

# Hydraulic Performance of Xbloc<sup>®</sup> Armour Units

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**ABSTRACT:** In this paper the hydraulic performance of the Xbloc<sup>®</sup> is described. The paper includes the results of an extensive hydraulic model test program and is focused on the hydraulic stability of the unit and on overtopping.

## 1 INTRODUCTION

The Xbloc<sup>®</sup> (Figure 1) is a new single layer breakwater armour unit that was introduced by Delta Marine Consultants in September 2003. The development of Xbloc<sup>®</sup> started in 2001 and the unit was applied firstly in 2004 on a small shore protection and secondly in 2005 on a breakwater. The Xbloc<sup>®</sup> development and the application of the unit is presented on this conference in a separate paper [Redijk et al. (2006)].



Figure 1. Xbloc

The hydraulic performance and the hydraulic stability of Xbloc<sup>®</sup> were studied intensively during the Xbloc<sup>®</sup> development phase. For this purpose a number of hydraulic model test series have been carried out by different hydraulic laboratories. The main results of these tests are (1) the hydraulic stability of the unit (the ability to withstand wave forces) and (2) its overtopping characteristics. The test procedure, the test results and other observations made during the model tests are described in this paper.

## 2 HYDRAULIC MODEL TESTS

Table 1 presents an overview of the various physical model tests performed. Apart from these tests, other project specific tests have been carried out, but as the objective of these tests was a design check, the tests were not performed up to damage and failure. Therefore these tests are not included in this paper.

Table 1. Selection of model tests performed

Year	Test institute		Focussed on
2002	Delft Hydraulics (NL)	2D	Stability + overtopping
2003	Delft Hydraulics (NL)	3D	Oblique wave attack
2003	Delft University (NL)	2D	Overtopping
2003	Danish Hydraulic Institute (DK)	2D	Stability + overtopping
2004	Delft Hydraulics (NL)	3D	Round head
2004	Edinburgh University (UK)	2D	Overtopping (CLASH program)
2005	Delft University (NL)	2D	Steep foreshores
2005	CSIR (SA)	3D	Toe stability + overtopping

### 2.1 Parameters Varied

The tests have been conducted with irregular waves (1000 waves each test) and with breaking and non-breaking wave conditions. The parameters that have been varied are summarized in Table 2.

Table 2. Main parameters varied

Wave steepness	2% - 6%
Slopes of foreshore*	1:∞, 1:30, 1:15, 1:8
Angle of wave incidence	0° (Perpendicular), 15°, 30°, 45°
Slope angles structure	1:2 and 3:4
Packing Density of Xblocs	$1.13 / D^2 - 1.23 / D^2$ [units per m <sup>2</sup> ] [D = unit height]
Placement pattern of Xblocs	Regular placement pattern and random orientation of units
Crest heights	Relative freeboard Rc/Hs between 1 and 4
Number of rows of units**	Up to 32 rows in 2D tests, 50 rows in 3D test
Breakwater head	Xbloc <sup>®</sup> breakwater head was tested

\* research on the influence of steep foreshores is still ongoing; results will be presented in forthcoming paper

\*\* for typical breakwaters the number of rows is below 15-20

### 3 HYDRAULIC STABILITY

#### 3.1 General

The hydraulic stability of breakwater armour units is determined by wave height, unit size, specific density (of armour unit and sea water) and by the shape of the unit. The primary stability factors are combined in the stability number  $N_s = H_s / \Delta D_n$  where:

- $H_s$  = significant wave height;
- $\Delta$  = relative density =  $\rho_c / \rho_w - 1$
- $\rho_c$  = concrete density
- $\rho_w$  = seawater density
- $D_n$  = nominal diameter of armour unit [ $V^{1/3}$ ]

The stability numbers derived from the various tests are plotted in Figure 2 against the surf similarity parameter  $\xi_z = \tan(\alpha) / \sqrt{(H_s/L)}$  where:

- $\alpha$  = structures slope angle
- $H_s$  = significant wave height
- $L$  = wave length

The figure shows that start of damage was observed between  $H_s / \Delta D_n = 3.3$  and  $H_s / \Delta D_n = 5.5$ . Failure occurred between  $H_s / \Delta D_n = 3.7$  and  $H_s / \Delta D_n = 6.0$ . Based on these results, the design stability number of Xbloc<sup>®</sup> of  $H_s / \Delta D_n = 2.8$  has been concluded, which corresponds with a  $K_d$  factor of 16 for a 3V:4H slope angle. (NB: In fact the Hudson formula is not applicable for single layer armour as the effect of the slope steepness is not correct; the  $K_d$  factor is presented for comparison with other armour units.) The concluded stability values are shown in Figure 3.

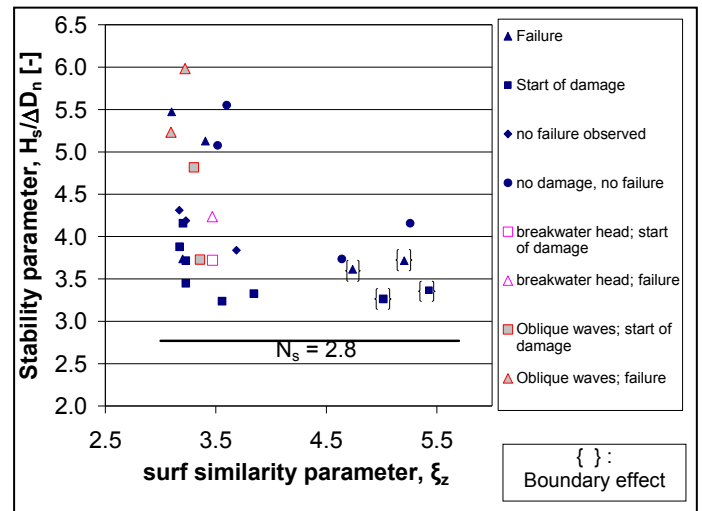


Figure 2. Hydraulic stability results of model tests

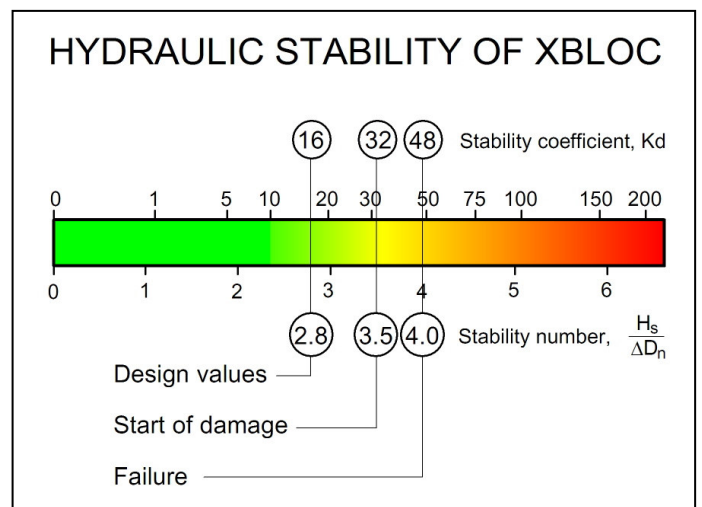


Figure 3. Concluded design stability values

Apart from these general conclusions regarding hydraulic stability, more detailed observations are described in the following sections.

#### 3.2 Influence of Xbloc<sup>®</sup> placement on hydraulic stability

##### 3.2.1 Placement Density

The influence of the placement density on the hydraulic stability, based on the 2D tests in 2002 is presented in Figure 4. The y-axis shows the stability number; the x-axis shows the placement density as Xbloc<sup>®</sup> units divided by  $D^2$ , where  $D$  is the unit height (not the nominal diameter  $D_n$ ).

The figure indicates that for placement densities above  $1.18 / D^2$ , higher placement densities lead to a better hydraulic stability. Furthermore it can be concluded that for lower placement densities, the hydraulic stability is constant.

In spite of the constant stability for lower placement densities, a design placement density of  $1.20 / D^2$  has been determined as lower packing densities led to some settlements. The test series with a packing density of  $1.13 / D^2$  showed significant settle-

ments but it should be noted that the test setup consisted of 28 rows of Xblocs<sup>®</sup> [Muttray et al. (2005)]. It was found that for lower placement densities, the units settle and obtain a placement density close to the design placement density.

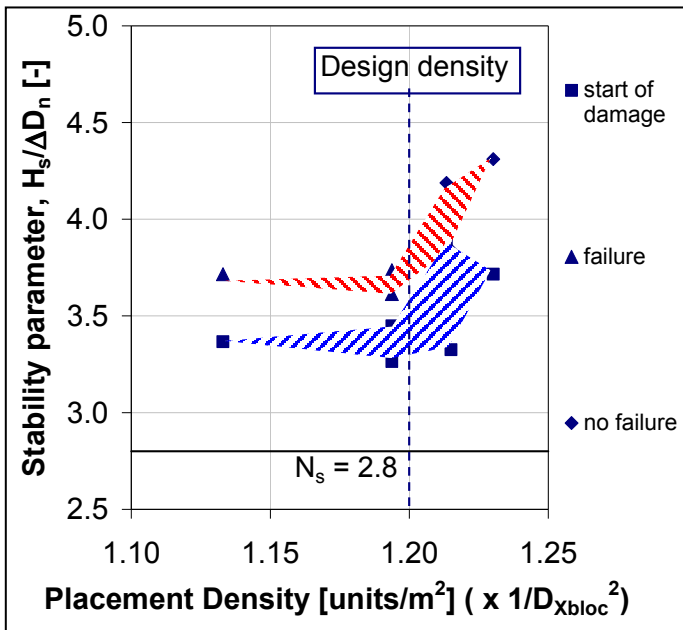


Figure 4. Influence of placement density (Delft Hydraulics 2002)

### 3.2.2 Placement Pattern

Apart from the placement density, the effect of pattern placement and random placement has been assessed. Examples of random placement and pattern placement are shown in Figure 5. With random placement, placement is meant where the orientation of the units is varied randomly whereas in case of pattern placement, they are placed according to a fixed pattern where the orientation of each unit is prescribed.

A test has been carried out with the pattern placement as shown in Figure 5 with a placement density of  $1.23 / D^2$ . During this test, no damage was observed, but the maximum wave height was only  $H_s/\Delta D_n = 3.74$ . During the test with random placement and with the same placement density, start of damage occurred at  $H_s/\Delta D_n = 3.72$  and no failure occurred whereas the maximum wave height was  $H_s/\Delta D_n = 4.31$ .

Based on the tests, there is no significant indication that pattern placement leads to a higher hydraulic stability. Because of practical difficulties of pattern placement, especially in curved sections, breakwater heads and in case of sloping bottoms, pattern placement has not been further investigated.

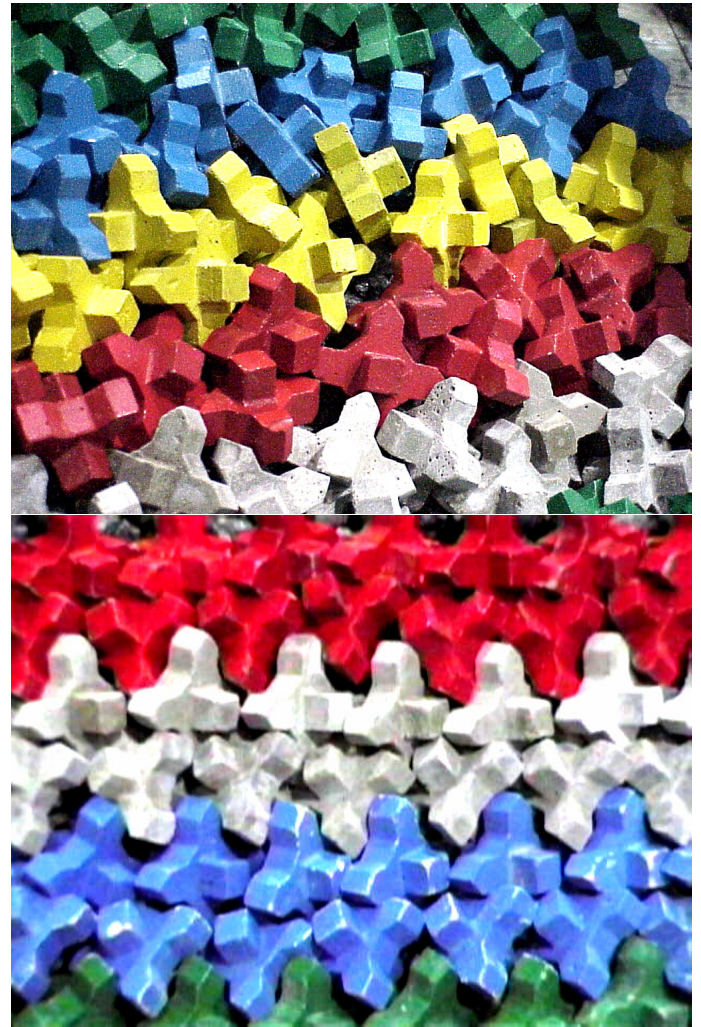


Figure 5. Example of random placement (top) and pattern placement (bottom)

### 3.2.3 Unit Orientation during Placement

During the model tests, each unit was easily placed by hand. In practice, placement of heavy units is more complex and the ease of placement depends on the orientation of the unit during placement, which depends on the sling technique. During the model tests, different sling techniques have been simulated by hand in order to investigate the effect of the sling technique on the hydraulic stability [Muttray et al. (2005)].

It was found, that placing the units with the sling technique as shown in Figure 1 (one of the legs of the X pointing downward) leads to a homogeneous armour layer with a high hydraulic stability. The influence of the sling technique is shown in Figure 6. The 2D tests at Delft Hydraulics were performed without the recommended sling technique (simulated by hand) whereas the tests at DHI were performed with this unit orientation. The figure clearly shows that the DHI tests lead to significantly higher stability numbers. Therefore this sling technique is recommended for the placement of Xbloc<sup>®</sup>. Apart from the influence on the quality of the armour layer, it was also found that this sling technique makes placement significantly easier.

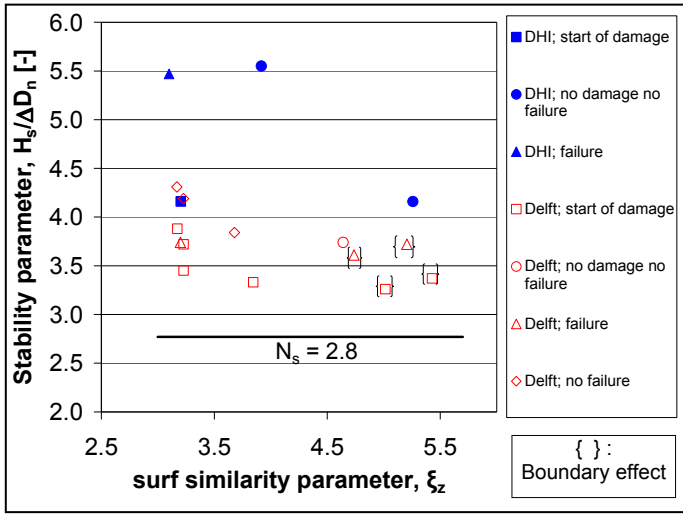


Figure 6. Influence of recommended sling technique: results without recommended sling technique (Delft Hydraulics 2002) and with recommended sling technique (DHI 2003)

### 3.3 Influence of oblique wave attack

The influence of oblique wave attack was investigated during 3D tests at Delft Hydraulics in 2003. A test section was tested for 4 different wave directions varying between  $0^\circ$  (waves coming in perpendicular to slope) and  $45^\circ$ . The results of these tests are shown in Figure 7. Although no damage was observed during the tests for  $15^\circ$ , the results of the other 3 wave directions show an increasing stability number for more oblique waves.

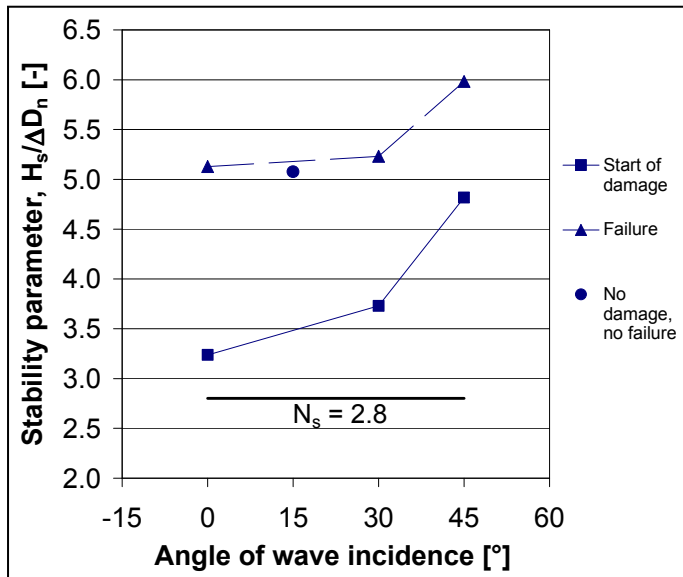


Figure 7. Influence of oblique wave attack on stability parameter

With respect to the limited number of points in Figure 7, the design stability values as shown in Figure 3 are recommended for concept design, even for oblique waves.

### 3.4 Influence of wave steepness

The influence of the wave steepness was investigated during the 2D tests at Delft Hydraulics in 2003 for a typical foreshore steepness of 1V:30H. The results of this investigation are shown in Figure 8.

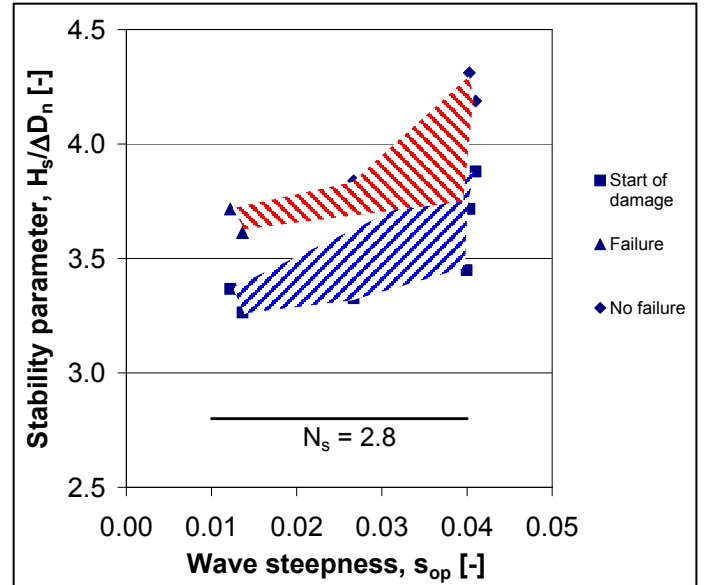


Figure 8. Influence of wave steepness on stability parameter for 1:30 foreshore

Based on the figure it can be concluded a larger wave steepness leads to a higher hydraulic stability and hence to a larger safety margin.

## 4 WAVE OVERTOPPING

### 4.1 Comparison of overtopping rates for Xbloc<sup>®</sup> and other single layer units

In 2004, comparative tests were carried out with various types of armour units within the frame work of the CLASH program [Pearson et al. (2004)]. For each tested armour unit, a slope roughness factor,  $\gamma_r$ , was determined, which indicates the run-up and overtopping (NB: a high roughness factor corresponds to a smooth slope hence high run-up values and overtopping discharges). The slope roughness factors for single layer and some other armour units are displayed in Table 3.

Table 3: Slope roughness factors based on CLASH tests

Type of armour	Slope roughness factor, $\gamma_r$
Rock breakwater	0.40
Coreloc <sup>®</sup>	0.44
Xbloc <sup>®</sup>	0.45
Accropode	0.46
Double layer cube	0.47
Smooth slope	1.00

The roughness factors for a smooth slope, for rock armour and for double layer cubes are included for comparison. The table shows that the roughness factor for a double layer cube layer is almost identical to the roughness factor for single layer units. It should be noted that the scatter in overtopping volumes was large and that the uncertainty of the results was about 50%. This means that e.g. a calculated overtopping volume of 70 l/s/m will in reality give overtopping volumes in the range 30 – 100 l/s/m. In this light, the overtopping volume of Xbloc<sup>®</sup>, Accropode<sup>®</sup> and Coreloc<sup>®</sup> are almost identical as the difference between these units is only 2%.

#### 4.2 Overtopping formulas for single layer armour

During the 2D Xbloc tests in 2002, overtopping measurements were performed. As the overtopping results did not fit well to common overtopping formulae [vd Meer, Janssen (1995)], the governing parameters for overtopping over single layer armoured slopes have been assessed.

Wave overtopping is mostly determined by wave height, wave length, freeboard and breakwater geometry. For a typical breakwater geometry, the wave height  $H_s$  and freeboard  $R_c$  govern the overtopping discharge. In many overtopping formulas, the parameters have been combined in a parameter called relative freeboard:  $R_c/H_s$  [e.g. Allsop et al. (1995); vd Meer et al. (1998)]. In Figure 9, the relative overtopping  $q/\sqrt{(H_s^3)}$  as measured during the CLASH test [Pearson et al. (2004)] and during the Xbloc<sup>®</sup> model tests at Delft Hydraulics is plotted against the relative freeboard.

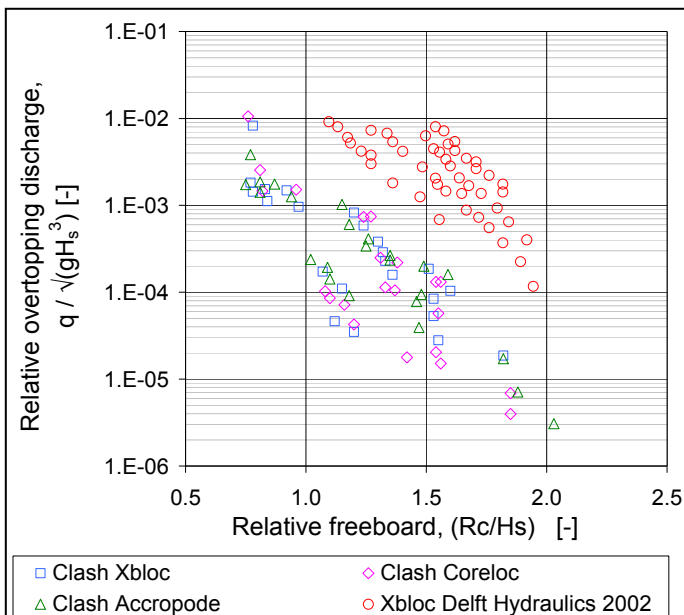


Figure 9. Overtopping results of Clash tests and Xbloc tests at Delft Hydraulics in 2002

Another parameter which is used in overtopping formulas is the surf similarity parameter, which is based on the slope angle and the wave steepness [vd Meer et al. (1998)]. Assessment of the Xbloc overtopping results however showed that wave overtopping volumes increase with both wave height and wave length. Therefore the use of the wave steepness as a governing parameter for wave overtopping does not seem justified.

It was further found that the asymmetry of the incoming waves (wave crest elevation/wave height) has a significant effect on the wave overtopping. In shallow water, the wave asymmetry is closely related to the Ursell parameter ( $Ur = H_s L^2/d^3$ ). As shallow water conditions are mostly applicable for coastal structures, it is proposed to include the Ursell parameter in the overtopping formula.

Based on comparison of Figure 9 and Figure 10, it can be concluded that there is a close relation between the relative overtopping divided by the Ursell parameter and the relative freeboard. This relation is different for the 2 different test setups with slightly different geometry.

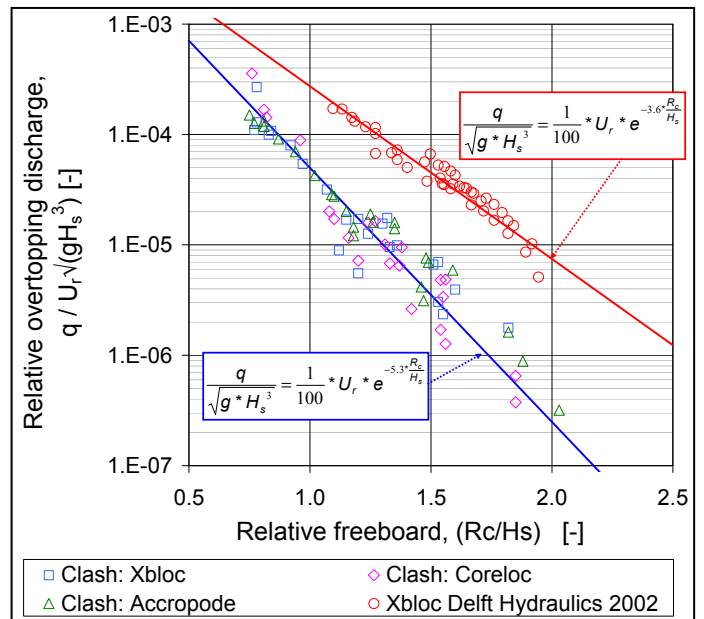


Figure 10. Overtopping results of Clash tests and Xbloc tests at Delft Hydraulics in 2002: relative overtopping divided by Ursell parameter

For the Xbloc<sup>®</sup> 2D test setup at Delft Hydraulics, the relation between the relative overtopping divided by the Ursell parameter and the relative freeboard can be described by:

$$\frac{q}{\sqrt{g * H_s^3}} = \frac{1}{100} * U_r * e^{-3.6 * \frac{R_c}{H_s}} \quad (1)$$

where:

- $g$  = gravitational acceleration
- $H_s$  = significant wave height at the structure;
- $U_r$  = Ursell parameter =  $H_s L^2/d^3$
- $L$  = wave length at the toe
- $d$  = water depth at the toe
- $R_c$  = freeboard

For the CLASH tests with Accropode, Coreloc<sup>®</sup> and Xbloc<sup>®</sup>, the following relation was found:

$$\frac{q}{\sqrt{g * H_s^3}} = \frac{1}{100} * U_r * e^{-5.3 * \frac{R_c}{H_s}} \quad (2)$$

The difference between both datasets (as described in Eq.1 and Eq.2) cannot be deduced to secondary overtopping parameters for roughness, shallow water conditions, oblique waves and berms as proposed by vd Meer & Janssen (1995). The difference might be related to crown wall geometry, to permeability of the core and under layer or to wave reflection. These possible influences are subject to further investigations.

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