

Xbloc armour unit development



Hydraulic performance of
Xbloc armour units - 2-D
model tests at WL Delft



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1. INTRODUCTION

1.1 General

The coastal team of Delta Marine Consultants [DMC] have taken the initiative to develop a new concrete armour unit for application on breakwaters and shore protections.

Following the preliminary model tests conducted at DMC, 2-D hydraulic model tests have been carried out at Delft Hydraulics in October 2002.

The experimental set-up and test procedure as well as the main results are briefly reported by Delft Hydraulics [report H4185, Jan 2003].

A comprehensive description of the 2-D hydraulic model tests, test results and further analysis on wave overtopping and hydraulic stability is presented in this report.

1.2 Objective

The main objective of the 2-D hydraulic model tests was to study the hydraulic stability of the Xbloc armour units

Besides this the wave overtopping of Xbloc slopes has been investigated. Furthermore placement procedures have been studied in order to optimise the ease of placement and packing density.

1.3 Methodology

The performance of the Xbloc is studied in 2-D hydraulic model tests with irregular waves. Shallow and intermediate water depths at the toe of the structure as well as moderate and large overtopping rates are considered. Hence, the water depth at the toe as well as the crest level of the structure have been varied.

Model tests have been conducted systematically with constant wave steepness, stepwise increasing wave height and varying wave length and water depth. Empirical relations between wave loading, damage and overtopping rates have been derived from the general experimental results. The applicability of these results is finally discussed.

2. TEST SET-UP

2.1 Wave flume

The hydraulic model tests have been performed in the renewed Scheldt flume of Delft Hydraulics. A picture of this flume is presented in Figure 1. The flume has a length of 55 m, a width of 1 m and a height of 1.2 m. The wave flume is equipped with a translating wave panel that is capable of generating irregular / random waves as well as regular/monochromatic waves. The control signal for the wave generator can be either defined by a wave spectrum or by a time series.



Figure 1 'Scheldt' wave flume

The wave panel has active wave absorption which means that the motion of the wave board compensates waves that are reflected by the structure. In the test series the active reflection compensation has been used. In the tests it was found that the capacity of the wave flume was limited to a H_s near the paddle of 28 cm [80 cm water depth and $T_p = 2.13$ s].

The wave conditions at the toe of the structure have been determined by a repetition of the test series after the structure was removed. At the backside of the flume a mild revetment was present for passive wave absorption.

2.2 Model configuration

Except for one of seven test series, all tests have been performed with a crest level that allows overtopping under extreme wave attack. The choice of freeboard relative to

wave height has been made based on recent breakwater projects of DMC. The crest level is considered as a realistic configuration for situations where no overtopping is accepted during normal conditions [operational conditions] while overtopping can be expected during extreme conditions. The ratio between freeboard and significant wave height varied between 1.1 and 1.9 for the conditions tested.

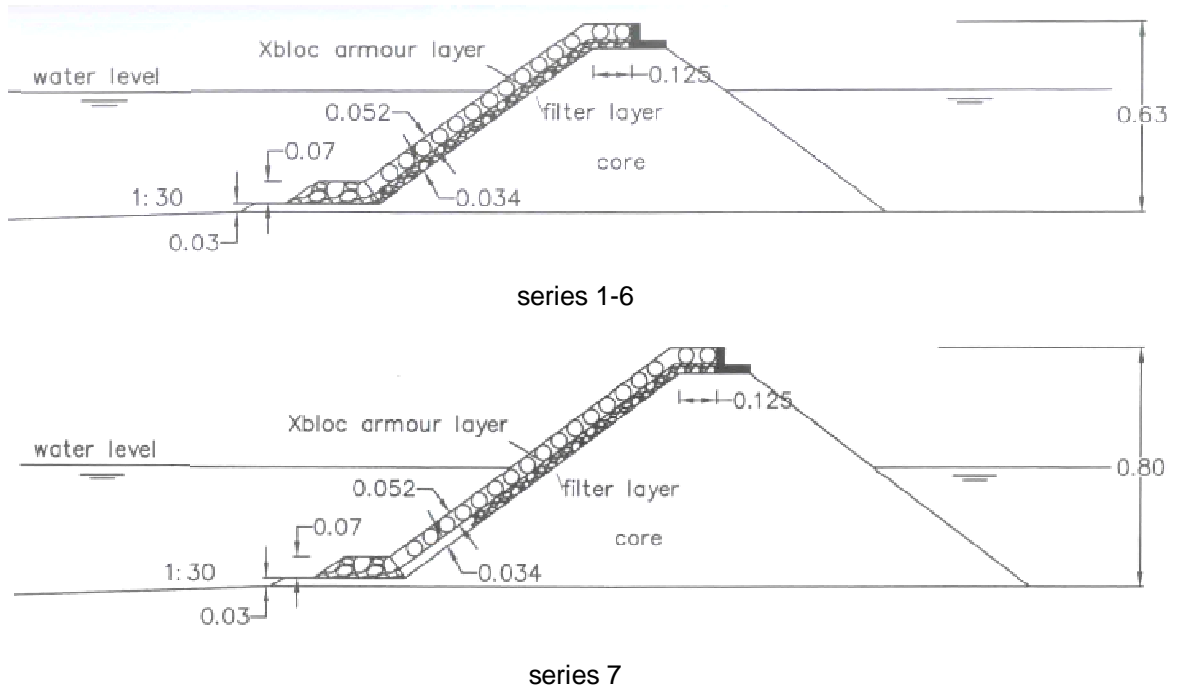


Figure 2 Tested configuration

The tested range of water depth before toe/ water depth upon toe [d/d_t] is 0.71 – 0.78.

The tested range of wave heights / water depth at the toe [$H_{s,toe}/d$] is 0.37 – 0.53.

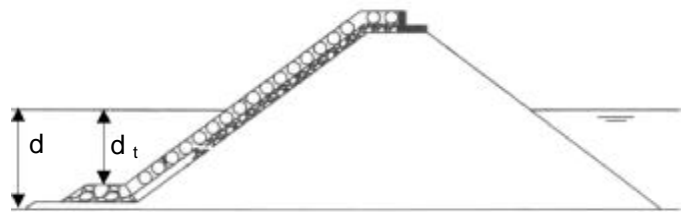


Figure 3 Relation between water depths near toe

The model is constructed with a foreshore with a slope of 1:30. The length of the foreshore is 12 m. The water depth at the wave paddle varied from 0.75 – 0.85 m; the water depth at the toe of the breakwater was 0.35 – 0.45 m.

A typical breakwater cross section has been selected consisting on core, filter layer, toe protection and L-shaped crest wall. The crest wall of plywood has been fixed at the

side-walls of the flume in order to guaranty the stability of the superstructure. As top layer the Xbloc units have been used in a single layer.

The properties of the various materials are summarised in Table 1.

Location	Layer thickness [mm]	Material	Mass [g]	Sizes [mm]				Density [kg/m ³]
				D	D _{n15}	D _{n50}	D _{n85}	
Xbloc armour layer [Single layer]	52	Concrete	121	54.0				2300
Filter layer	34	Stone	9.0-16.1		15.0	16.7	18.2	2740
Core	-	Stone	0.8-2.0		6.6	7.9	9.2	2650
Toe protection	70	Stone	84.0-187.5		31.7	36.4	41.3	2650

Table 1 Properties material in model

The armour layer has a slope of 3 [vertical] to 4 [horizontal], which is a typical slope for single layer armour units like the Core-loc and Accropode.

The model tests are focussed on Xbloc armour layer stability. Thus, the toe in the test set-up is over-dimensioned to exclude the influence of a failing toe structure on the stability of the armour layer.

In Figure 4 the dimensions of the Xbloc are given.

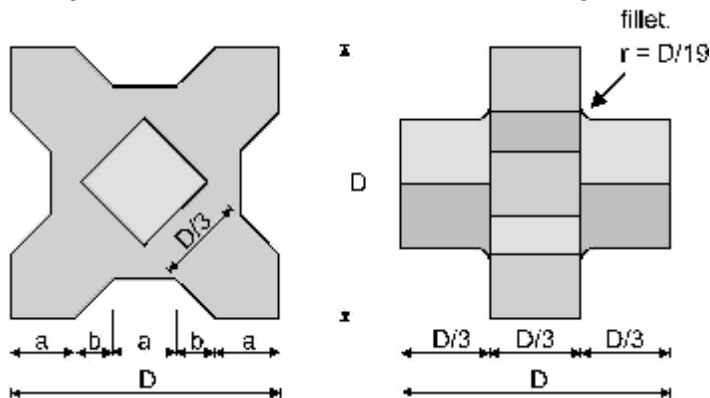


Figure 4 Xbloc dimensions

2.3 Measurement equipment

Wave heights have been measured using seven wave gauges. The incident and reflected wave spectra were determined by reflection analysis [“3-gauge-procedure” using least square method]. It is expected that the reflection analysis is less accurate for breaking wave conditions. Therefore additional tests have been performed without the structure in position to obtain the incident wave conditions at the toe of the structure. Incident wave heights have been determined at wave gauge 1, 2, 3 near the paddle and at gauge 4, 5, 6 at the toe of the structure as indicated in Figure 5. One wave gauge, gauge 7, has been placed at the crest of the breakwater in order to determine the number of overtopping waves.

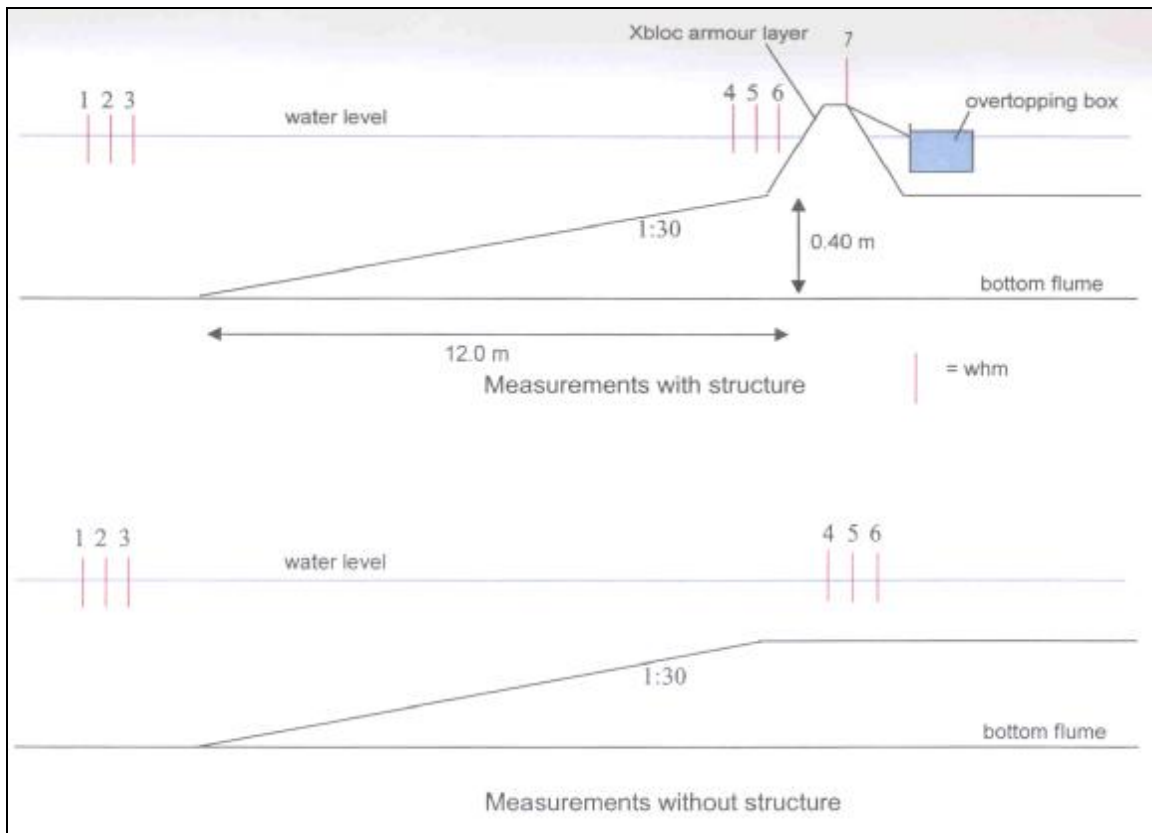


Figure 5 position wave gauges

The volume of overtopping water has been captured in a box behind the structure and is determined by water level measurements. In the test series with the highest crest level [test series 7] no overtopping volume has been measured.

In order to determine the settlement of the slope photographs have been taken before and after each test from a fixed camera position. These photos can also be used to determine the position of displaced or removed units during the tests.

2.4 Placement of armour units

2.4.1 Placement patterns

The Xbloc armour units are placed in a single layer. Placement of the units has been done by technicians of Delft Hydraulics without a strict guiding. Special attention has been paid to the units being placed in a way that is realistic for full scale unit placing. Examples of patterns as used in the model tests are presented in Figure 6 and Figure 7.



Figure 6 Example of random pattern



Figure 7 Example of regular pattern [test series 6]



2.4.2 General description of armour placement

Xbloc armour units are typically placed in a brick pattern. Units are placed in horizontal rows. The unit of the subsequent row will find a position in between 2 units of the previous row. The distances between the centre of gravity of the units within 1 row and in between 2 rows are predefined. The orientation of the units is either varied randomly [random placement] or predefined [regular placement]. Except for 1 of 7 test series the armour units have been random placed. Only one test series [test series no. 6] has been performed with regular placed armour units.

2.4.3 Packing density

The relation between placement pattern, packing density and hydraulic stability is required to determine a realistic packing density. The number of Xbloc armour units placed in the tests series is presented in Table 2.

Test series	No. of rows	No. of units / row	Total units	Pattern
<i>Configuration 1 [overtopping for extreme conditions]</i>				
1	28	13-14	373	Random
2	28	14	393	Random
3	28	14	393	Random
4	28	14	400	Random
5	27	15	405	Random
6	24	16-17	406	Regular
<i>Configuration 2 [no overtopping for extreme conditions]</i>				
7	32	15	491	Random

Table 2 Number of placed units

As the dimensions of the slope are known, the placements distances and packing densities relative to the unit size can be calculated. These values are presented in Table 3.

As unit size the height, D , of the model unit [5.4 cm] is used]. $D = 1.44 * D_n$, the nominal diameter.

Test series	Horizontal distance		Distance along slope [vertical]		Packing density	
<i>Configuration 1 [overtopping for extreme conditions]</i>						
1	0.075 m	1.39 * D	0.034 m	0.63 * D	389 units/m ²	1.13 / D ²
2	0.071 m	1.32 * D	0.034 m	0.63 * D	409 units/m ²	1.19 / D ²
3	0.071 m	1.32 * D	0.034 m	0.63 * D	409 units/m ²	1.19 / D ²
4	0.070 m	1.30 * D	0.034 m	0.63 * D	417 units/m ²	1.22 / D ²
5	0.067 m	1.23 * D	0.036 m	0.66 * D	422 units/m ²	1.23 / D ²
6	0.060 m	1.11 * D	0.040 m	0.73 * D	423 units/m ²	1.23 / D ²
<i>Configuration 2 [no overtopping for extreme conditions]</i>						
7	0.067 m	1.23 * D	0.036 m	0.67 * D	416 units/m ²	1.21 / D ²

Table 3 Packing density model units

As average value for random pattern the following values can be used.

Horizontal distance [m]	Vertical distance [m]	Packing density [units / m ²]
1.30 * D	0.64 * D	1.20 / D ²

Table 4 Average random packing density

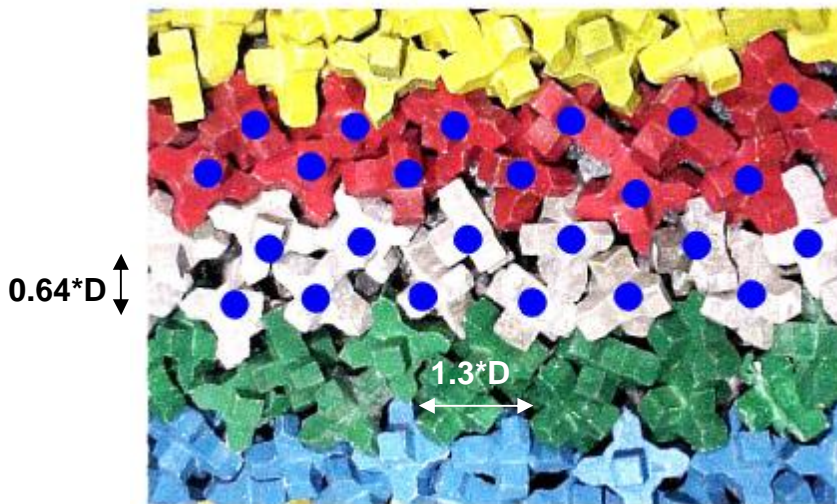


Figure 8 Definition of placement distances



The average packing density value can be used to estimate the number of full scale units that is required in a project. However, from experience with conventional concrete armour units it is known that for large size armour units the packing will be less dense due to more difficult placement of the units. The obtained packing density in the tests is therefore only realistic for small / medium size units. Based on the packing density value of Table 4 packing density for full scale units have been derived as presented in Table 5. Note that for unit with a volume above 5 m³ a lower packing density has been used.

Volume, V [m³]	Unit Height, D [m]	no. units/100 m² [-]
0.75	1.31	70.00
1.0	1.44	57.78
1.5	1.65	44.10
2.0	1.82	36.40
2.5	1.96	31.37
3.0	2.08	27.78
4.0	2.29	22.93
5.0	2.47	19.76
6.0	2.62	16.71
7.0	2.76	15.08
8.0	2.88	13.80
9.0	3.00	12.75
10.0	3.11	11.89
12.0	3.30	10.53
14.0	3.48	9.08
16.0	3.63	8.31
18.0	3.78	7.68
20.0	3.91	7.16
24.0	4.16	6.34
28.0	4.38	5.72

Table 5 Packing density various Xbloc sizes



3. TEST PROGRAMME

The test programme has been determined in consultation with Delft Hydraulics. A total number of seven test series has been executed. A number of individual tests have been conducted within every test series with increasing wave height in order to determine limiting conditions for the Xbloc armour layer stability. For each test series constant water level and wave steepness have been used.

Every test series started with two tests of 1000 moderate waves to allow initial settlements. Subsequently the wave height was increased. In order to maintain constant wave steepness, the wave period was also increased in each test. Each test consisted of 1000 waves.

The wave height [and period] have been measured stepwise until the slope failed or the limits of the wave generator were reached. The tests have been stopped when the filter layer was damaged even if the armour layer was damaged but still stable. After each test series the armour layer has been removed and the filter layer and armour layer have been reconstructed.

The following definitions have been used:

- Settlement: downward movement of unit[s] along slope without loss of interlocking function;
- Damage: unit[s] displaced out of grid, function armour layer intact;
- Failure: Loss of function of the armour layer, start of damage filter layer.

The wave conditions for the test series are summarised in Table 6. In all tests Jonswap wave spectra have been generated.

Test series	Placement pattern units	Water depth at toe [m]	Wave steepness, S_{om} [-]
1	random	0.40	0.02
2	random	0.35	0.06
3	random	0.35	0.02
4	random	0.35	0.04
5	random	0.40	0.06
6	regular	0.35	0.02
7	random	0.40	0.06

Table 6 Summary wave conditions

A photographic impression of the model and the tests is presented in Appendix A.

4. BASIC RESULTS

4.1 Wave conditions

The wave conditions at the wave paddle and at the toe of the structure [with and without structure in position] are listed in Appendix B, [according to Delft Hydraulics].

No results are presented for the two tests [per test series] used for initial settlement of the slope.

A summary of the wave conditions is presented in Table 7.

Test series	T_p toe	H_s [H_{m0}] wave paddle	Without structure	With structure
			H_s [H_{m0}] toe	H_s [H_{m0}] wave toe
1	2.9 – 3.2 s	0.151 – 0.193 m	0.155 – 0.181 m	0.155 – 0.187 m
2	1.6 – 2.0 s	0.153 – 0.245 m	0.144 – 0.182 m	0.141 – 0.203 m
3	2.7 – 3.3 s	0.159 – 0.207 m	0.154 – 0.176 m	0.156 – 0.191 m
4	2.0 – 2.6 s	0.157 – 0.261 m	0.146 – 0.187 m	0.153 – 0.214 m
5	1.6 – 2.2 s	0.159 – 0.277 m	0.148 – 0.210 m	0.150 – 0.233 m
6	2.7 – 3.4 s	0.158 – 0.231 m	0.154 – 0.182 m	0.158 – 0.203 m
7	1.6 – 2.1 s	0.160 – 0.261 m	0.149 – 0.204 m	0.146 – 0.225 m

Table 7 Summary measured wave conditions

From Table 7 and appendix B it can be seen that the wave heights at the toe with the structure present are mostly higher than the wave height without structure. This difference increases for higher wave heights and reaches up to 114% for the largest waves tested.

Possible reasons for these differences are:

- Uncertainties of the reflection analysis for highly non-linear and breaking wave conditions
- Shortcomings of the absorption control.

In case of a) it would be most reasonable to use the wave heights measured without structure for further analysis; in case of b) it would be most reasonable to use the wave heights measured with structure and in case the differences are caused by a likely combination of a) and b) it would be most reasonable to use average values for the wave height.

Nonetheless the incident wave heights determined from tests without structure have been applied for further analysis which will lead to the most conservative conclusion with respect to stability and overtopping.

It should be noted that this type of conservative approach, which covers the main uncertainties with respect to wave generation and wave measurements, provides results that are unlikely to be exceeded.

4.2 Damage

In Appendix C tables are present displaying the damage development during the test series [according to Delft Hydraulics]. No results are presented for the two tests [per test series] used for initial settlement of the slope. The indicated wave heights at the toe are the wave heights without structure present.

The wave heights for which start of damage, SoD, occurred as well as failure of the armour layer are presented in Table 8. Table 9 describes the observations on damage development during the test series.

Test series	Start of damage, SoD			Failure		
	T_p	H_{m0} paddle	H_{m0} toe	T_p	H_{m0} paddle	H_{m0} toe
1	2.97 s	0.166 m	0.164 m	3.21 s	0.193 m	0.181 m
2	1.82 s	0.205 m	0.168 m	1.99 s	0.245 m	0.182 m
3	2.82 s	0.169 m	0.159 m	3.25 s	0.207 m	0.176 m
4	2.11 s	0.184 m	0.162 m	no failure observed		
5	1.86 s	0.213 m	0.181 m	no failure observed		
6	no damage observed			no failure observed		
7	1.89 s	0.229 m	0.189 m	no failure observed		

Table 8 Summary damage conditions

Test series	Observations damage development
1	Start of damage / failure due to excessive settlement, too low packing density, start of damage 2 nd unit from window
2	Start of damage by two adjacent units removed from below waterline, failure due to settlement after 'closure' of the initial gap
3	Start of damage due to a single unit next to window, failure due to settlement of units into the formed gap
4	Start of damage due to two separate units removed from below water line, additional damage due to two units removed from initial gap, no failure observed
5	Start of damage due to two separate units removed from below water line, 1 unit from location next to window, no additional damage
6	No damage observed
7	Start of damage by two adjacent units removed from below waterline

Table 9 Observation on damage development

Appendix D presents photographs of the slope for all tests. From these photographs the damage development can be seen.

In chapter 5 the hydraulic stability is further analysed.

4.3 Overtopping

The overtopping discharge and percentage of overtopping waves [overtopping rates] for each test series are presented in Appendix C. No results are presented for the two tests [per test series] used only for initial settlement of the slope. The indicated wave heights at the toe are the wave heights without structure present.

Test	Water depth at toe [m]	Wave height H_{m0} toe [m]	Overtopping discharge Q [l/s/m]	Percentage of waves overtopping [%]
1	0.40	0.155 – 0.181	0.53 – 1.76	19.9 – 41.3
2	0.35	0.144 – 0.182	0.02 – 0.50	1.1 – 23.0
3	0.35	0.154 – 0.176	0.27 – 1.17	10.3 – 35.9
4	0.35	0.146 – 0.187	0.07 – 1.61	5.0 – 46.7
5	0.40	0.148 – 0.210	0.12 – 2.76	8.7 – 60.2
6	0.35	0.154 – 0.182	0.33 – 1.96	16.5 – 50.1
7	0.40	0.149 – 0.204	No overtopping values measured	

Table 10 Summary overtopping results

In chapter 0 the overtopping is further analysed.



4.4 Settlement of slope

An impression of the settlement of the armour units can be get from the pictures as presented in Appendix D



5. STABILITY OF XBLOC

5.1 General observations

5.1.1 Damage curves

Damage curves are displaying the relation between the damage and the wave height. With respect to the general application of results, non-dimensional values have been used.

The amount of damage is expressed by the dimensionless number of displaced units N_{od} . N_{od} is defined by the total number of units that are removed out of the armour layer [hydraulic damage] related to a width of D_n of the unit. The number of displaced units N_{od} can be easily related to a percentage of damage, as the number of units in the cross section is known [see Table 2].

The relative wave height is expressed by the dimensionless stability parameter, $H_s/\Delta D_n$. This stability parameter is commonly used for the presentation of model test results. The H_s used in this parameter is the H_s at the toe of the structure. The nominal diameter, D_{n50} or D_n , is a parameter which is originated from the size of rock material. For Xbloc units, D_n is related to the height of the unit, D , as follows:

$$D_n = 0.693 * D$$

Figure 9 presents the damage curves for all performed test series. Failure of the armour layer during a test is represented by a vertical line.

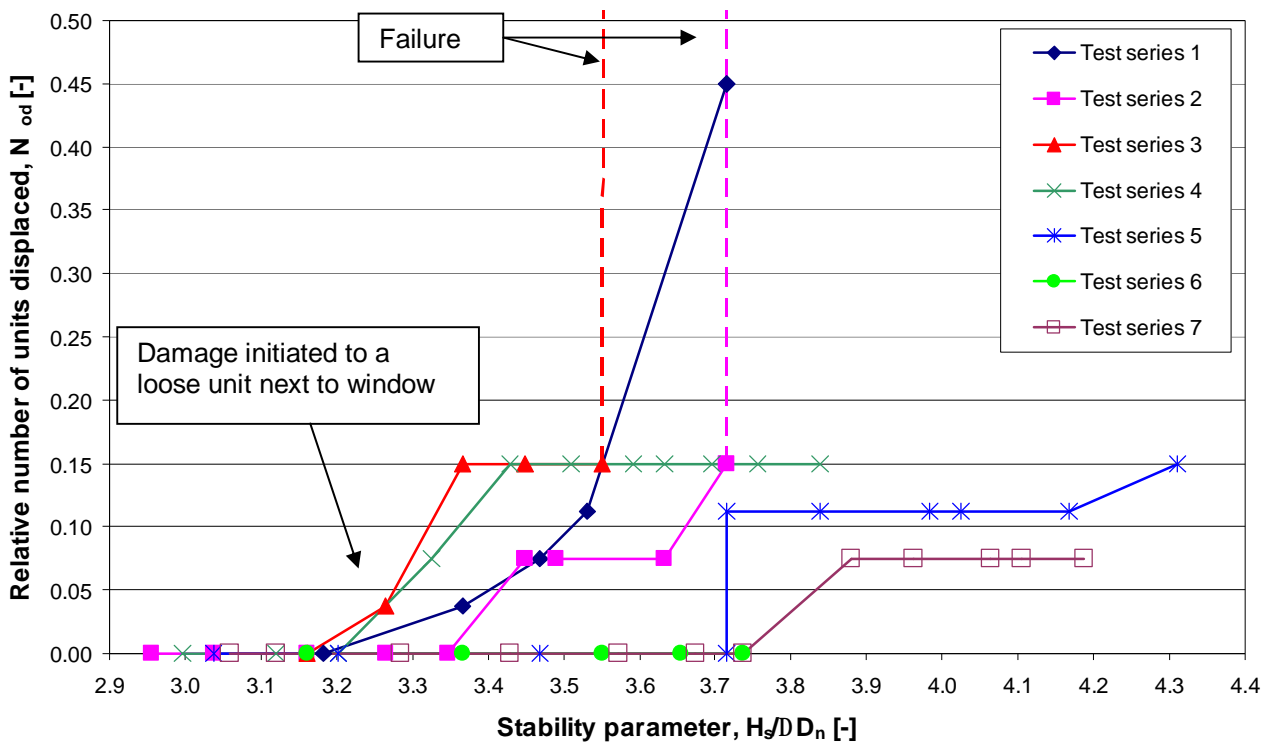


Figure 9 Damage curves Xbloc units

5.1.2 General damage development, non-progressive failure

Except for the test series with regular placed units [series 6], damage has occurred in all tests series. In two test series [series 2 & 3] failure of the armour slope occurred during the test. In a single tests series [series 1] the damage after the last test was such high that it was decided to continue with a following test series [although the armour layer had not actually failed]. The test series 4, 5, 6 & 7 were stopped when the test the maximum wave height that could be generated in the wave flume was reached.

After start of damage at least three further tests [with increasing wave height] of 1000 waves are required before failure occurs [see Figure 9]. In three of the six tests where damage occurred, no failure has been observed.

Table 11 presents the relative wave heights for start of damage and failure. In the column "start of damage" the wave height values are listed where the first units were displaced out of the armour layer. In the column "failure" the wave heights are listed that caused a progressive failure of the armour layer. In tests where no damage or failure was observed the maximum values of $H_s/\Delta D_n$ toe that have been tested are given. In the column "margin in wave height [toe] between start of damage and failure" the value of ΔH_s is presented. ΔH_s is defined by: $(H_{s, failure} - H_{s, SoD})/H_{s, SoD}$.



Test series	H_s/DD_n toe Start of damage	H_s/DD_n toe Failure	Margin in wave height [toe] between start of damage and failure, ΔH_s
1	3.37 *	3.72	10%
2	3.45	3.74	8%
3	3.26 *	3.61	11%
4	3.33	no failure [max value 3.84]	> 15 %
5	3.72	no failure [max value 4.31]	> 16 %
6	no damage [max value 3.74]	no failure [max value 3.74]	-
7	3.88	no failure [max value 4.19]	> 8 %

* SoD occurs near window [boundary effect]

Table 11 General failure data

In test series where the armour layer finally failed the margin ΔH_s was about 10 % [8-11%]. In test series where the limits of the wave generator were reached before the slope failed the margin from start of damage to the final wave height was 8% -to 16%. It appears reasonable to assume that the margin ΔH_s will be larger than 5% under all circumstances and in most cases about 10% or larger.

A progressive failure mechanism, that will start immediately after displacement of a very limited number of units and has been reported for other single layer armour units as Accropode and Core-loc, has not been observed for Xbloc. Furthermore it was observed that after start of damage the exposed filter layer at the 'gap' remained stable under wave attack. Only after failure of the armour layer the filter layer became damaged.

5.1.3 Re-arrangement of armour units

It was observed in most tests that after one or more units have been washed out, the units above the gap would gradually move down and close the gap. This process may continue during several tests until the gap is completely filled. It was found that the shifted units have reasonable interlocking with the adjacent units, albeit less than a placed unit. Hence the units above the gap will take over the function of the removed units [self-healing].

When the units above a gap are settling, the units from the next following row will also settle. It has been observed that this settling process continues up to the breakwater

and results in a protection of the damaged section while the overall packing density will decrease. The overall stability of the slope is only marginally affected by these settlements.

Start of damage normally occurs at the location with the most severe wave attack, which is usually near the still water line. Therefore, the 'self-healing' capacity of the Xbloc can prevent failure of the slope even in extreme loading conditions. It is further believed that this settlement and repair mechanism contributes to the observed slowly progressing damage under increasing wave load after start of damage.

The observed 'self-healing' behaviour of the units under wave attack is due to the large number of interlocking interfaces between adjacent Xbloc units. The unit orientation on the slope is therefore of less importance than for other single layer armour units like Accropodes.

5.1.4 Influence of placing density

As only limited experience existed with placing the units, the units of the first tests have been placed with a lower packing density than the units in the later tests. The packing density of the later tests was up to 5% to 9 % higher than the density of the first test.

Figure 10 presents the influence of the achieved packing density on the values of $H_s \cdot \Delta_n$ [toe] for which damage and failure was observed. As in the test with regular pattern placement no damage has been observed, this test is not included in the figure.

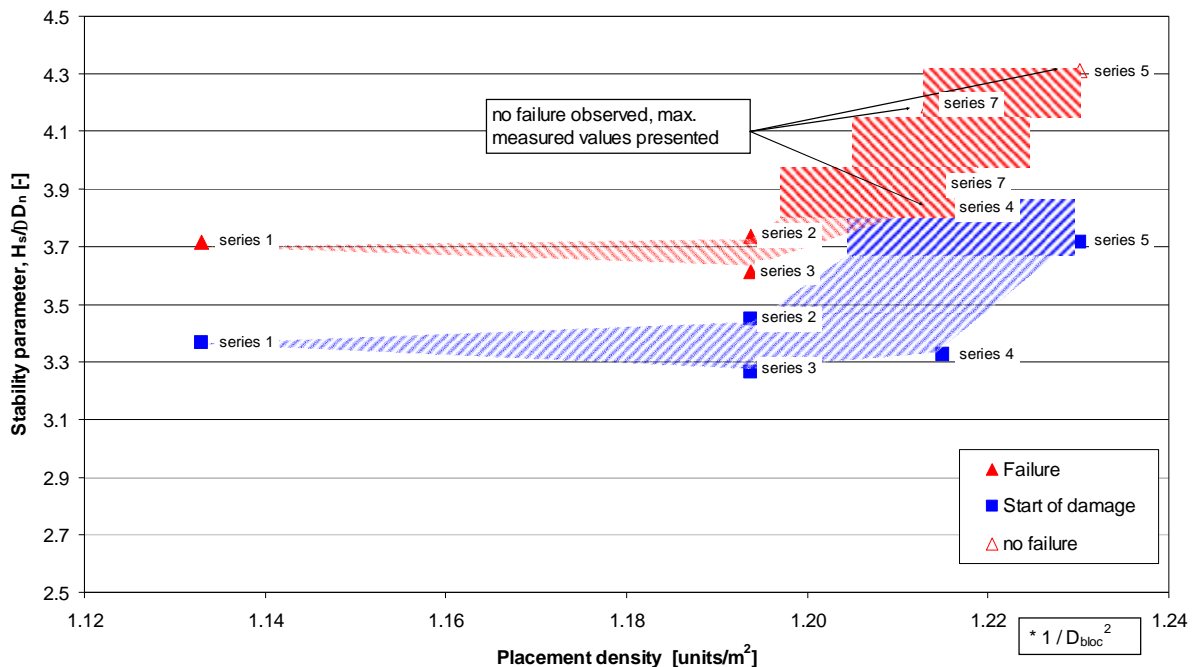


Figure 10 influence packing density on stability



It can be concluded that the stability increases for higher packing density. Both the start of damage as well as failure of the armour layer occurs at higher $H_s/\Delta D_n$ [toe] levels. Furthermore the margin in wave height between start of damage and failure of the armour layer increases at higher packing density. This margin varies between 10 % [test series with the lowest packing density and failure of the armour layer] and more than 15 % [test series with the highest packing density and no failure of the slope].

It is further interesting to note that with packing densities of 1.20 or less the slope failed in the test and with packing densities of 1.21 or more the limits of the wave generator have been reached before the slope failed. Based on these tests a packing density of at least 1.20 is recommended for the Xbloc.

5.1.5 Influence of placing pattern

As only one test with a regular pattern has been performed it is not considered appropriate to draw firm conclusions. In this test no damage has been observed, which indicates that a regular placed armour layer of Xbloc units has a very high stability.

It should however be kept in mind that a regular placed armour layer might be difficult to achieve in practice considering placement under water in a marine environment.

5.1.6 Influence of wave steepness

In Figure 11 the influence of the wave steepness on the stability of the armour units is presented. As in the test with regular pattern placement no damage has been observed, this test is not included in the figure.

The wave steepness at the toe differs from the wave steepness at the wave paddle. This is caused by change in water depths between the paddle and the breakwater toe causing changes in wave length and wave height [shoaling and wave breaking].

In order to facilitate the application of experimental results for general design purpose of Xbloc slopes it has been decided to define the wave steepness S_{op} as ratio of wave height at the paddle H_s and deepwater wave length L_{op} arrived from the peak period.

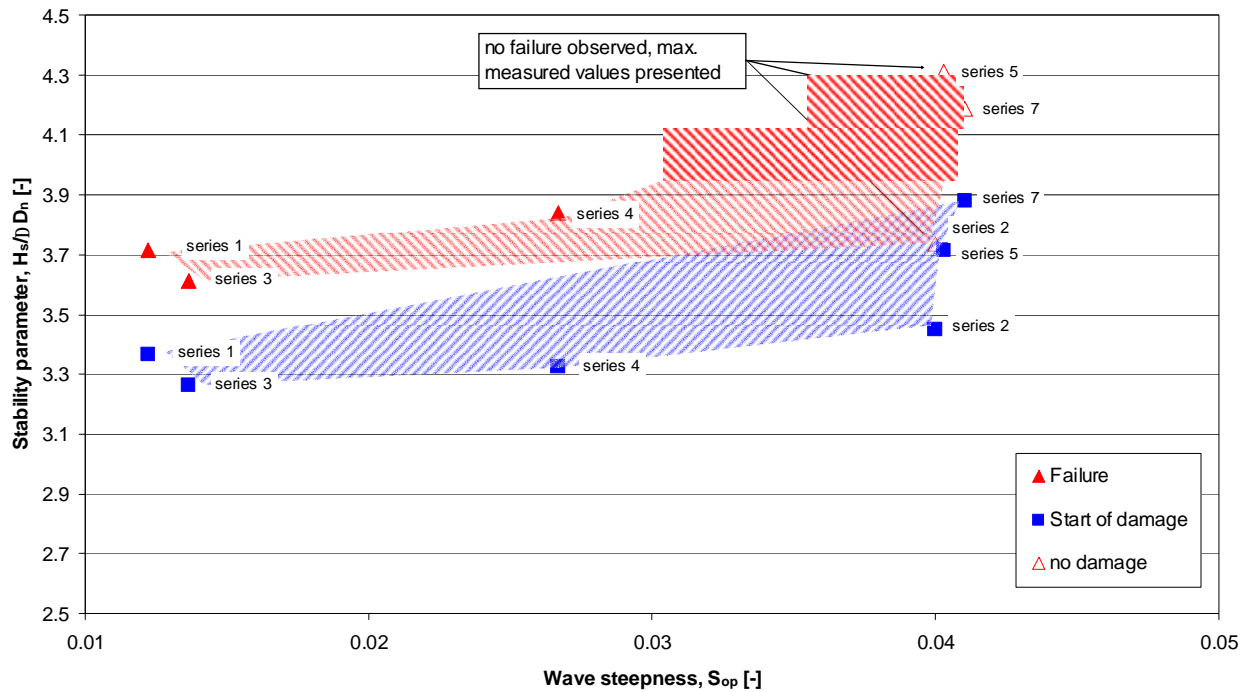


Figure 11 Influence wave steepness on stability

This figure shows increasing stability with increasing wave steepness. It should however be taken into account that this conclusion is based on 6 tests only, and other factors such as packing density and crest level will also influence the stability of the slope. If for example test series 5 and 7 with high packing density are not considered, the effect of wave steepness will vanish. It can therefore be concluded that the effect of wave steepness on the stability of the slope cannot be determined from this results.

5.1.7 Other influences

Besides packing density, placement pattern and wave steepness, there are other influences that may affect the stability of the armour layer.

The last test series was performed with a high crested structure. Therefore the armour on the slope is placed in more rows than in the configuration with the lower crest. The high crested configuration has 15 % more rows [average of number of rows = 27.8 for tests with randomly placed low crested structure, number of rows is 32 for test with high crested structure].

In the test with high crest no failure has been observed and the wave height for which damage occurred was the highest of all tests series [except for the test series with pattern placed units where no damage was observed].



A reason for the high stability could be the extra downward pressure on the blocks due to the increased number of rows, which increases the interlocking. On the other hand the hydrodynamic forces during wave run-down are increased as compared to a low crested structure where wave overtopping will reduce the run-down on the slope.

The sideward boundary of the slope may also affect the results. It was found that in some of the test series [test series 1 and 3], displacement of units located at the window caused start of damage. Apparently the units next to the window have less interlocking which results in a lower stability compared to other units.

5.2 Design formula

5.2.1 General

The results of the tests have been used to create a design formula, which is universally applicable for the basic design of slopes with Xbloc armour units.

5.2.2 Design philosophy

Breakwaters are designed to withstand extreme waves caused by storm events that occur during the design lifetime of the structure. The design wave height is derived from past storm events and can be exceeded during an extreme storm event within the lifetime of the breakwater. Exceedance of design waves might cause damage to a breakwater; however a severe damage or complete failure shall be prevented. Therefore, the design formula should contain a safety margin to decrease the effects of an underestimated wave height.

Another item that plays a role in the stability of the slope is fracture of units. Units under wave attack may move while maintaining its position on the slope. This is called rocking. In projects with slender concrete armour units, it was found that rocking of units can cause partial or complete fracture of the unit, which reduces the function of the unit. As the Xbloc is not a slender armour unit with a high structural stability [refer to DMC report 210006-r-02] rocking is not considered to be a major risk for failure.



5.2.3 Design criteria

In order to create a safe design the Xbloc slope shall be completely stable for design wave conditions. Based on the results of the 2-D model tests as described in this report, the limiting wave conditions shall be as follows:

[significant] design wave height, H_d	Effect on Xbloc slope
$1.0 * H_d$	Slope is completely stable
$> 1.1 * H_d$	Start of rocking
$> 1.25 * H_d$	Start of damage [1 or more units displaced]
$> 1.3 * H_d$	Continues damage [further units displaced]
$> 1.4 * H_d$	Start of progressive failure

Table 12 Limiting wave conditions for design purpose

This means that, for whatever reason, when the wave height in the design of an Xbloc armour layer is exceeded up to 25 % only start of damage may occur. Failure of an Xbloc armour slope will only occur when the design wave height is exceeded with more than 40 % [based on average H_s value in the last test of a test series]

The design criterion for start of damage is similar to the criterion used in the model tests of construction with Accropode armour units.

5.2.4 Design formula

The start of damage value of $H_s/\Delta D_n$ as observed in the tests is in average 3.5 [only randomly placed units considered] and varies between 3.25 and 3.85. Rocking starts approximately at $H_s/\Delta D_n = 3.1$. Start of failure is in average at 3.9 and varies between 3.61 and 4.31 [in the test series where no failure has been observed, the highest measured $H_s/\Delta D_n$ values have been used].

To meet the criteria in the model tests the following design formula should be used for preliminary design of slopes using Xbloc armour units:

$$H_s/\Delta D_n = 2.8$$

which is similar to

$$H_s/\Delta D = 1.94$$

in which:

H_s	incident wave height near the toe	[m]
Δ	relative density [$(\rho_a - \rho_w) / \rho_w$]	[-]
	[ρ_a = density of armour material ρ_w = density of water]	
D_n	nominal diameter of unit [= W / ρ_a] ^{1/3}	[m]
D	unit height [=1.44 * D_n]	[m]

The design formula is based on the average value for start of damage. It should be noticed that the derived formula is based on a limited amount of test series in which several items have been varied. Further model test should be performed to validate the formula. Model testing of specific structures is always required.

No distinction has been made between breaking and non-breaking wave conditions. In the test series incident wave height to water level [at the structure] ratios varied between 0.38 and 0.75. Thus, non-breaking wave conditions only occurred in the first tests of each test series. In future tests it should be investigated whether higher K_d values can be applied for non-breaking wave conditions.

Furthermore no distinction has been made for the various packing densities and the various wave steepnesses. Regarding the first item, the packing densities should be as dense as possible, a packing density of at least 1.20 is recommended.

Regarding the wave steepness, it is not practical to include this in the formula until further results on the influence of wave steepness on stability are known.

5.2.5 Hudson formula

A widely used formula for the design of concrete armour units is the Hudson formula, although it does not include the influence of the wave period [and thus wave steepness] and surf similarity parameter, ξ .

The Hudson formula can be written as follows:

$$H_s / \Delta D_n = [K_d * \cot \alpha]^{1/3}$$

In which:

H_s	incident wave height near the toe	[m]
Δ	relative density [$(\rho_a - \rho_w) / \rho_w$]	[-]
D_n	nominal diameter of unit = $[W / \rho_a]^{1/3}$	[m]
K_d	stability factor	[-]
α	slope angle	[degrees]



ρ_a density of armour [kg / m³]
 ρ_w density of water [kg / m³]

In the model test the following factors are used:

$\Delta = 1.3$ [based on ρ_a , of 2300 kg/m³ and ρ_w of 1000 kg/m³]
 $D_n = 0.0375$ m
 $\cot \alpha = 1.333$

In order to achieve a similar result with the Hudson formula as with the proposed design formula as described in 5.2.4 a K_d value of 16 should be used [$H_s/\Delta D_n = 2.77$]

Figure 12 presents a damage graph including the $H_s/\Delta D_n$ value which results from a design according the Hudson formula, using a K_d factor of 16 and a slope of 4:3. On the horizontal axis the surf similarity parameter, ξ_z , is plotted, which is defined as:

$$x_z = \frac{\tan a}{\sqrt{s_{0,z}}} \text{ in which: } \tan \alpha: \text{ slope} = 3/4,$$

$s_{0,z}$ = ratio of wave height at the paddle H_s and deepwater wave length L_{-oz} [arrived from the zero crossing period]

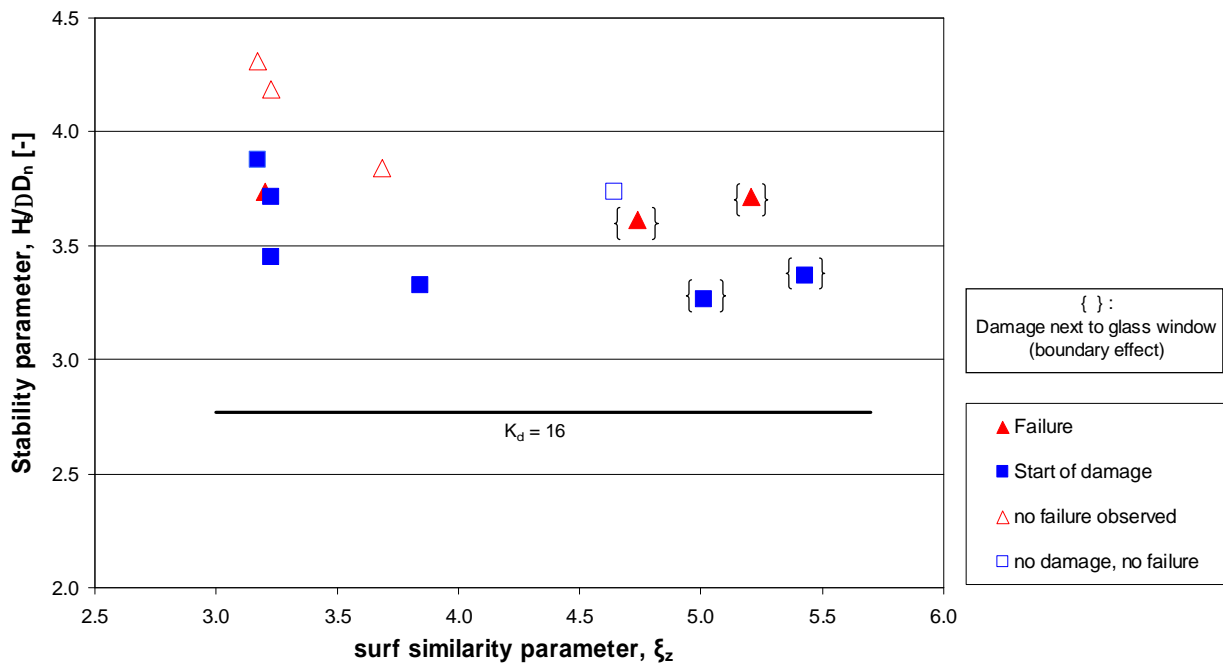


Figure 12 Damage graph including design value

5.2.6 Need for model tests

Although a design formula has been determined, hydraulic model tests have to be performed for each design where Xbloc units are applied. These tests are required to verify the hydraulic stability of the structure in general and of the armour layer in particular. This is common practice for all slope protection with concrete armour units.

5.3 Comparison with other units

In 1987 hydraulic model tests have been performed on the stability of Accropode units [Report H546, Sept 1987, Delft Hydraulics]. Test conditions and slope configuration are comparable with the Xbloc model tests. However, testing of the Accropodes has been done with a Pierson-Moskovitz wave spectrum, while the Xbloc units have been tested with a Jonswap spectrum.

In Figure 13 the results of both the Xbloc model tests as well as the Accropode model tests are displayed.

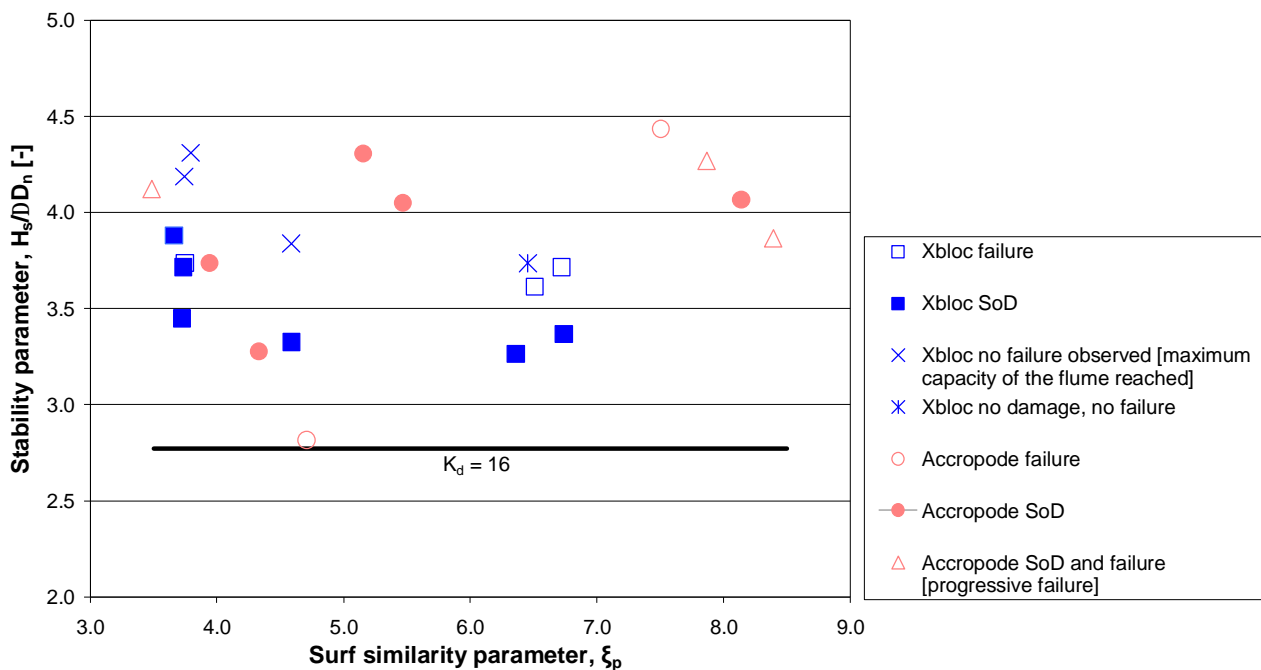


Figure 13 Comparison with Accropode model tests

It can be concluded from the figure that the average $H_s/\Delta D_n$ value for which start of damage occurs is 6 % higher for Accropodes than for Xbloc units. However, the range for start of damage is wider for Accropodes than for the Xbloc armour units. The lowest value for start of damage as found in the Accropode test is 2.82 while for Xbloc units the lowest value is 3.26 [which is 16 % higher].



The situation that start of damage occurred followed by failure of the slope without an increase of the wave height has been reported several times in the Accropode tests [progressive failure]. For Xbloc units this situation did not occur.

5.4 Conclusion on stability of Xbloc

- Failure of the slope was only observed in 3 of the 7 test series [max capacity of flume reached]
- No failure was observed for regular placed armour units [1 test series only]
- No failure was observed for high crested configuration [1 test series only]
- Both random as regular placement gives high stability
- After damage still stable, slowly proceeding failure mechanism
- At start of damage the wave height is 25% higher [average] than the design wave height
- At failure the wave height is 40% higher [average] than the design wave height
- Self healing behaviour of damaged areas observed [due to settlement of above lying units]
- Stability of slope increases for higher packing densities
- Recommended design formula for preliminary design: $H_s/\Delta D_n = 2.8$ [or $H_s/\Delta D = 1.94$] ¹⁾
- In a preliminary design of the armour layer according the Hudson formula a K_d factor of 16 can be used; which is higher than for Accropodes
- For each application of Xbloc armour hydraulic model tests are required [common practice]

¹⁾ based on use of 1:100 year wave condition. In case of a considerably higher design conditions than 1:100 year conditions more conservative design values should be considered

Use of the Hudson formula with a K_d factor of 16 will result in relative small units on the slope. However it may be considered to apply larger unit sizes to reduce the total number of units placed on a structure and thus decrease the construction period. Another reason to apply larger Xbloc units sizes may be a different philosophy of safety or maintenance. In other words, lower K_d values than 16 may be used if desired.

6. OVERTOPPING

6.1 General observations

6.1.1 Overtopping curves

Table 10 presents measured values of overtopping discharges and percentage of waves overtopping.

It can be concluded from literature on wave overtopping that the amount of overtopping is mainly related to the freeboard and the wave height [Coastal Engineering Manual, US Army Corps of Engineers]. In the overtopping formula of van der Meer [van der Meer and Janssen, 1995] the wave steepness and slope angle of the structure are included as well.

With respect to the general applicability of the results the following dimensionless parameters have been used in further analysis:

1. Percentages of overtopping waves;
2. Relative overtopping discharge, Q:

$$Q = \frac{q}{\sqrt{gH_s^3}}$$

In which:

q	average overtopping rate	[m ³ /s per m width]
g	gravitational acceleration	m/s ²
H _s	incident wave height near the toe	[m]

3. Relative freeboard, R:

$$R = \frac{R_c}{H_s}$$

In which:

R _c	freeboard [= crest level – still water level]	[m]
H _s	incident wave height at toe	[m]

Figure 14 and Figure 15 present the rates of overtopping on Xbloc slopes. It was found that the relation between Q and R is best described by exponential functions. The values on the vertical axis are therefore displayed on a logarithmical scale.

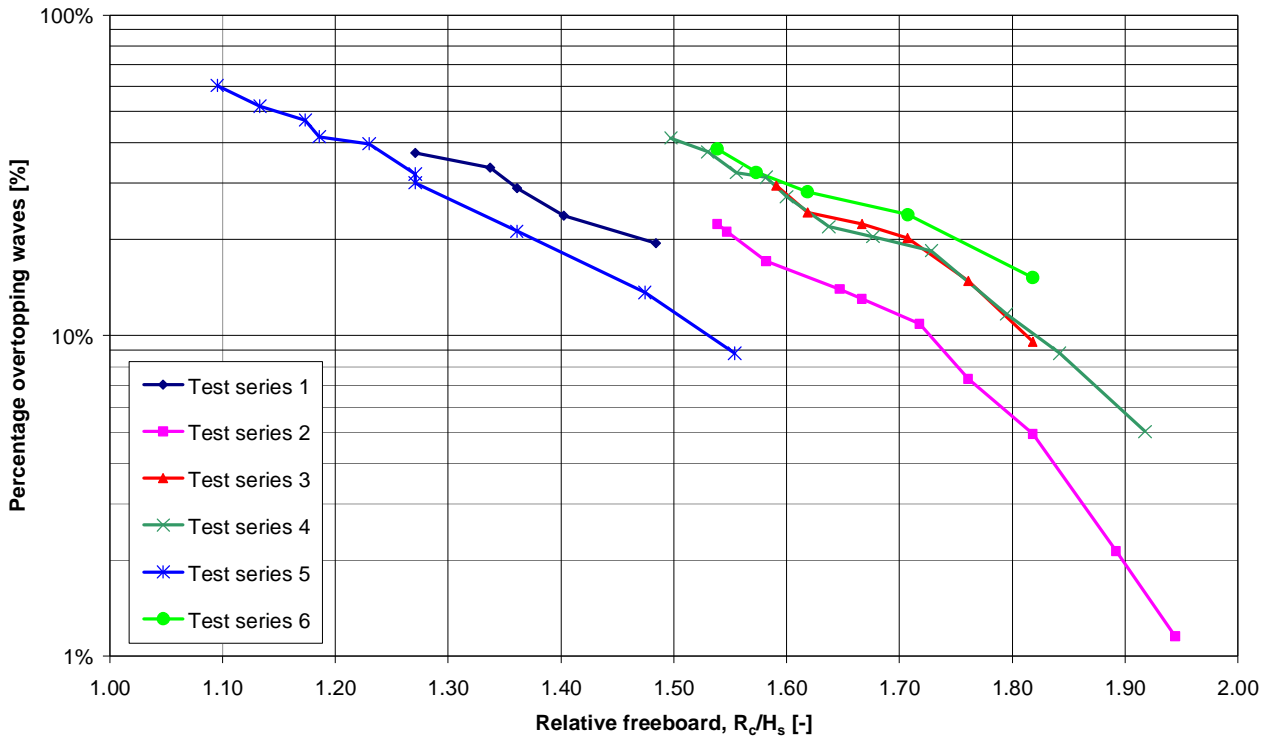


Figure 14 Percentage overtopping waves

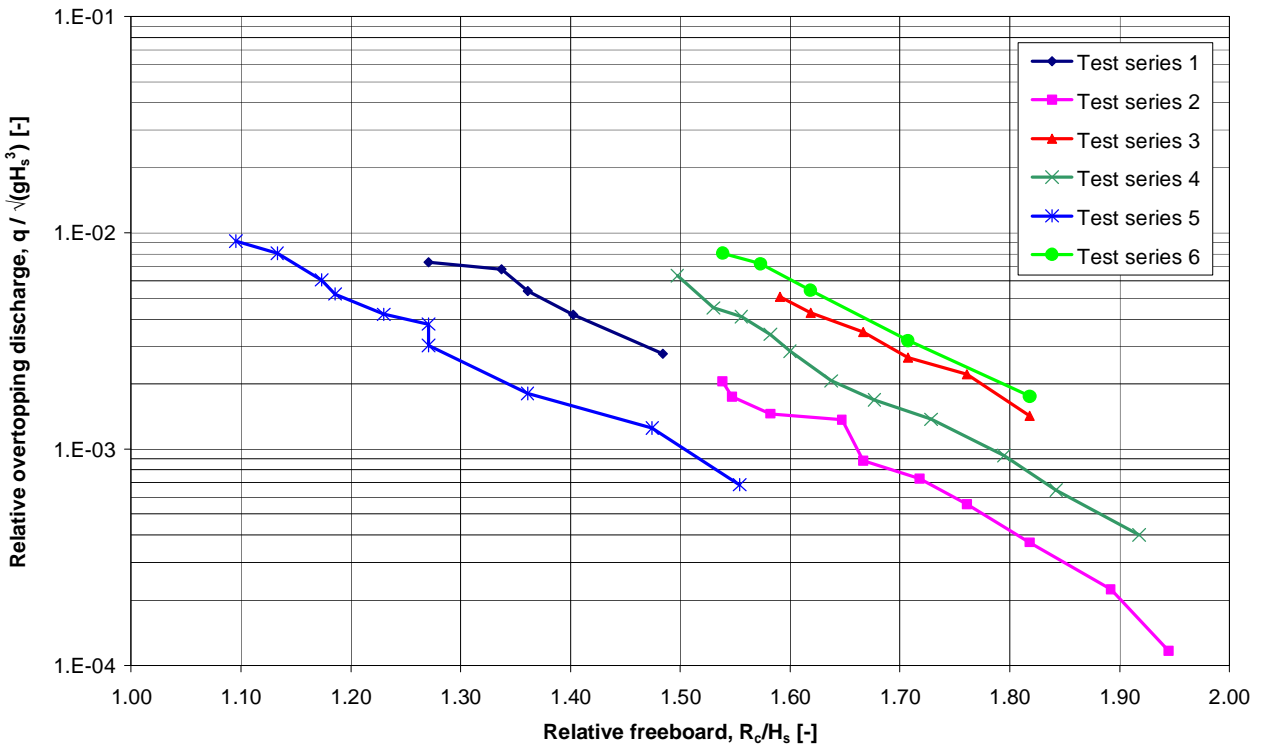


Figure 15 Overtopping discharge



As the figures show a similar pattern, further analysis of overtopping will focus on the relative overtopping discharge.

6.2 Design formula

6.2.1 Range of application

From Figure 15 it can be concluded that regular placement of the Xbloc units [test series 6] will result in increased overtopping rates compared to randomly placed units. Obviously regular placed units will create a smoother slope compared to randomly placed units, which results in increased overtopping values.

As the Xbloc armouring is likely to be placed in a random pattern, the development of a general design formula for Xbloc armouring is based on the test series with random Xbloc placement. The overtopping results of test series 6 have therefore not been considered in the analysis.

6.2.2 General form of formula

It was found that the results can best be described with a formula in the form of:

$$Q = a * \exp (-b * R)$$

In which:

Q	dimensionless discharge parameter	[-]
R	dimensionless freeboard parameter	[-]
a, b	coefficients	

This type of formula is similar to the van der Meer formulae for wave overtopping.

6.2.3 Fit of general form of overtopping formula

Figure 16 displays the fit of this formula based on $Q = \frac{q}{\sqrt{gH_s^3}}$ and $R = R_c / H_s$ [see paragraph 6.1.1 for details]. It can be seen that the overtopping formula can be described by:

$$Q = 0.531 * \exp (-3.58 * R).$$

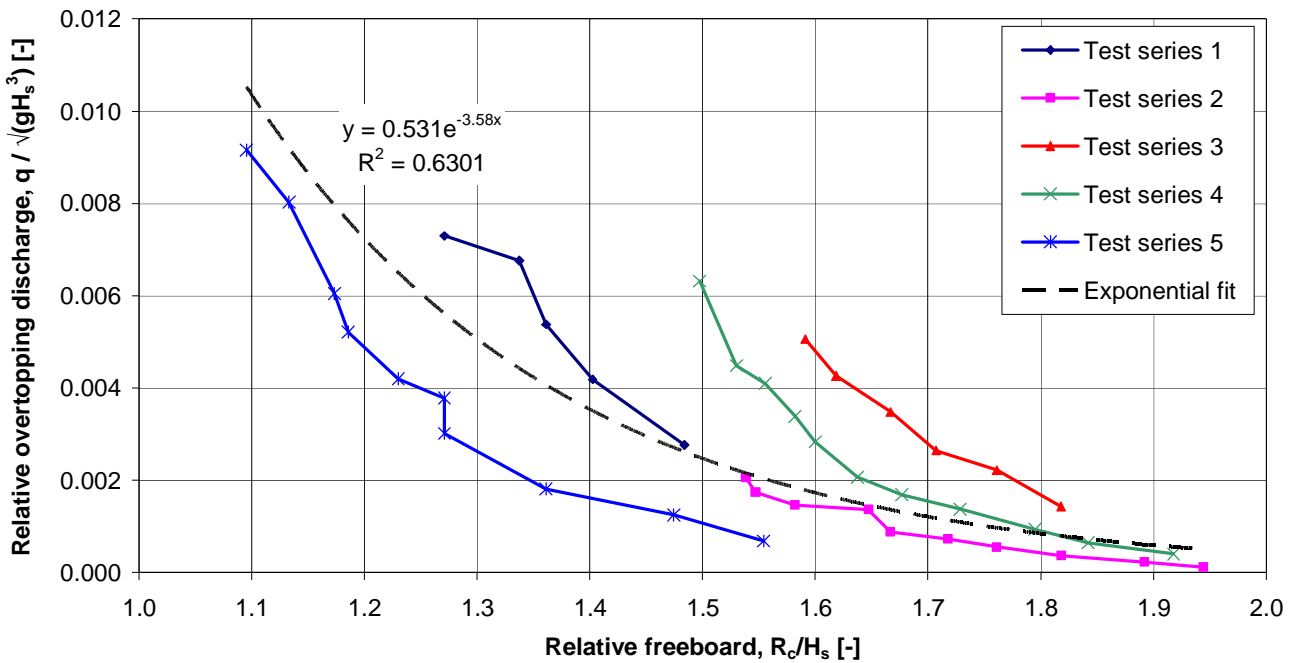


Figure 16 exponential fit of overtopping curve

6.2.4 Wave steepness

The formula as stated in paragraph 6.2.3 is purely based on the relation between freeboard, R_c , and the wave height, H_s , at the toe. In order to improve the fit of the design formula, other aspects that have influence on the amount of overtopping can be included in the formula.

Often the wave steepness [ratio wave height, wave length] is considered as an influence factor on wave overtopping. The influence of both components of the wave steepness on wave overtopping has been further analysed.

Figure 17 presents the relation between wave lengths at deep water, L_{op} , on the general overtopping formula. On the vertical axis the ratio $Q / f(R)$ is given in which:

$$f(R) = 0.531 * \exp (-3.58 * R) \quad [-]$$

In Figure 18 the relation between wave height at the paddle, H_s , and the $Q / f(R)$ ratio is presented.

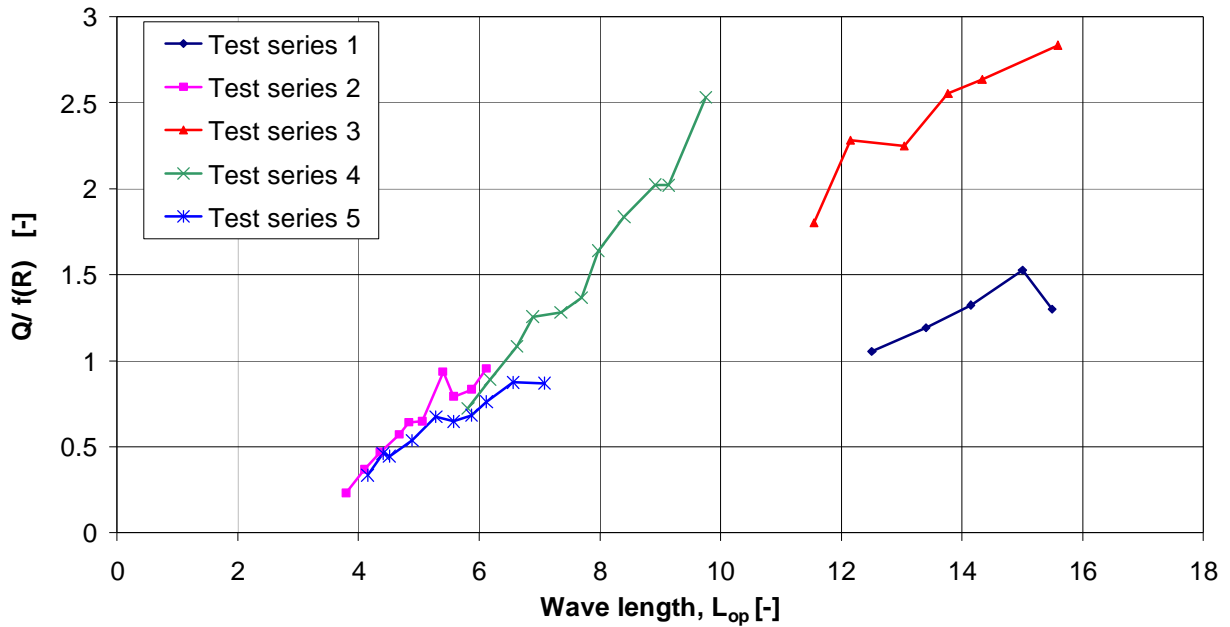


Figure 17 Influence of wave length on overtopping

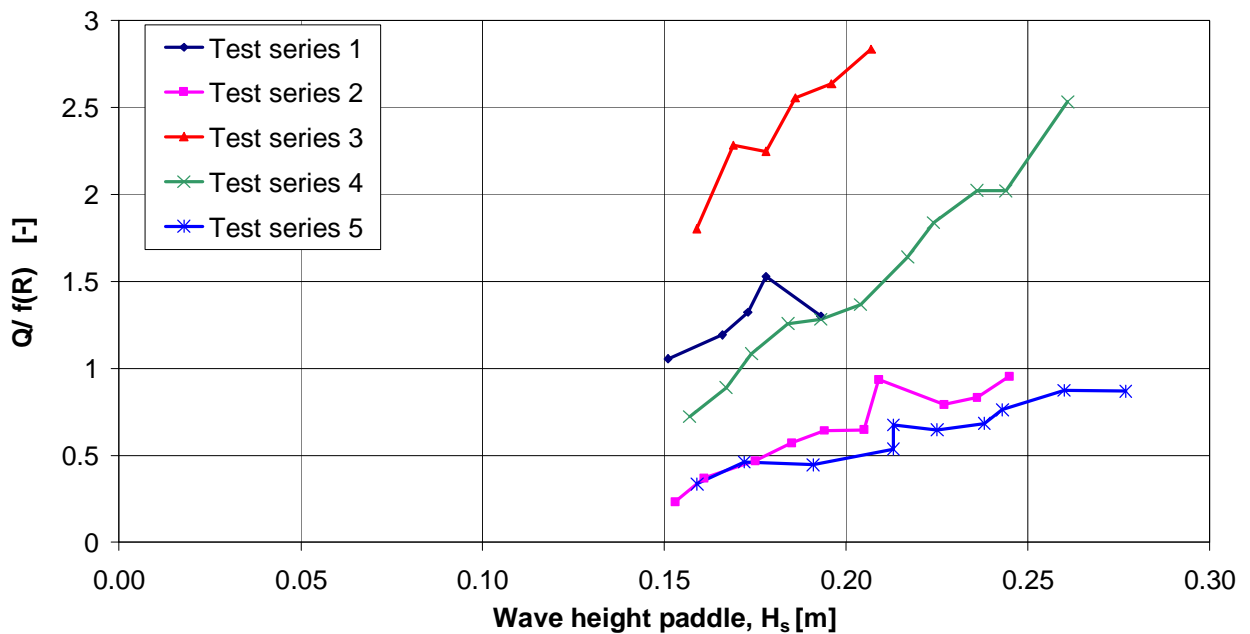


Figure 18 Influence of wave height on overtopping

It can be concluded from Figure 17 and Figure 18 that the components of the wave steepness, H_s and L_0 [or T_p] both have a similar influence on the overtopping: The amount of overtopping increases for increased values of H_s and L_0 , while the wave steepness is H_s divided by L_0 . It is therefore not justified to include the steepness in the overtopping formula.

6.2.5 Ursell parameter

An alternative dimensionless parameter in which both wave height and wave length are present in the multiplier is the Ursell parameter, U_r . This parameter is commonly applied to quantify non-linear effects of waves in shallow water.

$$U_r = \frac{H_s * L_t^2}{d^3}$$

In which:

H_s	significant wave height at toe	[m]
$L_{t,p}$	local wave length at toe, based on T_p	[m]
d	local water depth at toe	[m]

Figure 19 presents the relation between Ursell parameter, U_r , on the general overtopping formula. On the vertical axis the ratio $Q / f(R)$ is given, similar to paragraph 6.2.4.

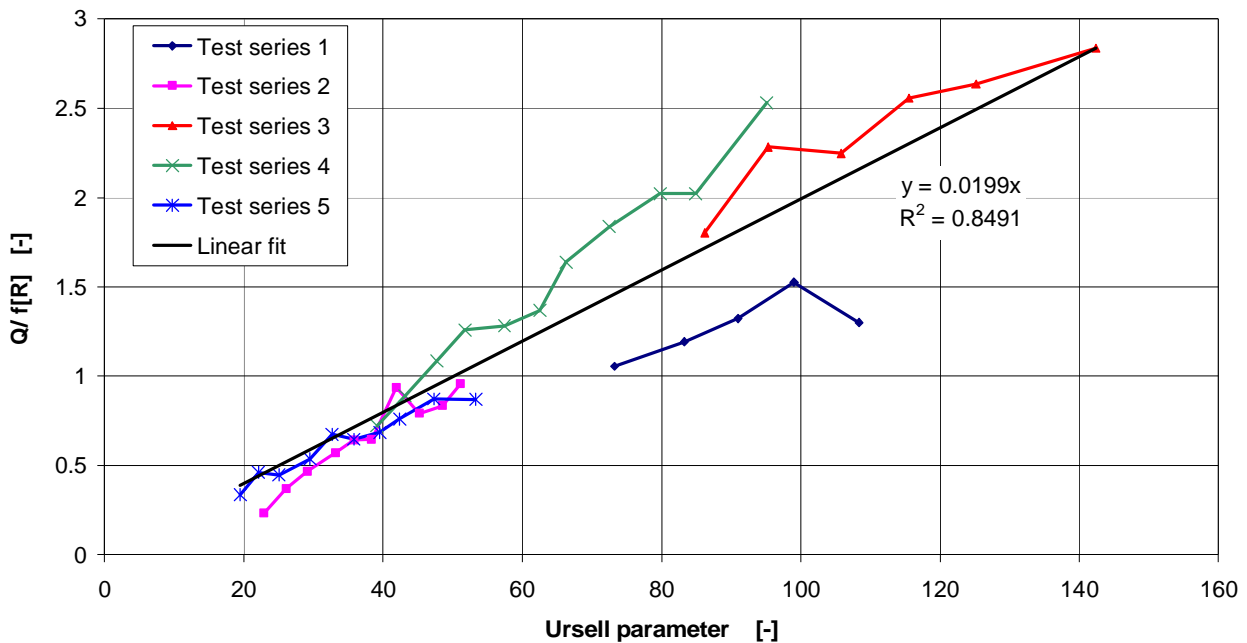


Figure 19 Influence of Ursell parameter on overtopping

It was found that an increased value of U_r will result in increased values of Q : The asymmetry of the wave profile [η_{crest}/H_s] is increasing with increasing U_r [which will increase the overtopping rate]. Thus it is recommended to include the Ursell parameter in the overtopping formula.

6.2.6 Recommended design formula for overtopping Xbloc

The overtopping formula with Ursell parameter included will be as follows:

$$\frac{q}{\sqrt{gH_s^3}} = 0.0098 U_r \exp \left(-3.58 \frac{R_c}{H_s} \right)$$

in which:

q	average overtopping rate	[m ³ /s per m width]
U _r	Ursell parameter [U _r = H _s *L _t ² / d ³]	[-]
g	gravitational acceleration	[m/s ²]
R _c	freeboard [= crest level – still water level]	[m]
H _s	incident wave height near the toe	[m]

Figure 20 presents overtopping formula as well as the relative overtopping volumes measured in the test series.

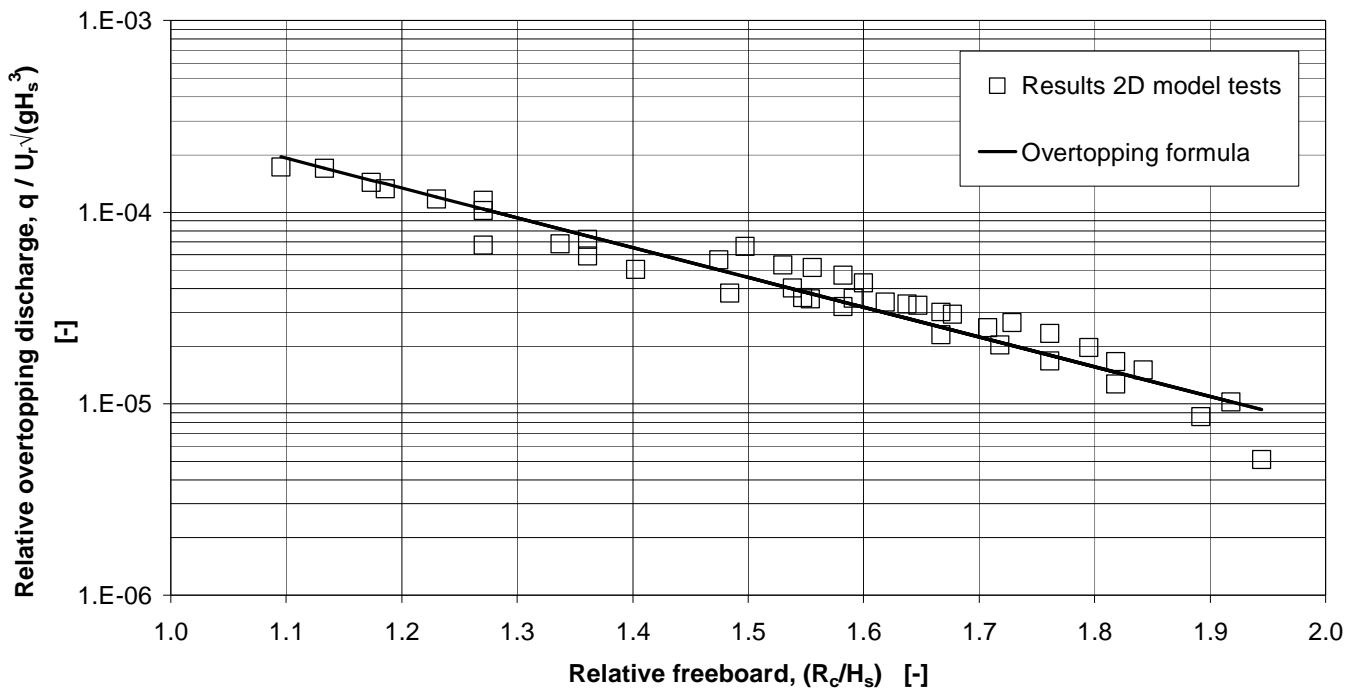


Figure 20 Fit of formula for overtopping discharge

The standard deviation of the difference between calculated and measured values of overtopping discharges is 2.1 E-04. The uncertainty of the overtopping formula, given by the ratio standard deviation / mean calculated overtopping discharge, is 29.4%.

6.2.7 Design formula for percentage of overtopping waves

In order to develop a design formula for the percentage of overtopping waves, a similar approach has been used as with the formula for overtopping volumes. It is found that the percentage of overtopping over Xbloc slopes can be described with the following formula with Ursell parameter included:

$$\% = 0.2829 U_r \exp \left(-2.92 \frac{R_c}{H_s} \right)$$

in which:

- % percentage overtopping waves [%]
- U_r Ursell parameter [$U_r = H_s * L_t^2 / d^3$] [-]
- R_c freeboard [= crest level – still water level] [m]
- H_s incident wave height near the toe [m]

Figure 21 presents overtopping formula as well as the relative overtopping volumes measured in the test series.

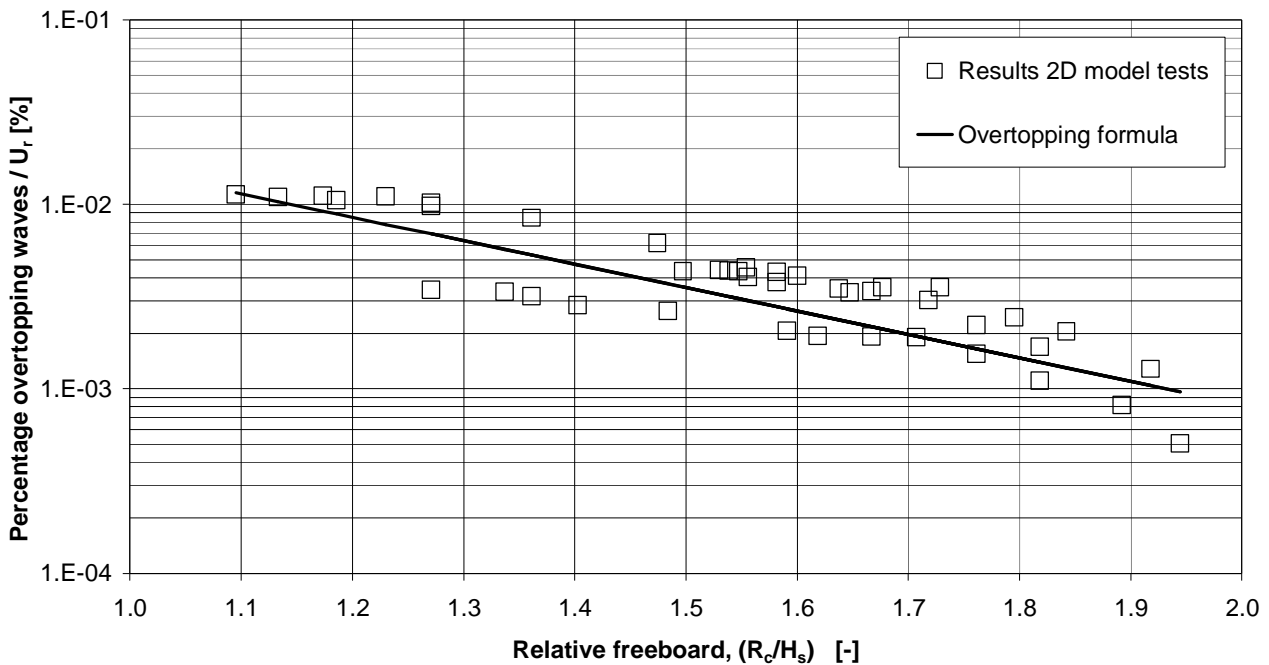


Figure 21 Fit of formula for percentage of overtopping waves



6.3 Conclusion on overtopping of Xbloc slope

- An exponential relation can be found between relative freeboard and overtopping volume as well as overtopping percentage.
- Use of the wave steepness in the design formula is not recommended, as both components of the fraction have a similar influence on the overtopping discharge.
- Non-linear effects [increased wave asymmetry] will increase the overtopping volume and can be quantified in shallow water by the Ursell parameter, $U_r = H_s^* L_t^2 / d^3$.
- Use of the Ursell parameter in the design formula increases the accuracy of the formula.
- The overtopping discharge of a slope with Xbloc armour units can be described using the formula:

$$\frac{q}{\sqrt{gH_s^3}} = 0.0098 U_r \exp\left(-3.58 \frac{R_c}{H_s}\right)$$

- The percentage of overtopping waves of an Xbloc armoured slope can be described using the formula:

$$\% = 0.2829 U_r \exp\left(-2.92 \frac{R_c}{H_s}\right)$$



7. OTHER OBSERVATIONS

7.1 Placement comfort

According to the involved assistants of Delft hydraulics the Xbloc units are relative easy to place compared to other state of the art units such as Accropodes and Corelocs. With the latter armour units, the position and orientation of each single unit is specified.

It was found that the Xbloc armour units will easily find a stable position on the slope. It is therefore not desired to predefine the orientation of the Xbloc. The placement requirement for the Xbloc can therefore be based on position on the slope. This allows easy and fast placement of an armour slope consisting of Xbloc units.

It is expected that in full scale an armour layer of Xbloc can be constructed faster and with more ease than units such as Accropodes and Corelocs.



8. CONCLUSIONS

From the tests and subsequent study of the results the following conclusions can be drawn.

8.1 Placement

Average values for random placement:

- Horizontal distance [m c.t.c.] $1.30 * D$
- Vertical distance [m c.t.c.] $0.64 * D$
- Packing density: [units / m²] $1.19 / D^2$

- Units can be placed in a random pattern as well as in a regular pattern.
- Xbloc armour units are easier to place than other state of the art armour units such as Accropode and Coreloc.
- It is expected that in full scale an armour layer of Xbloc can be constructed faster and with more ease than units such as Accropodes and Coreloc.

8.2 Stability

- Failure of the slope was only observed in 3 of the 7 test series [max capacity of flume reached]
- No failure was observed for regular placed armour units [1 test series only]
- No failure was observed for high crested configuration [1 test series only]
- Both random as regular placement gives high stability
- After damage still stable, slowly proceeding failure mechanism
- At start of damage the wave height is 25% higher [average] than the design wave height
- At failure the wave height is 40% higher [average] than the design wave height
- Self healing behaviour of damaged areas observed [due to settlement of above lying units]
- Stability of slope increases for higher packing densities
- Recommended design formula for preliminary design: $H_s/\Delta D_n = 2.8$ [or $H_s/\Delta D = 1.94$]¹⁾
- In a preliminary design of the armour layer according the Hudson formula a K_d factor of 16 can be used; which is higher than for Accropodes
- For each application of Xbloc armour hydraulic model tests are required [common practice]

¹⁾ based on use of 1:100 year wave condition. In case of a considerably higher design conditions than 1:100 year conditions more conservative design values should be considered



8.3 Overtopping

- An exponential relation can be found between relative freeboard and overtopping volume as well as overtopping percentage.
- Use of the wave steepness in the design formula is not recommended, as both components of the fraction have a similar influence on the overtopping discharge.
- Non-linear effects [increased wave asymmetry] will increase the overtopping volume and can be quantified in shallow water by the Ursell parameter, $U_r = H_s * L_t^2 / d^3$.
- Use of the Ursell parameter in the design formula increases the accuracy of the formula.
- The overtopping discharge of a slope with Xbloc armour units can be described using the formula:

$$\frac{q}{\sqrt{gH_s^3}} = 0.0098 U_r \exp\left(-3.58 \frac{R_c}{H_s}\right)$$

- The percentage of overtopping waves of an Xbloc armoured slope can be described using the formula:

$$\% = 0.2829 U_r \exp\left(-2.92 \frac{R_c}{H_s}\right)$$



210006-r-03

Appendix A

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Appendix A Photographic impression of the test [no test data included]



Appendix B Measured wave conditions [with and without structure present]



Appendix C Observed damage and overtopping values



Appendix D Photographs of damage development per test series