94	1,9049	0,052
17 Failure	16,658	2,03	1,9671	0,054

Test series 10

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,018	1,21	1,2098	0,045
9	9,069	1,3	1,3031	0,045
10 S.O.D.	9,945	1,39	1,3934	0,044
11	10,901	1,47	1,4793	0,044
12	11,943	1,56	1,559	0,045
13	12,951	1,66	1,6435	0,045
14	14,102	1,75	1,7394	0,046
15	15,031	1,84	1,8472	0,045
16	16,314	1,94	1,9632	0,045
17	17,19	2,03	2,0335	0,045
18	18,114	2,13	2,1108	0,046
19	18,854	2,23	2,2607	0,044
19 Failure	19,337	2,23	2,1814	0,047

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,194	1,21	1,1875	0,051
9	9,223	1,3	1,3026	0,05
10 S.O.D.	10,058	1,39	1,3794	0,051
11	10,967	1,47	1,464	0,051
12	11,941	1,56	1,5578	0,051
13	12,858	1,66	1,6435	0,051
14	13,924	1,75	1,7394	0,052
15	14,701	1,84	1,8494	0,051
16	15,846	1,94	1,9046	0,053
17	16,625	2,03	2,0335	0,052
18	17,511	2,13	2,1823	0,05
19	18,095	2,23	2,2578	0,05
19 Failure	18,595	2,23	2,1814	0,053

Test series 11

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	7,981	1,21	1,2109	0,045
9 S.O.D.	9,084	1,3	1,3029	0,045
10	9,949	1,39	1,3944	0,044
11	10,935	1,47	1,4636	0,045
12	11,965	1,56	1,5591	0,045
13	13,145	1,66	1,6665	0,045
14	14,119	1,75	1,7385	0,046
15	15,251	1,84	1,8496	0,046
16	15,965	1,94	1,963	0,044
17 Failure	17,211	2,03	2,0338	0,046

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,156	1,21	1,2106	0,05
9 S.O.D.	9,24	1,3	1,3025	0,05
10	10,026	1,39	1,394	0,05
11	11,003	1,47	1,4639	0,051
12	11,965	1,56	1,5776	0,05
13	13,049	1,66	1,6871	0,051
14	13,946	1,75	1,7164	0,053
15	14,86	1,84	1,9047	0,05
16	15,569	1,94	1,9048	0,052
17 Failure	16,657	2,03	2,0338	0,052

Test series 12

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	7,911	1,21	1,2116	0,044
9	9,082	1,3	1,3026	0,045
10	9,921	1,39	1,3938	0,043
11 S.O.D.	10,976	1,47	1,48	0,045
12	11,919	1,56	1,5774	0,044
13	13,07	1,66	1,6877	0,044
14	14,092	1,75	1,7167	0,046
15	15,137	1,84	1,8476	0,045
16	16,156	1,94	1,9042	0,046
17	17,052	2,03	2,0338	0,045
18	17,977	2,13	2,1815	0,044
19 Failure	18,901	2,23	2,2593	0,044

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,084	1,21	1,2006	0,05
9	9,238	1,3	1,3022	0,05
10	10,036	1,39	1,3787	0,051
11 S.O.D.	11,044	1,47	1,4798	0,051
12	11,919	1,56	1,5762	0,05
13	12,98	1,66	1,6872	0,05
14	13,922	1,75	1,6938	0,054
15	14,752	1,84	1,8498	0,051
16	15,753	1,94	1,9042	0,053
17	16,493	2,03	2,0338	0,051
18	17,348	2,13	2,1815	0,05
19 Failure	18,192	2,23	2,1824	0,052

Test series 13

	section 1: deep water			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	7,982	1,21	1,2107	0,045
9 S.O.D.	9,127	1,3	1,3162	0,045
10	9,981	1,39	1,3798	0,045
11	10,977	1,47	1,4647	0,045
12	12,083	1,56	1,5599	0,046
13	12,911	1,66	1,6872	0,044
14	14,113	1,75	1,6929	0,047
15	15,053	1,84	1,8498	0,045
16 Failure	16,257	1,94	1,9052	0,047

	section 2: foreshore			
Hm0 desired (cm)	Hm0 measured (cm)	Tp desired (s)	Tp measured (s)	wave steepness s (-) desired s = 0,045
8	8,159	1,21	1,2104	0,05
9 S.O.D.	9,286	1,3	1,3159	0,05
10	10,098	1,39	1,3796	0,051
11	11,046	1,47	1,465	0,051
12	12,081	1,56	1,5587	0,052
13	12,82	1,66	1,6866	0,05
14	13,944	1,75	1,6923	0,054
15	14,675	1,84	1,9049	0,049
16 Failure	15,859	1,94	1,9052	0,053

To reduce the size of this report the following appendices are put on a DVD:

Appendix E: Position of displaced Xbloc armour units

Appendix F: Pictures of damage progression armour layer

In these appendices the file for a specific wave height of a test series has a name like ir012045_s1_15pr12. For a filename the following holds:

ir: stands for irregular waves;
012: stands for the desired significant wave height (in this case 12cm);
045: stands for the desired local wave steepness of 0.045;
s1: stands for the section of the measurement;
15pr: stands for the percentage of broken Xbloc armour units in the armour layer;
12: stands for the number of the test series.