UNESCO-IHE
Institute for Water Education

Set-up to design guidance for the Crablock armour unit

Comparison of single layer armour units investigation

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Design guidance for a new single layer armour unit as result of a comparison in previous investigation on Accropode and Xbloc.

Contents

LIST OF FIGURES

LIST OF TABLES

1 Introduction

1.1 General

There are quite some “single layer armour units” that have been developed over the past thirty years. The Accropode in the beginning of the Eighties was the first development with now more than 250 applications to breakwaters and coastal defenses. Since then the Core-Loc, the Xbloc and the Accropode II have been developed, where the Xbloc is the most recent one of them (10 years now with about 20 projects realized or under construction). Other even more recent developments are the A-jack (applied in Indonesia) and the Cubipod (developed at the University of Valencia, Spain).

The Crablock is a symmetrical unit, this in contrast to the units that have been applied most in the past. Essentially, this is the main difference. All other units have six “obstacles” that insure interlocking, but they are not symmetrical. All those units are placed randomly in a certain way with more or less contacts to neighbouring units. A symmetrical unit may give the opportunity to place the units in a more or less rectangular pattern. This may ease the construction requirements. It may also have influence on stability, where the expectation is that it could be more stable than a random placement. Uniform placement may, however, increase the packing density (number of units per square meter) and/or wave overtopping. But at least one can say that the Crablock can distinguish itself from the well-known units by the symmetrical shape.

Till now the shape of the unit has been developed and a few tests have been performed in South Africa at CSIR. Results will be summarized in this report. In order to make the unit market ready all required design information should be developed. This is not a short term process as results from a certain phase may be input for a next phase and because hardly anything is known about the Crablock. The process, therefore, can be divided into a start with academic research, followed-up by research at commercial laboratories and/or in combination with a real project.

Van der Meer Consulting was asked for guidance, where UNESCO-IHE, in combination with TU Delft, that can provide a wave flume, could perform the first phase of academic research. The all concerned on this topic are Van der Meer Consulting with UNESCO-IHE, TU Delft. and AM Marine Works, in cooperation with CDR International.

The main objective for the Crablock is to develop the Crablock to a market ready product. This main objective may be divided in two phases, which are an academic research on approach to follow and on main design aspects and a commercial research to give all required design aspects and/or design of an application and testing for validation.

This report focusses on the first phase.

1.2 Objectives

The main objectives of this report are:

- outline the recommendations for a fast and efficient approach to come to a design guidance;
- establish what design parameters are most important for the new single layer armour unit investigation, such as the placing pattern, the crest height, the settlement, etc.
- identify what kind of tests should be done for Crablock in a wave flume.

1.3 Approach

As existing single layer units have also been developed and have followed a certain approach, in this study the approach was investigated. The investigated single layer armour units were the Cube in single layer, the Accropode, the Core-Loc, the Xbloc and the Cubipod. Good information on Accropode are available, as Professor J.W. Van der Meer provided the report *"Stability Formula for breakwaters armored with Accropode" [Van der Meer, J.W., 1987]*. Good information, also, are available on Xbloc, as the website of DMC gives the design guidance for the Xbloc. No useful data on performed 2D hydraulic stability tests on Core-Loc are available. So Core-Loc will be not compared to other units. Moreover Cubipod has a difficult definition of damage, far from the typical relative number of units displaced, Nod. In addition no available data on Cubipod hydraulic stability performance are available. So nor Cubipod will be considered in the comparison.

Data on single layer Cube are available but test conditions and slope configuration result different from the ones used on Accropode and Xbloc tests. As massive CAU (Concrete Armour Unit), also, Cube is very different in shape from Accropode and Xbloc, which are sendler units.

In the end conditions and slope configuration of Accropode and Xbloc result comparable.

For these reasons it is possible to compare Accropode and Xbloc investigation. This comparison will result in a quicker approach for the Crablock and will give an input in what kind of model investigations should be done and what kind of tests should be performed in the first series in a wave flume. Such an investigation will give the first “design data” for Crablock.

2 Existing knowledge

2.1 History of types

Breakwaters are used for protection against waves and flooding. In general breakwaters are used to protect ships and harbours against incoming waves. Furthermore, a breakwater can be applied to protect valuable habitats that are threatened by the destructive force from the sea. Breakwaters, also, are used to protect beaches from erosion. In some situations a breakwater is used to prevent or reduce the siltation of navigation channels. Rubble mound sea defenses may look like breakwaters from the seaside. The main difference with a breakwater is that they do not have water on the landward side [1].

Breakwaters vary in shape and type of armour layer. This study focuses on conventional breakwaters. A conventional breakwater consists of different parts: an armour layer, a toe, one or more sub layers and a core.

The armour layer is the outer layer of the breakwater and can be constructed out of natural rock or concrete armour units. The usage of concrete armour units is a good alternative at the usage of larger rock when higher wave loads at the breakwaters occur.

When concrete armour units are used, the placement pattern is of great importance for the hydraulic stability of the armour layer.

The first concrete armour units were Cubes in double layer. Easy to produce, they had a high structural strength. However, cube shaped armour units had a high concrete consumption.

The hydraulic stability of the cube is primarily generated by its own weight; this is the same principle as with rock.

In 1950 the Laboratory Dauphinios d'Hydraulique (predecessor of Sogreah) introduced the Tetrapod, the first interlocking armour unit. The main advantages of the Tetrapod over the Cube were improved interlocking and a larger porosity of the armour layer, resulting in a lower concrete consumption [3].

From 1950 – 1980 a large variety of concrete armour units has been developed. The armour units were typically either randomly or uniformly placed in double layers.

2.2 Single layer units

The failure of the Sines breakwater (Portugal, 1978) and the introduction of the first single layer armour unit the Accropode by Sogreah in 1980 set an end to the rapid development of randomly placed slender concrete armour units. A single layer armour unit is applied in a layer thickness of one unit. The Accropode is also strong and not slender, but has many protruding elements for a good interlocking.

Since 1980 single layer randomly placed armour units have been applied as an alternative to the traditional double layer armour layers, of these single layer armour units the Accropode became the leading armour unit worldwide for the next 20 years.

In September 2009 Cube in single layer was investigated. This study showed that the use of a single top layer of Cubes was feasible and the armour layer became very stable if placed in a stretching bond [1].

Core-Loc is another example of single layer randomly placed armour units that have been developed subsequently. Hence, these blocks were more economical than traditional double armour layers. The Core-Loc, developed by the US Army of Engineers in 1994, appeared to be more slender then the Accropode and to have a higher hydraulic stability. Core-Loc, also, showed residual stability after breaking as well as ease of casting and placement [2].

In 2004 Delta Marine Consultants introduced a new block, the Xbloc. The hydraulic stability of the Xbloc was tested and results demonstrated that the Xbloc has similar hydraulic stability as Core-Loc and slightly higher than Accropode. These studies showed that Xbloc had similar structural strength, as Accropode, and was significantly stronger than Core-Loc. Due to the simple shape of the Xbloc production and handling was easier than that of Accropode and Core-Loc. The important advantage in comparison to other units like Accropode and Core-Loc was the ease of placement [3].

The recent introduction of the Cubipod aimed to benefit from the advantages of the traditional cubic block, like the high structural strength and easy placement, but to correct the drawbacks by preventing self-packing and increasing the friction with the filter layer [2].

In recent years HE Abdulla Al Masaood has developed a new single layer, the Crablock. Some preliminary physical model tests have been performed by Al Masaood Advanced

Group of Companies on 10 tons Crablock units. The 10 tons armour units resulted stable for wave condition up to 4 meters, after that minor movement occurred [8].

Further developments will be done under AM Marine Works, in cooperation with CDR International.

2.3 Xbloc as lead for Crablock

2.3.1 Introduction of Crablock

The Crablock has been proposed in the United Arab Emirates to act as a single layer armour unit for breakwaters. It also could be used as groyne for catching sand and channeling currents, offshore breakwater, underwater reef for coral growth and attract marine life, and rubble mound seawalls [xxx]. In the Figure 2-1 Crablock geometry is presented.

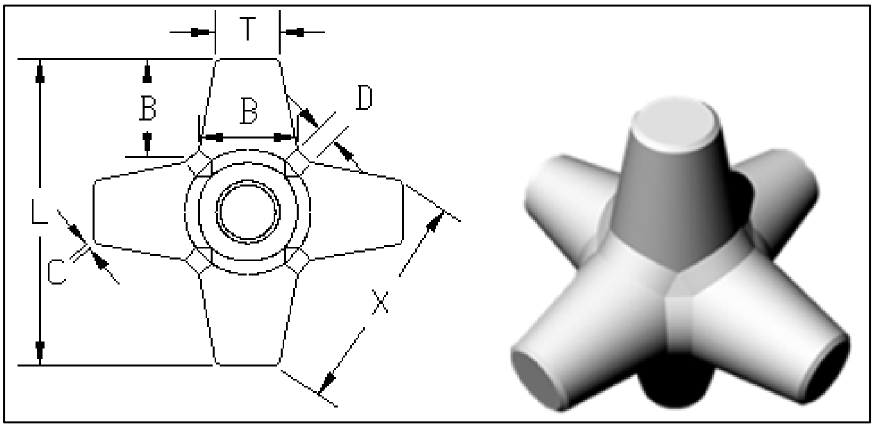

Figure 2-1 Crablock

The Crablock can be described as a composition of six truncated cones (legs), one for each face of an hypothetical central cube. Its geometry shows symmetry in the three directions of the development of the block. Standard dimensions range from 2.5 ton to 25 ton. Table 1 shows the geometric characteristics and the proposed models for Crablock:

Table 1 Models proposed for Crablock and relative measures [7]

	L	B	T	B	C	D	X		
MODEL	UNIT SPAN (mm)	ARM'S BASE DIA (mm)	ARM'S TIP DIA (mm)	ARM'S LENGTH (mm)	TIP'S CHAMFER (mm)	BASE'S CHAMFER (mm)	X SPAN (mm)	VOLUME (cu.m)	WEIGHT (tons)
CB100	1880	599	385	599	34	115	1570	1	2,5
CB200	2366	754	484	754	43	145	1977	2	5
CB300	2712	865	555	865	49	166	2256	3	7,5
CB400	2980	950	610	950	54	183	2479	4	10
CB500	3211	1024	657	1024	58	197	2671	5	12,5
CB600	3413	1088	698	1088	62	209	2839	6	15
CB700	3595	1146	735	1146	65	220	2991	7	17,5
CB800	3756	1198	769	1198	68	230	3125	8	20
CB900	3907	1246	799	1246	71	239	3251	9	22,5
CB1000	4049	1291	828	1291	73	248	3369	10	25

2.3.2 Placing pattern of Crablock

In this section, the description of proposed placement options for the Crablock is reported. Four options as result of two different proposed grid (*rectangular grid* and *diamond shaped grid*) in both *uniform* and *random* placement: “Uniform placement on rectangular grid”, “Random placement on rectangular grid”, “Uniform placement on diamond shape grid“ and “Random placement on diamond shape grid”.

2.3.2.1 Placing grids

In the first proposed placing grid, the *rectangular grid*, the centers of mass of the Crablock are placed on the corners of a rectangle (Figure 2-2). This grid is characterized by a horizontal distance, D_x, and an upslope distance, D_y.

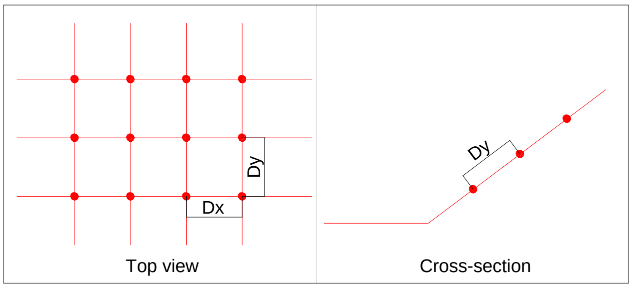

Figure 2-2 Rectangular grid for Crablock

In the second proposed placing grid, the *diamond-shaped grid*, the centers of mass of the Crablock are placed on the corners of a parallelogram with angle of 120° (Figure 2-3). This diamond shape grid is characterized by horizontal distance, D_x, and upslope distance, D_y.

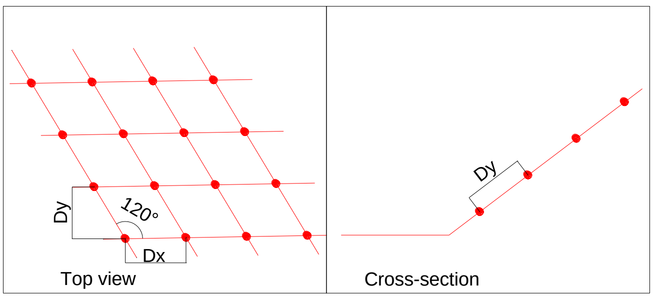

Figure 2-3 Diamond-shaped grid for Crablock

2.3.2.2 Patterns

In the *uniform pattern* the orientation of the units on the slope is predefined, while in the random pattern the units on the slope are placed in a random orientation, although they lie on a predefined grid.

Uniform pattern on rectangular grid

The orientation of the units is predefined on the rectangular grid. It is assumed that the block is placed in two arrangements. The first block of the first line is arranged with an inclination of legs 45° to the line of greatest slope of the embankment; one leg is upward and two legs are downward. The second block of the same line has an inclination of legs 45° to the line of greatest slope of the embankment but the direction of legs is inverted: a leg is downward and two legs are upward. The third block of the first line is arranged as the first one and so on for the other blocks on the same line. In the second line the blocks are placed exactly on the lower blocks with the same angle. In that case the leg downward touches the notch (the conjunction point of the two legs) of the lower block, the right upward leg touches the leg of the right neighboring block, while the left upward leg touches the leg of the left neighboring block. Indeed, the leg of the first lower bloc acts as mark to place the notch of the upper block. So the blocks of the same vertical line are placed in the same position. There is, of course, alternation of position between each vertical line, a line of blocks ‘leg in bottom’ next to a vertical line of blocks ‘leg in top’. The blocks have three-point support on the filter obtained by three legs, a triangle pointing to top for the blocks posed ‘leg in top’ and a triangle pointed downwards for the blocks posed ‘leg in bottom’. Each block also has the three-point support on the subjacent blocks.

Random pattern on rectangular grid

The blocks arranged in a random pattern are placed randomly on the rectangular grid, and do not follow any strict rule and any specific orientation.

Uniform pattern on diamond-shaped grid

The orientation of the units is predefined. It is assumed that the block is placed in one arrangement. In the first line, all blocks are arranged with an inclination of legs 45° to the line of greatest slope of the embankment. The upward leg makes a 120° angle with the horizontal one leg is upward this inclination and two legs downward. In the second line, the blocks are placed between two lower blocks with the same angle. In that case, the leg upward touches the notch of the upper block, the right leg of the downward legs touches the notch of the right block and the left leg of the downward legs touches the notch of the lower block. Indeed, the leg of the lower block serves as mark to place the notch of the upper block. The blocks of the same horizontal line are placed in the same position. The blocks have three-point support on the filter obtained by the three legs, a triangle pointing to top for the blocks posed “leg in top”; a triangle pointed downwards for the blocks posed “leg in bottom”. Each block also has the six-point support on the subjacent blocks. It is suggested to investigate the hydraulic stability in this configuration, as the higher number of points of contact leads to a higher interlocking. It is expected that the armour has a better response in this pattern.

Random pattern on diamond-shaped grid

The blocks arranged in a random pattern are placed randomly on the rectangular grid, and do not follow any strict rule and any specific orientation.

2.3.2.3 Packing density

Both proposed placement grid should contain the proper packing density. In general when the achieved placement deviates from the design grid it is possible to directly see the influence on packing density and it can then be decided to replace the unit or a whole section. Packing density will be discussed in [4.1.2.7] and [5.1].

2.3.3 Crablock and Xbloc similarities

In this section the similarities in shape and placement between Xbloc and Crablock are described. The aim of this comparison is to show that Xbloc could lead for Crablock guidelines.

2.3.3.1 Similarities in shape

1. Both Xbloc and Crablock have a *center-based construction*. Slender units are composed of bars, these bars together create a 3-D shape unit, but the bars itself can be placed in two directions or three direction. Both Xbloc and Crablock have three bars in perpendicular directions. These results in a center-based construction for Xbloc and Crablock, see Figure 2-4. Both Xbloc and Crablock have four legs in front side and a 'nose', in the center in the third direction: for Xbloc the nose is different from the legs, while for Crablock the nose is the same as the legs.

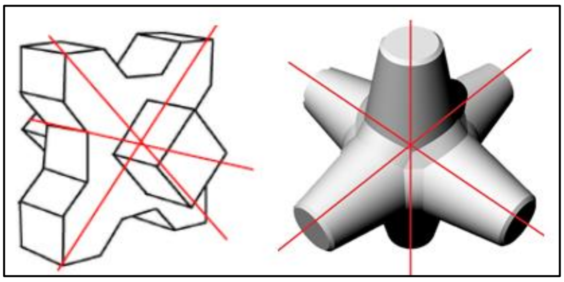

Figure 2-4 Center based construction for Xbloc and Crablock

For the sake of completeness in Figure 2-5 the *stacked bars construction* is shown: it consists on bars placed in two different directions. Accropode and Core-Loc, for instance, have two bars in the same direction and one perpendicular to these bars:

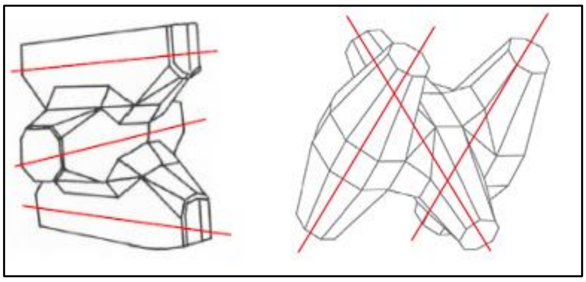

Figure 2-5 Stacked bars construction for Accropode and Core-Loc [3]

2. Both Xbloc and Crablock have four legs in front side and a nose in the center in the third direction (see Figure 2-6): for Xbloc the nose is different in shape from the leg, and for Crablock the nose is another leg;

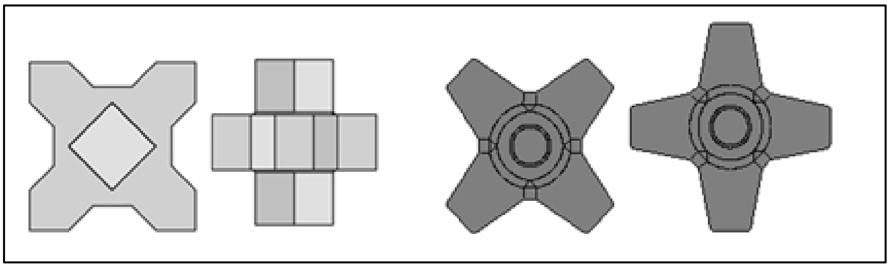

Figure 2-6 Front view and lateral view of a) Xbloc and b) Crablock

3. Both Xblock and Crablock present an inclination 45° on two legs, although Xbloc is stable on two legs while CRAblock cannot (see Figure 2-7); notice that Crablock is stable on one leg; the same does not happen for Xbloc.

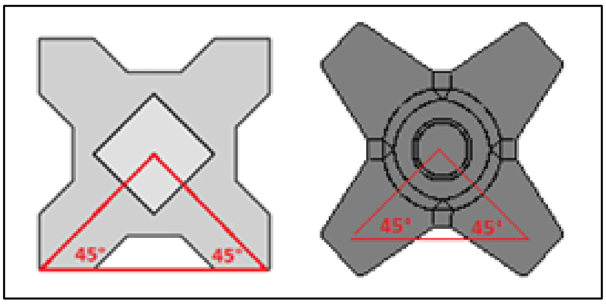

Figure 2-7 Inclination of 45° on two legs for Xbloc and Crablock

4. Both have the inclination of 45° on three legs. Both Xbloc and Crablock are stable under their own weight on three supports: two legs and one nose for the Xbloc and three legs for the Crablock (see Figure 2-8);

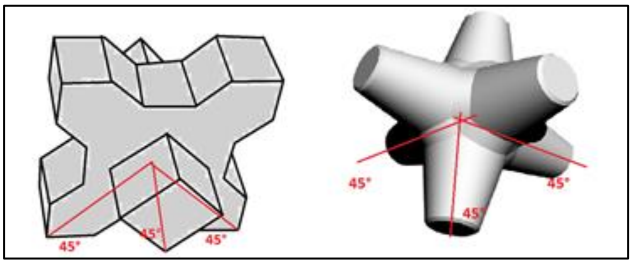

Figure 2-8 Inclination of 45° on three legs- self stable for Xbloc and Crablock

The only difference in features between Xblock and Crablock is that the Crablock is symmetrical in three directions while the Xbloc in two directions. This aspect can result in a better performance of Crablock, in comparison with Xbloc.

2.3.3.2 Similarities in placement

Both Xbloc and Crablock armour units are designed to be placed in a single layer.

For Xbloc a “staggered grid” was proposed. It consisted in a diamond-shaped pattern, which can be characterized by two values, horizontal distance, Dx, and upslope distance, Dy. Xbloc armour units were placed in a brick pattern. Units were placed in horizontal rows. The unit of the subsequent row found a position in between 2 units of the previous row. The distances between the center of gravity of the units within 1 row and in between 2 rows were predefined. The orientation of the units was either varied randomly (random placement) or predefined (rectangular placement) [3].

This in-line-with the diamond-shaped pattern proposed for Crablock and described in the previous section.

In view of these considerations it can be concluded that the investigation on Crablock placement and hydraulic stability can refer to Xbloc investigation.

3 Important design issues

In order to come to an efficient “Crablock design guidance”, the first objective was to consider the conducted investigation on existing single layer armour units. The considered single layer armour units were the Cube in single layer, the Accropode, the Core-Loc, the Xbloc and the Cubipod.

From the available literature on each single layer unit, information on hydraulic performance investigation and placement investigation were searched. The idea was to compare 2D physical model tests set-up and test programmes on single layer armour units in order to outline the most important parameters which play an important role on the hydraulic performance.

Good information on Accropode were available, as Professor J.W. Van der Meer provided the report "Stability Formula for breakwaters armored with Accropode" [4]. Good information, also, are available on Xbloc, as the website of DMC gave the design guidance for the Xbloc. No useful data on performed 2D hydraulic stability tests on Core-Loc were available. So Core-Loc was not compared to other units. Moreover Cubipod had a difficult definition of damage, far from the typical relative number of units displaced, Nod. In addition no available data on Cubipod hydraulic stability performance were available. So nor Cubipod was considered in the comparison.

Data on single layer Cube were avilable but test conditions and slope configuration resulted different from the Accropode and Xbloc tests. As massive CAU (Concrete Armour Unit), also, Cube is very different in shape from Accropode and Xbloc, which are sendler units.

Test conditions and slope configuration of Accropode and Xbloc resulted comparable.

For these reasons it was possible to compare Accropode and Xbloc investigation. In the following section the main results of the comparison between Accropode and Xbloc are reported.

3.1 Accropode vs Xbloc

In 1987 hydraulic model tests were performed on the stability of Accropode units [4]. In 2003 hydraulic model tests were performed on the stability of Xbloc units [6].

Schematic comparison between Accropode and Xbloc in materials and structural parameters used in the tests, test programme, placing pattern and hydraulic stability is given below.

3.1.1 Comparison in materials

In Table 2 the main characteristics of material used in model tests for Accropode and Xbloc are reported:

Table 2 Material characteristics used in Accropode and Xbloc physical model tests

	Accropode	**Xbloc**
Model weight, W [g]	161	121
Model height [m]	h = 0,06	D = 0,054
Model material density, ρ [kg/m^3]	2320	2300
Nominal diameter, D_n [m]	0,0411	0,0375
Armour layer thickness, t_a [m]	0,054	0,052
Under layer average mass [g]	0,02 [ratio armour /underlayer=8]	0,0125 [ratio armour /underlayer=10]
Under layer Dn50 [m]	0,03	0,017
Under layer thickness, 2*D_{n50} [m]	0,06	0,034
Toe (rock) D_{n50} [m]	0,03	0,017
Core D_{n50} [m]	0,011	0,0079

3.1.1.1 Armour layer

The armour layer consisted of a single layer of units, Accropode or Xbloc, with a constant mass density. The following Formula was used to determine the nominal diameter for both units:

$$D_n = \left(\frac{W}{\rho}\right)^{1/3}$$

where W was the model weight and ρ was the model density [4] and [6].

3.1.1.2 Under layer

In general before armour layer can be placed the under layer, as proper foundation, is required. The under layer has two main functions: firstly a “filter function” between the small core material and the large armour units; secondly provides a smooth surface for the placement of the armour layer. The first function, prevention of scour holes in the core is obvious. If a scour hole develops below the armour layer, the armour layer becomes instable which can result in the failure of the armour layer. The second function, smoothness of the under layer, has a great influence on the quality of the armour layer. The hydraulic stability of the armour layer is largely originated by interlocking, irregularity in the under layer makes it more difficult to obtain proper interlocking, if reached at all. Lack of interlocking will result in loss of hydraulic stability of the armour layer [3]. To ensure a proper armour layer, design specifications for the armour layer were used for both the Accropode and the Xbloc.

Weight of the under layer: The weight of the under layer is based on the hydraulic stability. The required weight of the under layer was chosen based on the size of the armour unit.

In Accropode investigation [4] a mass ratio armour / under layer = 8 was used to prescribe the weight and the dimensions of the under layer stones, while in Xbloc investigation [6] a mass ratio armour / under layer ≈ 10 was used to prescribe the weight and the dimensions of the under layer stones.

Thickness of under layer: The normal design thickness of the under layer is two times the D_{n50} (D_{n50} is the nominal diameter of the rock in the under layer). The D_{n50} is directly connected with weight of the rock by:

$$D_{n50} = \left(\frac{W_{50}}{\rho_{rock}}\right)^{1/3}$$

The value of two times D_{n50} is derived from the hydraulic stability and the constructability in prototype. Both Accropode and Xblock followed this rule.

3.1.1.3 Toe

Because the armour layer is relatively expensive part of the breakwater it is tried to minimize the area on which the armour layer has to be applied. For the stability of the breakwater it is not always necessary to extend the armour layer to full water depth. The *Shore Protection Manual* gives a rule-of-thumb, indication that the armour layer should extend down to about 1 wave height below the still water level. Below this water level the armour layer should be supported by rock with 1/10 of the armour weight, this is approximately the same size as the under layer [3].

The standard toe consists of natural rock but when the armour layer is extended down to the sea bed it is also possible to use the armour units itself to construct a toe. This is necessary to prevent the other units to slide down the slope. In this regard, in later investigation on Xbloc, a special Xbloc toe unit was designed. The modified unit had only one nose.

In both Accropode and Xbloc investigation on hydraulic stability toe consisted in rock.

3.1.2 Comparison in structural parameters

In Table 3Table 1 the structural parameters used during the Accropode and Xbloc hydraulic stability tests are reported:

Table 3 Structural parameters used in the Accropode and Xbloc physical model tests

	Accropode	**Xbloc**
Foreshore slope	1:30	1:30
Slope, cotα	1:4/3	1:4/3
Crest height [m]	0,25	0,23
	0,45	0,28
		0,40
Water depth [m]	0,4 (deep water)	0,35 (shallow water)
		0,40 (intermediate water)

3.1.3 Comparison in placing pattern

3.1.3.1 Accropode

The Accropode was placed according to the specifications of SOGREAH. The method of placing is shown in Figure 3-1:

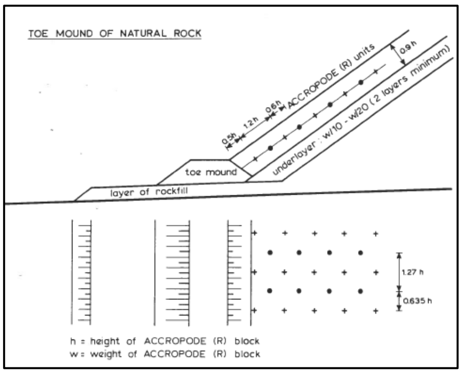

Figure 3-1 Placing grid proposed for Accropode [4]

The armour layer was constructed with colored horizontal bands with a width of two units (1,2 h, h = height of the unit). The width of the flume was 1 m which equals 24,3*D_n (D_n=0,7 h). The damage number was calculated by dividing the total number of displaced Accropode by 24,3 [4].

According to the specification of SOGREAH an armour layer with Accropode was built in the following way: the Accropode were placed from the toe up to the transition between the slope and the horizontal layer on the crest. The layer on the crest was placed starting from the crest element (if any) to the transition between slope and horizontal layer. Finally the gap between the two layers of Accropode (one on the slope and one on the crest) was filled up [4].

As the placements distances between the units were known the packing density relative to the unit size could be calculated. It is reported in the Table 4:

Table 4 Packing density of Accropode

Horizontal distance [m]	Upslope distance [m]	Packing density [units/m²]	Packing density [units/m²]
1,27 * h	0,6 * h	$1{,}31 / h^2$	$0{,}64 / D_n^2$

3.1.3.2 Xbloc

The Xbloc armour units were placed in a single layer. Placement of the units has been done 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. Uniform and random patterns were used.

Xbloc armour units were placed in a brick pattern. Units were placed in horizontal rows. The unit of the subsequent row finds 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 were predefined. The orientation of the units was either varied randomly [random placement] or predefined [regular placement]. Only one test series was performed with regular placed armour units but was not considered in this study [6].

As the dimensions of the slope are known, the placements distances and packing densities relative to the unit size were calculated. As average value for random pattern the values in Table 5 were used.

Table 5 Average packing density for Xbloc [6]

Horizontal distance [m]	Upslope distance [m]	Packing density	Packing density
1,30 * D	0,64 * D	$1{,}20 / D^2$	$0{,}58 / D_n^2$

3.1.4 Comparison in test programme

Two different types of tests were performed during Accropode and Xbloc investigation on hydraulic stability. For Accropode “constant wave height tests” were performed, while for Xbloc “increasing wave height test series” were performed.

The investigation of Accropode was based on investigation on rock slopes. It was restricted to only one cross-section. Therefore the influence of the slope angle and the permeability of the structure were not considered. This means that the parameters investigated for breakwaters armoured with the Accropode were: the stability number, $Ns=Hs/\Delta Dn$, the surf similarity parameter, ξz, the damage level, S, or number, No, and the number of the waves (storm duration), N.

The investigation of Xbloc considered irregular waves. Shallow and intermediate water depths at the toe of the structure as well as moderate and large overtopping rates were considered. Hence, the water depth at the toe, as well as the crest level of the structure, has been varied. Model tests were conducted systematically with constant wave steepness, stepwise increasing wave height and varying wave length and water depth.

3.1.4.1 Accropode

The main purpose of the investigation was to establish damage curves for a wide range of wave periods and for different storm durations. Four wave periods were chosen, Tz=1,4 s, 1,7 s, 2,15 s and 2,8s. Wave heights varied between 0,15m and 0,24 m and so wave steepness (Hs/Lz) was in the range of 0,015 to 0,06, where Lz=1,56 Tz2. In total 18 tests were performed, 12 tests with a relatively low crest (0,25 m above SWL) and 6 tests with non-overtopped structure (crest 0,45 m above SWL). For each wave period 2 to 5 tests were performed with a different wave height in order to establish the damage curve. After each complete test the armour layer was removed and rebuilt [4].

3.1.4.2 Xbloc

A total number of seven test series was performed. A number of individual tests were 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 tests were stopped when the filter layer was damaged even if the armour layer was damaged but still stable. After each test series the armour layer was removed and the filter layer and armour layer was reconstructed [6].

3.2 Hydraulic stability

3.2.1 Steepness influence on hydraulic stability

In Figure 3-2 the influence of the steepness on the Accropode hydraulic stability is plotted.

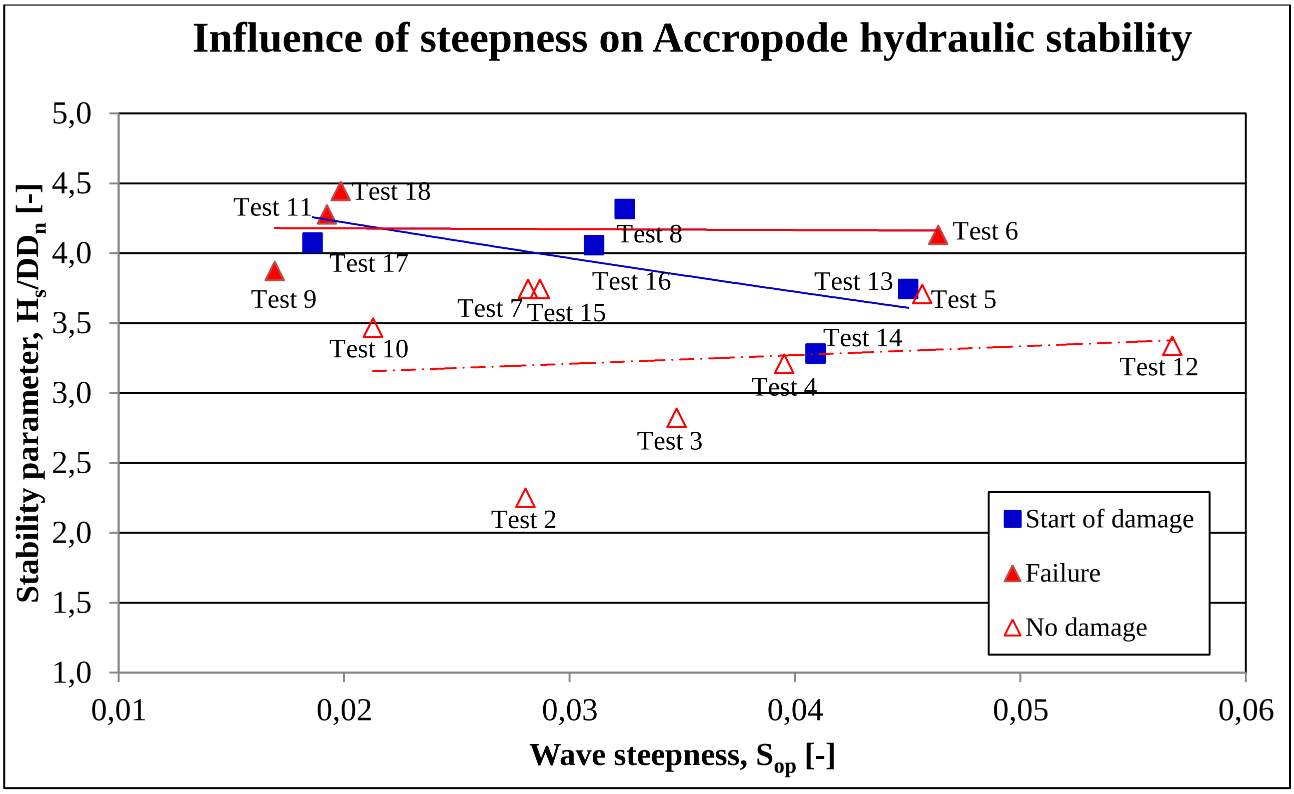

Figure 3-2 Influence of steepness on Accropode hydraulic stability

No influence of wave steepness was observed for failure and no damage values, while for start of damage values a slight decreasing stability with increasing wave steepness was observed.

In Figure 3-3 the influence of the steepness on the Xblock hydraulic stability is plotted.

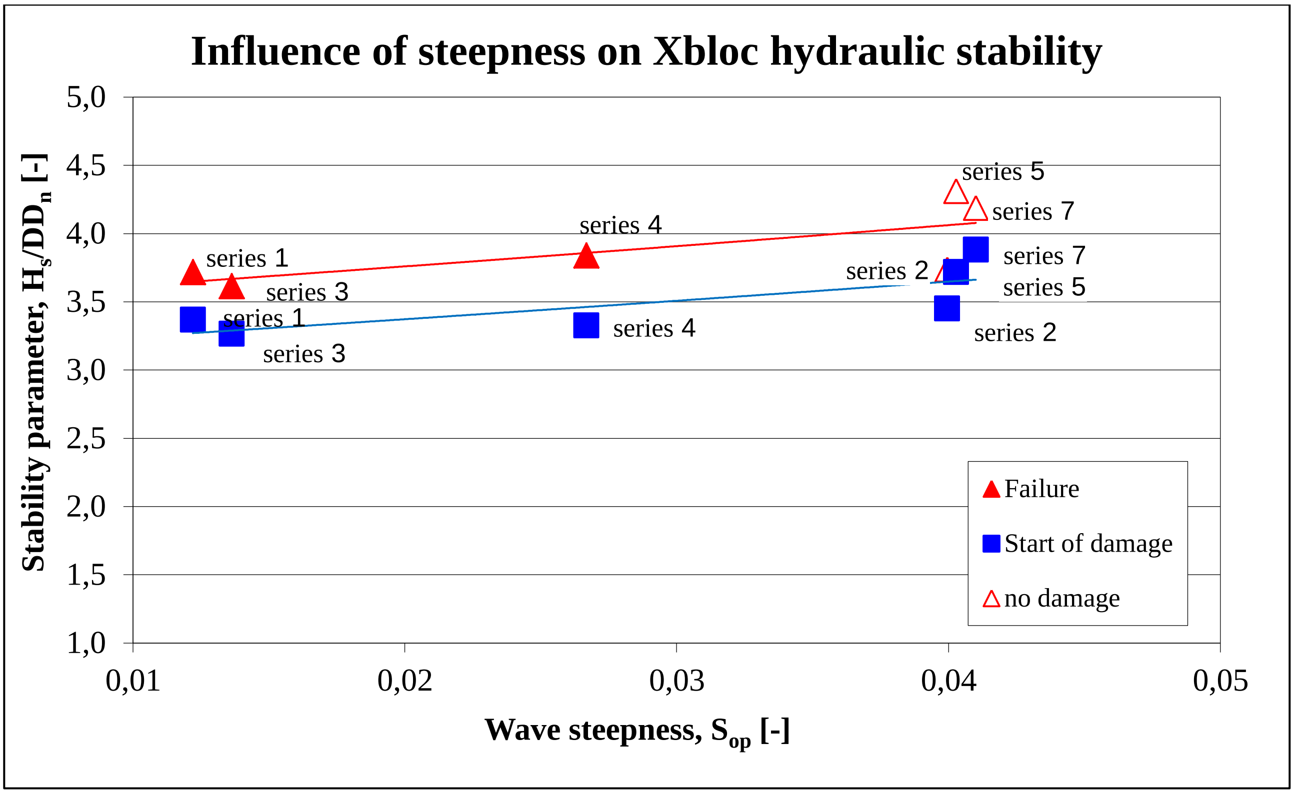

Figure 3-3 Influence of steepness on Xbloc hydraulic stability

During the tests on Xbloc increasing stability with increasing wave steepness was observed. But this conclusion was based on 6 tests only, and other factors such as packing density and crest level could have influenced the stability of the slope. So it was concluded that the wave steepness on the stability of the slope could not be determined from this results.

3.2.2 Packing density influence on hydraulic stability

Figure 3-4 shows the influence of packing density on Xbloc hydraulic stability.

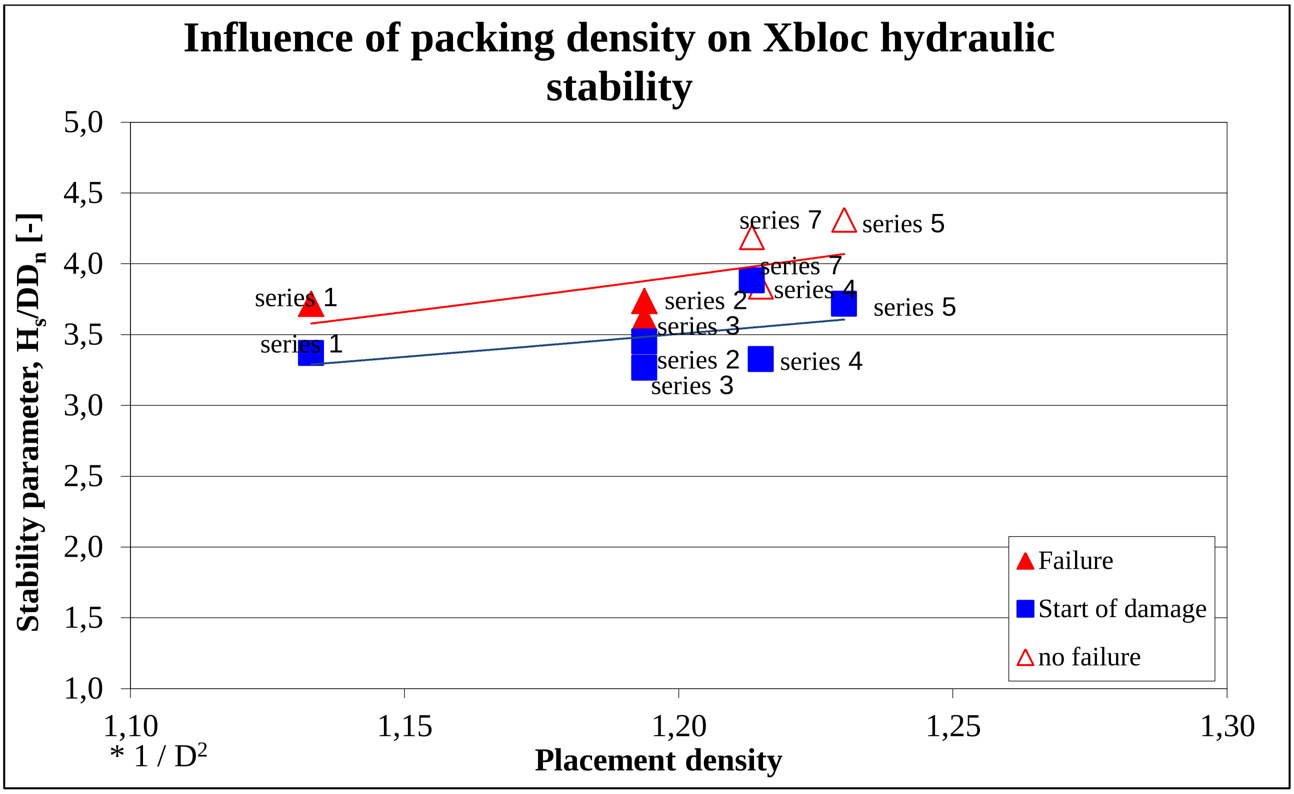

Figure 3-4 Influence of placement density on Xbloc hydraulic stability

From the Figure 3-4 it could be concluded that the stability increased for higher packing density. Both the start of damage as well as failure of the armour layer occurred at higher Hs/ΔDn levels. Furthermore the margin in wave height between start of damage and (non) failure of the armour layer increased at higher packing density.

In Accropode investigation only one packing density was tested. So its influence on hydraulic stability was not considered.

3.2.3 Crest height influence on the hydraulic stability

In Figure 3-5the influence of the crest height in Accropode hydraulic stability tests is plotted.

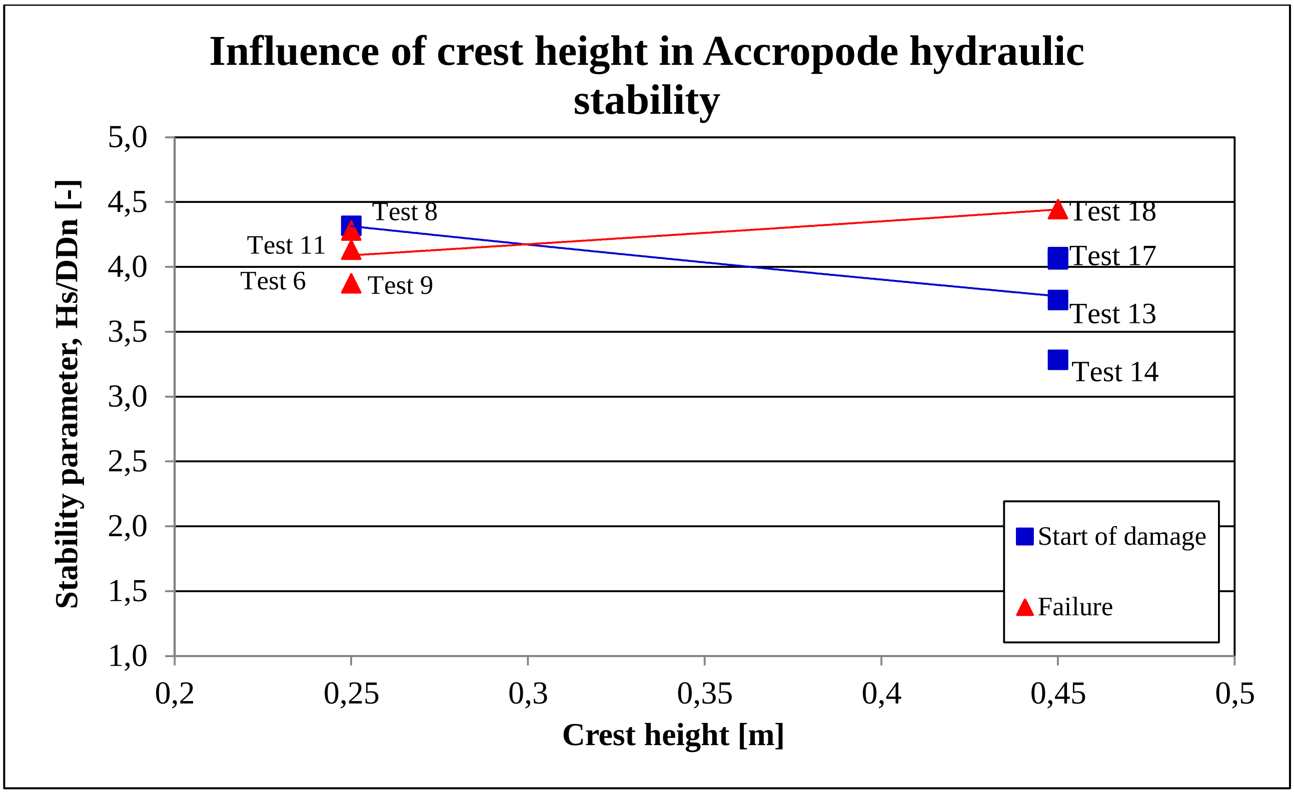

Figure 3-5 Influence of crest height on Accropode hydraulic stability

For failure values a slight increasing stability with increasing crest height was observed, while for start of damage values the opposite behavior was observed.

In general from tests on Accropode it was concluded that the damage was not influenced by the wave period. The test results of tests 1 to 12 (overtopping) and of test 13 to 18 (non-overtopping) showed no significant differences. This meant that the damage to Accropode was not influenced by the crest height of the structure or the number of overtopping waves if the number of the waves is less than 40% (range of test results).

In Figure 3-6 the influence of the crest height in Xbloc hydraulic stability tests is represented.

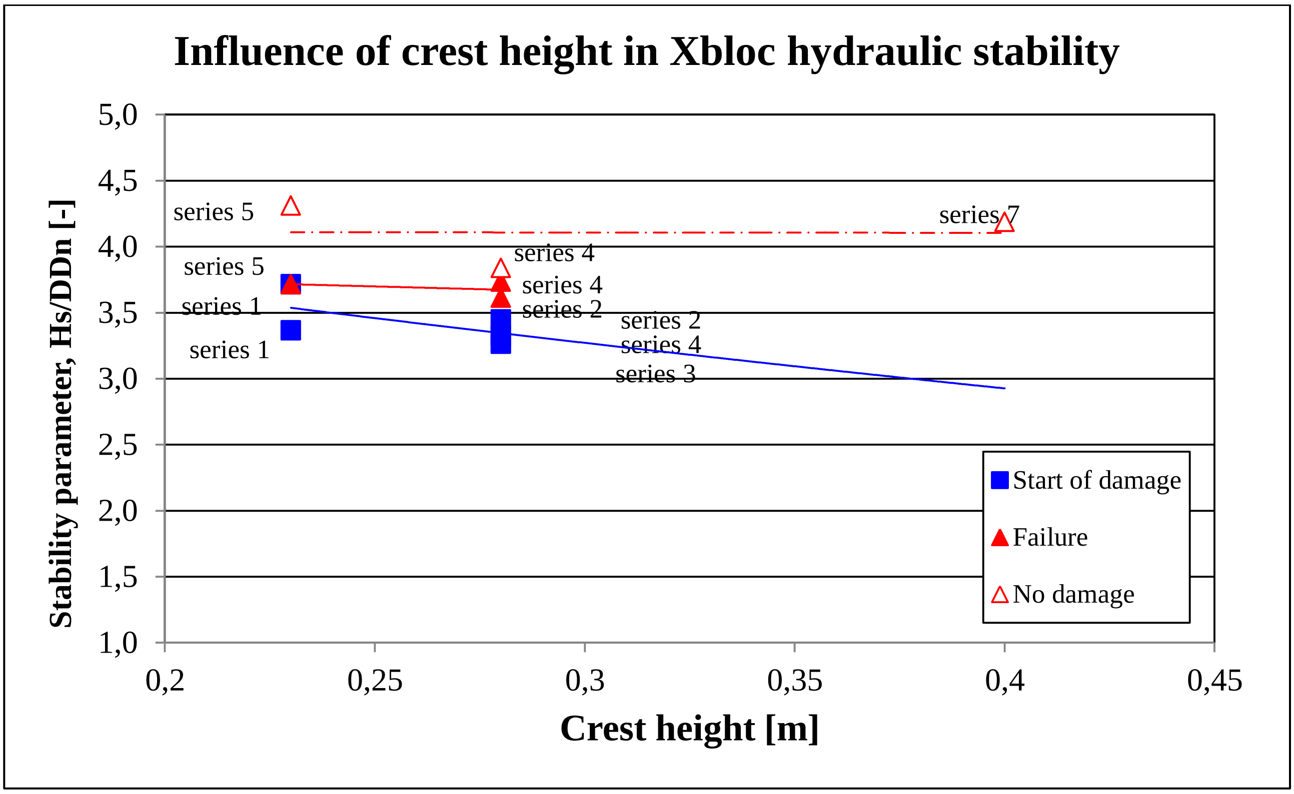

Figure 3-6 Influence of crest height on Xbloc hydraulic stability

For Xbloc only the test series 7 was performed with a high crested structure. Therefore the armour on the slope was placed in more rows than in the configuration with the lower crest. The high crested configuration had 15 % more rows [average of number of rows = 27.8 for tests with randomly placed low crested structure, number of rows was 32 for test with high crested structure]. In test with high crest no failure was observed and the wave height, for which damage occurred, was the highest of all tests series.

A reason for the high stability could be the extra downward pressure on the blocks due to the increased number of rows, which increased 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 [6].

3.2.4 Damage definition and curves

Figure 3-7 represents the damage curves for Accropode and Xbloc performed test series. Damage curves display the relation between the damage and the wave height, Hs using non-dimensional values.

The amount of damage (vertical axis) is expressed by the dimensionless number of displaced units Nod. Nod computed both in Accropode and in Xbloc is defined by the following Formula:

$$N_{od} = \frac{n_{displ}}{B_{test}/D_n}$$

In which:

n_{displ} = total number of units that are removed out of the armour layer [hydraulic damage] [-]

B_{test} = Width of test area [m]

D_n = nominal diameter unit [m]

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.

The relative wave height is expressed by the dimensionless stability parameter, $H_s/\Delta D_n$ (horizontal axis). The Hs used in this parameter is the Hs at the toe of the structure. The nominal diameter, D_{n50} or D_n, for Accropode and Xbloc were introduced in previous section. Δ is the relative density and is given by the following Formula:

$$\Delta = \frac{\rho_{armour} - \rho_{water}}{\rho_{water}}$$

where ρ_{armour} is the mass density of the armour layer and ρ_{water} is the water mass density.

Design value for the stability parameter is represented by a vertical continuous line. Start of damage is represented by a vertical dashed line and failure of the armour layer during a test is represented by a dash-dot vertical line.

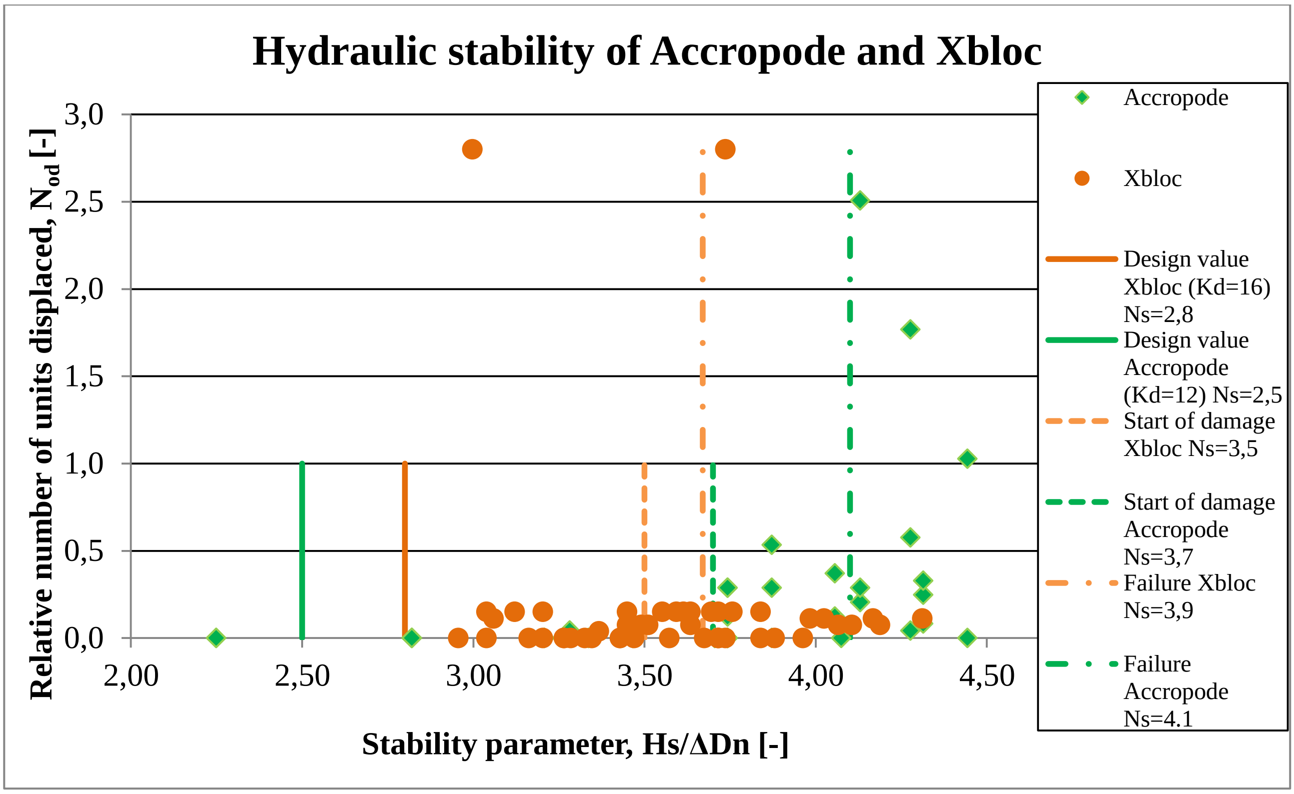

Figure 3-7 Hydraulic stability of Accropode and Xbloc

It can be concluded from the Figure 3-7 that the average $H_s/\Delta D_n$ value for which start of damage occurs is 6 % higher for Accropodes [N_s = 3,7] than for Xbloc [N_s = 3,5] units. However the lowest value for start of damage as found in the Accropode test is Ns = 3,28 while for Xbloc units the lowest value is N_s = 3,04 [which is about 8% lower].

The situation that start of damage occurred followed by failure of the slope without an increase of the wave height was reported several times in the Accropode tests [progressive failure]. For Xbloc units this happened twice (it is shown in the Figure 3-7). The first one was for a (too) low packing density, the other was due to a side effect of the window. [6].

3.2.5 Safety factor

3.2.5.1 Accropode

Due to the effect of storm duration on damage the stability curves were very steep and the difference in wave height for the no damage criterion and for the failure criterion consequently small. The stability formula for the Accropode resulted in:

No damage No = 0 or $S \leq 1$: $H_s/\Delta D_n = 3{,}7$

Large damage/failure No > 0,5 – 1,0 or $S > 2$: $H_s/\Delta D_n = 4{,}1$

In practical design a safety factor SF= 1,5 should be used. This means that a design wave could be exceeded by 50% before the first unit extractions would occur [4].

3.2.5.2 Xbloc

The stability formula for the Xbloc resulted in:

No damage No = 0 or $S \leq 1$: $H_s/\Delta D_n = 3{,}5$

Large damage/failure No > 0,5 – 1,0 or $S > 2$: $H_s/\Delta D_n = 3{,}9$

In practical design a safety factor SF= 1,25 should be used. This means that a design wave could be exceeded by 25% before the first unit extractions would occur [6].

Comparing the safety factor for Accropode and Xbloc, it is clear that the Accropode is designed more safely than the Xbloc even if actually the Accropode is more stable. The reason why the safety factor of Accropode is higher than the Xbloc one should be sought in the interlocking. The optimized interlocking features of the Xbloc unit include an easy interlocking ('automatic interlocking'). The Xbloc finds a stable position on the slope more easily than the Accropode. Xbloc is widely independent from the block orientation and from the orientation of the neighbouring blocks. These automatic interlocking features facilitate the placement of armour units and thus increase the speed of placement. Furthermore the variation of interlocking is reduced by automatic interlocking. The armour layer is more homogeneous and the required safety margins are lower [9].

3.2.6 Other important outcomes

3.2.6.1 Slope angle in Accropode

The steep slope 1:4/3 resulted favourable for an armour layer constructed with Accropode as it caused settlement of the units. The settlement was essential for the design of the Accropode and gave a blanket of armour units where each unit contacted several neighbours. Therefore rocking was hardly shown during the tests and large wave forces ware required for moving or displacing a unit [4].

3.2.6.2 Regular pattern in Xbloc

As only one test with a regular pattern was performed no firm conclusions were given after the tests. In this study, also, the only test with regular pattern was not considered, as specified previously. As for Crablock two regular patterns are recommended, in order to come to the guidance, the observations on this test are reported.

During the test with regular pattern no damage was observed. This indicated that a regular placed armour layer of Xbloc units had a very high stability.

By the other hand a regular placed armour layer might be difficult to achieve in practice considering placement under water in a marine environment [6]. But it should kept in mind that there may be a difference in placing with a non-symmetrical unit and a symmetrical one. So it is possible that a symmetrical unit, as the Crablock, is easier to be placed regularly.

3.2.7 Placement design

No specifications on Accropode were found on placement tests, while an extensive guideline for Xbloc is given in [3]. In next Chapter 5 possible dry tests on placing pattern on Crablock are described using as guideline the report [3]. In next chapter preliminary tests set-up and results on Crablock hydraulic stability are summarized.

4 PRELIMINARY TESTS ON CRABLOCK

4.1.1 Introduction

In June 2009 preliminary 2D and 3D physical model tests were performed by Al Masaood Advanced Group of Companies. As this study is aimed at the hydraulic stability of the trunk section only 2D tests are discussed.

2D physical model tests were performed on 10 tons Crablock units. A scale 1:60 was used for the cross-section.

A 1:60 foreshore slope was built out of concrete to resemble a sea bottom slope. At the offshore deep water side of the basin (with a depth of 0.6 m in the model) a wave generator was located, for generating irregular waves.

Test series 1 and Test series 2 were uniformly placed and Test series 3 to Test series 8 was randomly placed. A total of 36 tests were carried out to evaluate the stability of the armour units. All tests were conducted for durations of 1000 waves [8].

4.1.2 Structural parameters used in the tests

4.1.2.1 Armour layer

The armour layer consisted in Crablock model units of 45 g (without fillet) placed in single layer. In **Errore. L'origine riferimento non è stata trovata.** the characteristics of the Crablock model used in the preliminary tests are presented. Approximately 470 to 490 units where used.

Table 6 Crablock model characteristics 1:60 scale

Height L [m]	Volume [m^3]	Weight [kg]	Mass density [kg/m^3]	Water denity [kg/m^3]	Dn [m]	Δ	Dn*Δ [m]
0,05	0,004199	0,045	2413,45	1000	0,027	1,41	0,037

4.1.2.2 Under layer, core, toe and crest

Two different under layer were tested depending on the pattern considered. The other materials were the same in all tests.

For Test series 1 and Test series 2 a uniform pattern on rectangular grid was tested. The under layer consisted of 600kg to 800kg rock stones. It corresponded to a mass ratio armour layer/ under layer of ≈14. The cross-section material characteristics used in Test series 1 and Test series 2 are reported in Table 7:

Table 7 Cross-section material used in Test1 and Test2

Test 1 – Test 2	
Armour	10 tons Crablock units
Under layer	600 kg - 800 kg
Toe	3000 kg rock
Crest	3000 kg rock
Core	1 kg - 50 kg rock

For Test series 3 to Test series 8 a random pattern on rectangular grid was tested. The under layer consisted of 1000kg to 1200kg rock stones. It corresponded to a mass ratio armour layer/ under layer of ≈ 9. The cross-section material characteristics used in Test series 3 to Test series 8 are reported in Table 8:

Table 8 Cross-section material used for Test3 to Test8

Test 3 – Test 8	
Armour	10 tons Crablock units
Under layer	1000 kg - 1200 kg
Toe	3000 kg rock
Crest	3000 kg rock
Core	1 kg - 50 kg rock

4.1.2.3 Cross-section

For all Tests series 1:1.5 seaward slope cross-section was tested. The cross-section tested in Test series 1 and 2 is shown inFigure 4-1:

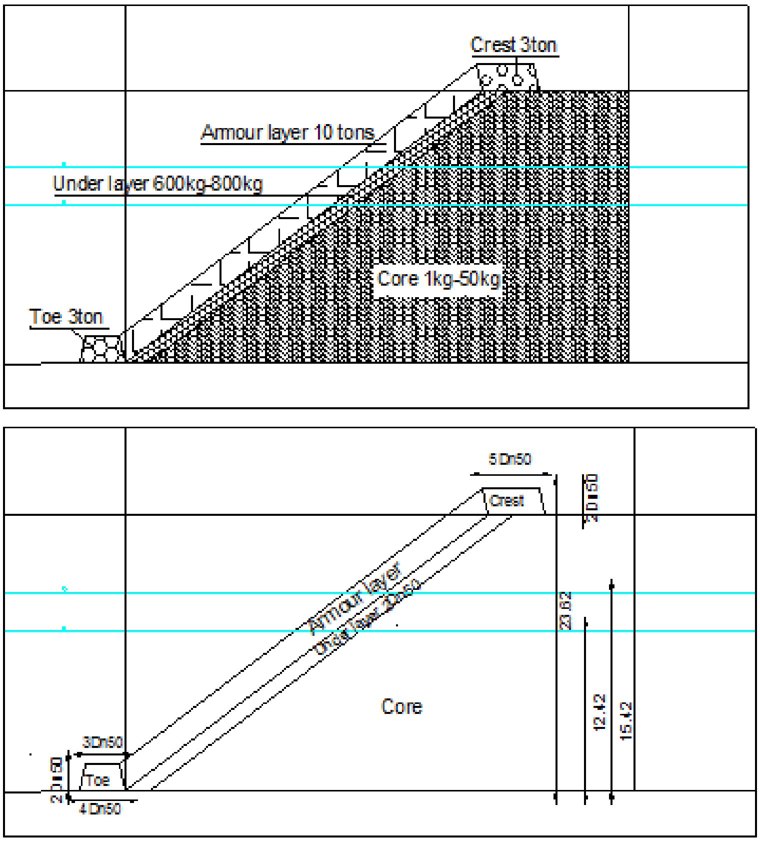

Figure 4-1 Cross-section tested in Test series 1 and 2 (slope angle 1:1,5)

The cross-section tested in Test series 3 to 8 is shown in Figure 4-2:

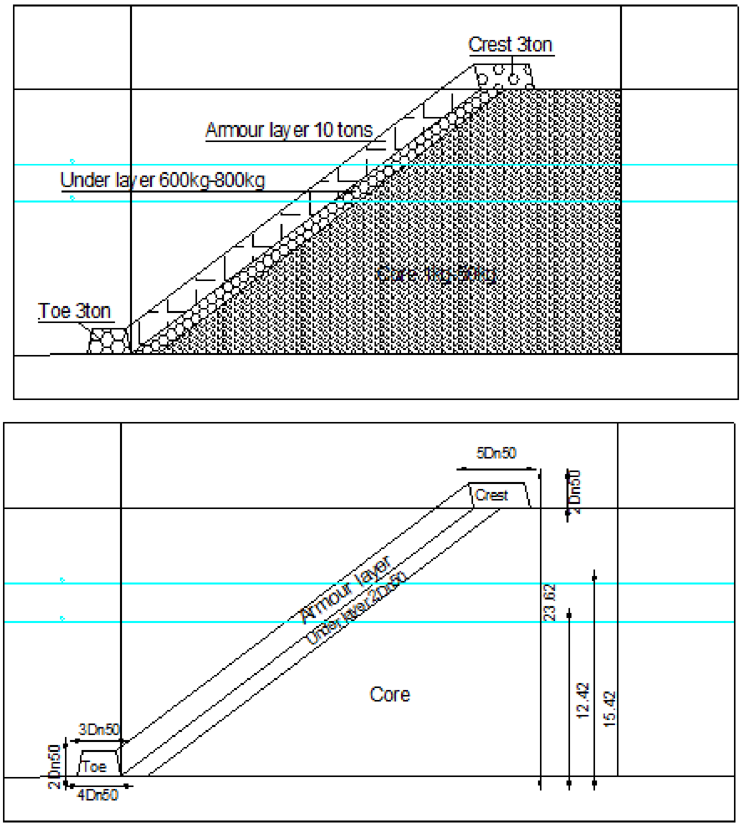

Figure 4-2 Cross-section tested in Test series 3 to 8 (slope angle 1:1,5)

4.1.2.4 Placing patterns

During the preliminary tests on hydraulic stability only the rectangular grid was tested. Diamond-shaped grid was not considered. For Test series 1 and Test series 2 a uniform pattern was tested, while for Test series 3 to Test series 8 random pattern was tested (Figure 4-3).

Figure 4-3 Rectangular grid a) uniform pattern and b) random pattern

4.1.2.5 Test programme

The performed wave conditions are reported in Table 9:

Table 9 Performed wave conditions in preliminary tests

Model Test Criteria					
Series	Type of test	Water Level	Depth at Toe	Target Hs at Toe	Peak Period
1	HW	+3,00 m	-15,42 m	2	8
2	HW	+3,00 m	-15,42 m	3	10
3	HW	+3,00 m	-15,42 m	3,5	12
4	HW	+3,00 m	-15,42 m	4	14
5	HW	+3,00 m	-15,42 m	5	16
6	HW	+3,00 m	-15,42 m	6	16
7	LW	+0,00 m	-12,42 m	2	8
8	LW	+0,00 m	-12,42 m	3	10
9	LW	+0,00 m	-12,42 m	3,5	12
10	LW	+0,00 m	-12,42 m	4	14
11	LW	+0,00 m	-12,42 m	5	16
12	LW	+0,00 m	-12,42 m	6	16

4.1.2.6 Preliminary results

Most of the displacements occurred at the extreme end of the test series. The majority of the movements of the armour units were noticed at the above water section of the slope. Test 3 and Test 4 results showed settlement of the units. These settlements may cause stresses on the legs of the unit therefore may cause potential damage. After test 4 the slope was re-packed for repeat tests. Test 5 and Test 6 evaluated the type of movement that occurred if a storm condition happens immediately after construction has been completed. The results showed that the damage that may occur is up to 1,8%.

The grid placement distance was 0,71*C for the horizontal and 0,57*C for the vertical. The fourth repack was a slightly looser placement with a placement grid of 0,8*C for the horizontal and 0,6*C for the vertical. Test 7 and Test 8 showed that with a loser placement more settlement would occur and this resulted in greater damage. In all tests the toe of breakwater appeared to be stable.

4.1.2.7 *Calculation of the packing density for Crablock*

As from the results the most appropriate placement was the random placement with a grid spacing of 0,71*L for the horizontal and 0,57*L for the vertical, the packing density was evaluated as follows.

Using the formula by Delta Marine Consultants [6], the given distances resulted in the below packing density:

$$PD = \frac{1}{D_x} * \frac{1}{D_y} = \frac{1}{0{,}71 * L} * \frac{1}{0{,}57 * L} = \frac{2{,}47}{L^2} = \frac{0{,}70}{{D_n}^2}$$

It is possible to evaluate the packing density considering the looser placement with a placement grid of 0,8*C for the horizontal and 0,6*C for the vertical:

$$PD = \frac{1}{D_x} * \frac{1}{D_y} = \frac{1}{0{,}8 * L} * \frac{1}{0{,}6 * L} = \frac{2{,}08}{L^2} = \frac{0{,}58}{{D_n}^2}$$

4.1.2.8 *Calculation of stability parameter for Crablock*

The 10 tons armour units resulted stable for wave condition up to 4 meters (Hs = 4 m), after that minor movement occurred. Considering the scale factor of 1:60 the scaled wave height results Hs = 0,06667 m. So it could be concluded that for a stability parameter of Ns = 1,76 no damage occurred.

According to Table 9, the highest wave high at the toe in the preliminary tests on Crablock was Hs = 6 m. Considering the scale factor of 1:60 the scaled wave height results Hs = 0,1 m. So it could be concluded that for a stability parameter of Ns = 2,64 no failure occurred.

In Figure 4-4 the results of the preliminary tests are plotted:

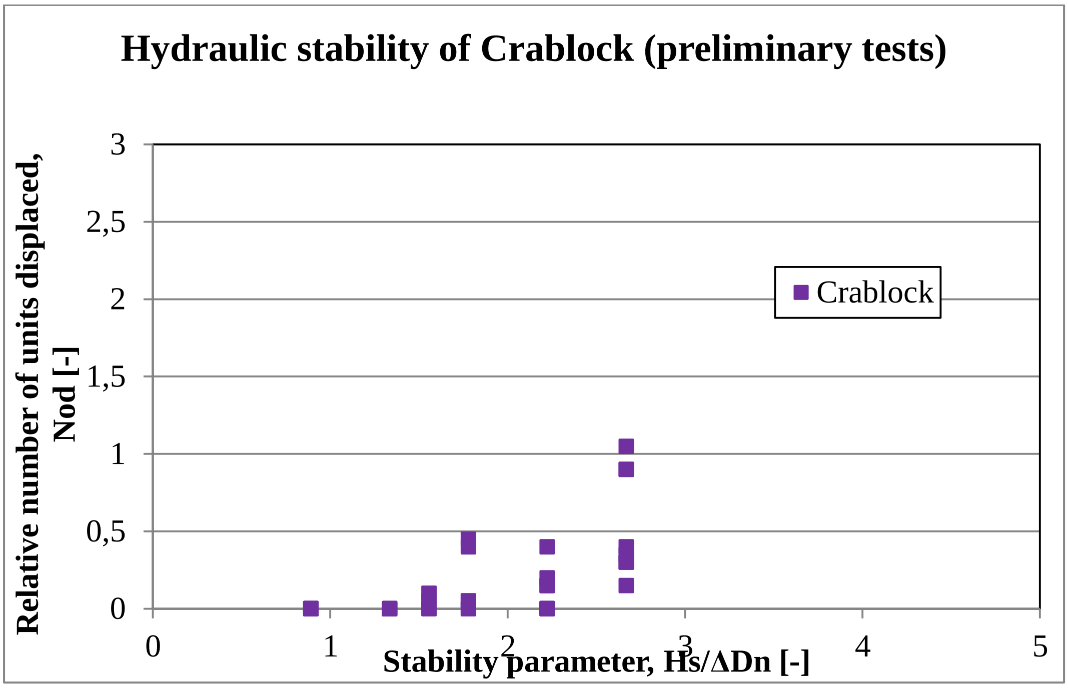

Figure 4-4 Hydraulic stability of Crablock in preliminary tests

5 Placement guidelines for Crablock units

After analyzing the investigation on Xbloc placement the parameters which play an important role in the placement were found. They are the placing pattern, the horizontal and upslope distance between the units and the resulting packing density.

5.1 Importance of packing density in placement tests

A predefined placement grid is the basis of every single layer armour layer which has to be constructed. The most important parameter of an armour layer is the packing density. If the required packing density is reached it is almost certain that there are no major faults in the armour layer. A high packing density will result in good interlocking between the units.

To achieve proper interlocking the placement grid of single layer armour units has to comply with the following requirements: horizontal rows have to be approximately parallel with the contour line of the slope and the distance between the base units must be in a proper range (not to wide not to small) [3].

For the whole breakwater the achieved packing density should be within 98% and 105% of this recommended packing density.

The recommended packing density from the preliminary tests of PD=0,70 D_n^2 [4.1.2.7] will be used to perform tests on the rectangular grid.

For the placements of Crablock on diamond-shaped grid no specifications exist at this moment. The placement could be done by the hand based on experience gained from other single layer armour units. As two Crablock model units were available during my study, some visual observations and practical measurements on diamond-shaped grid were done. These measurements resulted in a proposed packing density for the diamond-shaped grid.

A theoretical study on the diamond-shaped grid resulting in a packing density value will be discussed in next section.

5.1.1 Proposed packing density for diamond-shaped grid

For a diamond-shaped grid proper interlocking is reached by placing an armour unit in the middle between two base units (two units, one row below on which the unit is placed) [3].

The basic concept of placement pattern of Crablock on a diamond-shaped grid is that each unit is in contact with six other units, two below, two above, one to the left and one to the right, as shown on Figure 5-1.

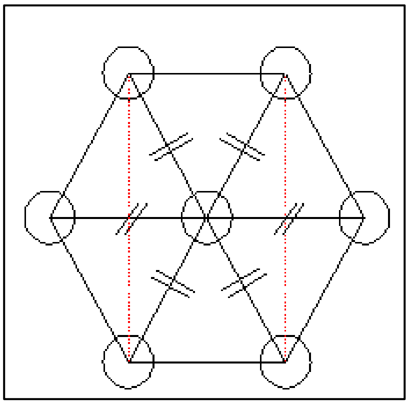

Figure 5-1 Contact between units in diamond-shaped grid, black lines indicate contact red lines no contact

To derive the theoretical relation between de horizontal placing distance and the distance upslope two observations were done. The first is that the distances between the central units and the "round" units are constant (Figure 5-1). Therefore when the horizontal distance increases the upslope distance decreases, as shown in Figure 5-2:

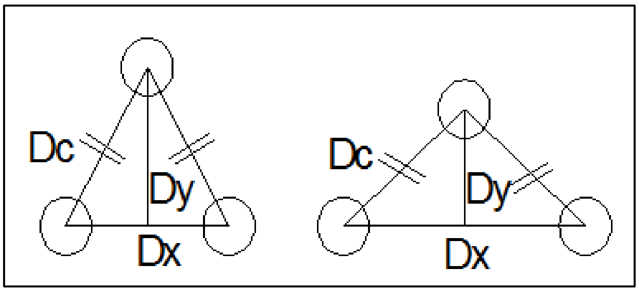

Figure 5-2 Constant distance between units which are in contact with each other

The second observation is that when the units are placed in minimum horizontal and upslope spacing the angle between the base-units line, D_x, and constant distance line, D_c, is approximately 60 degrees.

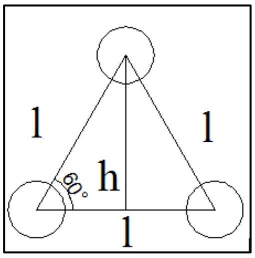

Figure 5-3 Equilateral triangle

The units lying on the edges of the equilateral triangle measure $\mathrm{D}_{\mathrm{x,min}} = l = 3{,}3\ cm$ (Figure 5-3). The height of the equilateral triangle will give the minimum upslope distance, as follow:

$$\mathrm{D}_{\mathrm{y,min}} = \mathrm{h} = \frac{l * \sqrt{3}}{2} = 2{,}8\ \mathrm{cm}$$

By dividing the minimum horizontal distance and the minimum upslope distance for the model unit height L, the following relations for the grid spacing are given:

$$\mathrm{D}_{\mathrm{x,min}} = 0{,}6\ L$$

$$\mathrm{D}_{\mathrm{y,min}} = 0{,}5\mathrm{L}$$

This spacing distances result in a packing density of:

$$PD = \frac{1}{D_x} * \frac{1}{D_y} = \frac{1}{0{,}6 * L} * \frac{1}{0{,}5 * L} = \frac{3{,}33}{L^2} = \frac{0{,}94}{{D_n}^2}$$

5.2 Placement tests

The objective of the placement tests is to check the packing density and the horizontal versus upslope placement distance for each placing pattern considered for Crablock. The packing density required in prototype will be determined by small scale Crablock units placed by hand. The horizontal versus upslope placement distance will be checked indirectly by measuring all individual horizontal and upslope placement distances [3].

5.2.1 Description model tests

Four series of placement tests in dry may be performed on a straight breakwater section to verify assumptions and results of the theoretical study. The tests will be performed on both rectangular and diamond-shaped grid with both uniform and random orientation of the units.

The grid tests that should be performed are:

− Test 1: Rectangular grid placed with uniform orientation of the units;

− Test 2: Rectangular grid placed with random orientation of the units;

− Test 3: Diamond-shaped grid placed with uniform orientation of the units;

− Test 4: Standard diamond-shaped grid placed with random orientation of the units;

All placement tests might be executed three times to create larger and more reliable data sets. From each placement all units will be measured on position (X and Y coordinates). From the coordinates other parameters, like deviation on the designed position and packing density, will be calculated.

During placement in prototype the quality control will be based on pictures of the placement. Therefore it is important to provide a link between the visual information and quantifiable data. To give this link each placement will be described visually and on measured position. The orientation of the individual units will be recorded. If no other instrument will be available, the orientation of the placed units will be recorded by pictures taken always in the same position of the placement.

5.2.1.1 Units

The units that will be used for the placement test and for hydraulic stability tests weigh 63,55 g (with fillet). The characteristics model size of the model units are reported in Table 10. They will be prepared by A M MARINE WORKS Est.

Table 10 Crablock model characteristics for coming tests

Height L [m]	Volume [m^3]	Weight [kg]	Mass density [kg/m^3]	Water denity [kg/m^3]	Dn [m]	Δ	Dn*Δ [m]
0,056	2,65E-05	0,06355	2413,45	1000	0,030	1,41	0,042

Approximately 970 to 990 Crablock units are available.

5.2.1.2 Model set-up

The core of the breakwater in the test will consist of a steel frame with a wooden surface, the recommended slope of this frame is 1:4/3. This steep slope 1:4/3 results favourable for the armour layer as it causes settlement of the units. The settlement is essential for the design of the Crablock and gives a blanket of armour units where each unit contacted several neighbours. The toe of the breakwater may consist of a wooden structure, but a rock toe structure is also acceptable. The rock size is scaled down to match the scale model Crablock units. The dimensions of this breakwater are decided based on the Xbloc guidance, and are given in Figure 5-4Figure 5-4 Profile of tested breakwater:

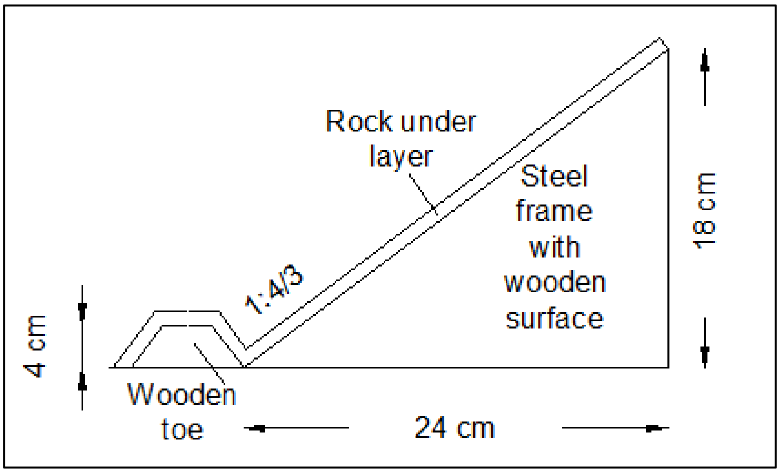

Figure 5-4 Profile of tested breakwater

5.2.1.3 Underlayer

The material characteristics and structural parameters for the test set-up can be established, by using the common design rules, which were used for the investigation on Accropode and Xbloc. So that the W_{50} of the under layer should be $W_{Crablock}$/10. As the weight of Crablock model unit is 63,55 gr, W50 should be approximately 6,4 gr.

5.2.1.4 Test 1: Rectangular grid placed with uniform orientation of the units

This test will be used to determine the achievable packing density. The accuracy results will be used as a benchmark for achieved accuracy of all other placement tests.

The grid will be a trapezoidal shaped grid with the horizontal and upslope placement distances recommended in preliminary tests, $D_x = 0{,}71 * L$ and $D_y = 0{,}57 * L$ (see also Figure 5-5).

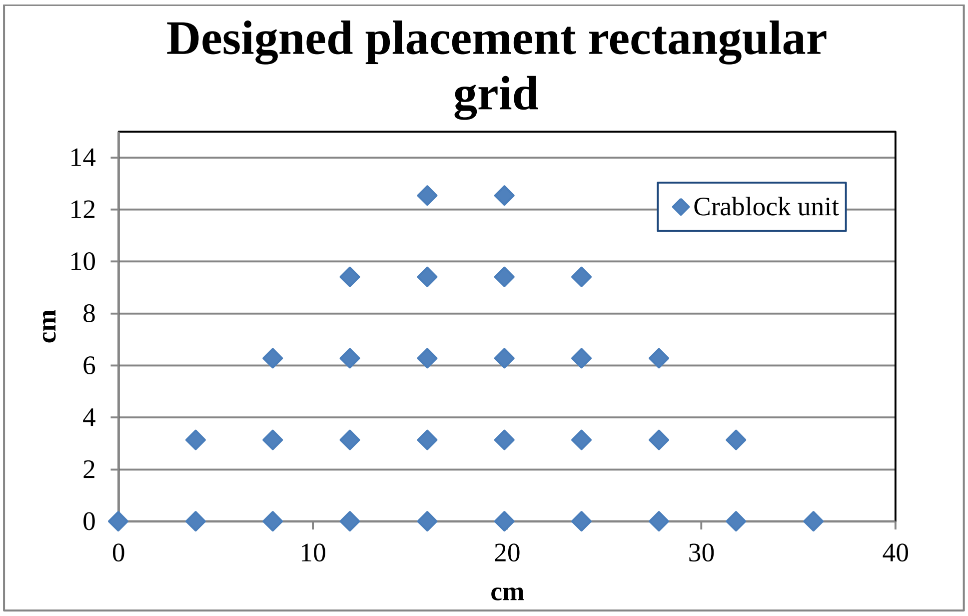

Figure 5-5 Designed placement rectangular grid

The maximal number of units in 1 row is 10, which results in a total of 30 units. To enlarge the dataset this placement test will be performed three times.

All units will be placed at their predefined position onto the slope by hand. During placement the units will have the orientations described in Section 2.3.2.

The positions of placement tests will be measured, plotted and compared to the designed grid in Figure 5-5, to find any misplacements for all performed tests and data will be elaborated to reach the deviation on the designed position and packing density.

5.2.1.5 Test 2: Rectangular grid placed with random orientation of the units

The second test will be performed as the Test 1. The only difference will be the random orientation of the units. The same designed grid in Figure 5-5 will be used for the comparison and the data analysis.

5.2.1.6 Test 3: Diamond-shaped grid placed with uniform orientation of the units

For the third test a triangle shaped grid is proposed. Placing distances results in a diamond-shaped placement grid. The horizontal and upslope placement distances derive by the theoretical study $D_x = 0{,}6 * L$ and $D_y = 0{,}5 * L$ (see also Figure 5-6).

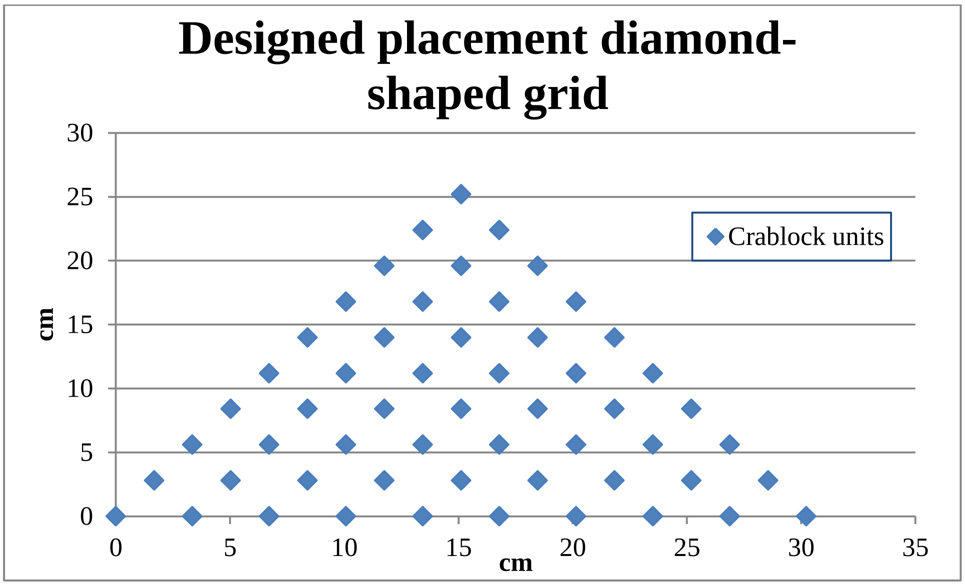

Figure 5-6 Designed placement diamond-shaped grid

The maximal number of units in 1 row is 10, which results in a total of 55units. To enlarge the dataset this placement test will performed three times.

All units will be placed at their predefined position onto the slope by hand. During placement the units will have the orientations described in Section 2.3.2.

The positions of placement tests will be measured, plotted and compared to the designed grid in Figure 5-6, to find any misplacements for all performed tests and data will be elaborated to reach the deviation on the designed position and packing density.

5.2.1.7 Test 4: Diamond-shaped grid placed with random orientation of the units

The fourth test will be performed as the Test 3. The only difference will be the random orientation of the units. The same designed grid in Figure 5-6 will be used for the comparison and the data analysis.

6 Hydraulic stability tests in wave flume

In this section stability tests on Crablock in wave flume will be described. As result of the comparison in investigation between Accropode and Xbloc it was easy to identify the most important parameters to look at for a new single layer armour unit investigation. These parameters are both structural and environmental and are: the placing pattern, the packing density, the height of the crest as result of variable number of rows on the slope, the slope angle and relative settlement, and the wave steepness, as function of the wave height and the wave length.

In this chapter a test set-up for Crablock will be proposed: the material characteristics scaled according to the available model units will follow the same rules used for Accropode and Xbloc, the structural parameters of the cross-section will be proposed according to the general outcomes of existing single layer armour units and the proposed test programme will emulate the tests programme proposed for the Xbloc.

6.1 Model configuration

Ten “increasing wave height test series” will be performed on Crablock. Except for one of ten proposed test series, all tests will be performed with a crest level that allows overtopping under extreme wave attack. The water depth at the toe of the breakwater will be 0.20 – 0.35 m. Both rectangular and diamond-shaped grid in uniform and random pattern will be tested. Different number of rows will be tested. The number of rows will confer to the structure the characteristic of height crest or low crest. Different number of units per rows will be tested. In this way different packing densities will be tested in order to investigate the influence on hydraulic stability.

6.1.1 Cross-section

The breakwater cross-section will consist on core, under layer, toe protection and L-shaped crest wall (Figure 6-1).

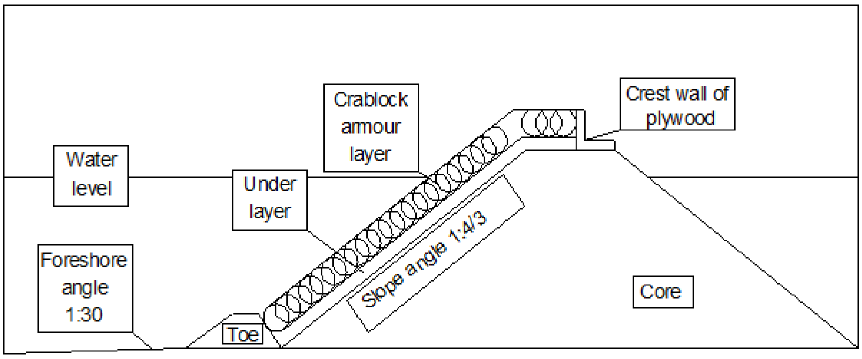

Figure 6-1 Proposed breakwater cross section for Crablock

The crest wall of plywood will be fixed at the side-walls of the flume in order to guaranty the stability of the superstructure. The model will be constructed with a foreshore with a slope of 1:30. The armour layer will have a slope 1:4/3, which is a typical slope for single layer armour units like and Accropode and Xbloc.

As the model tests are focused on Crablock armour layer stability, the toe in the test set-up can be over-dimensioned to exclude the influence of a failing toe structure on the stability of the armour layer. As top layer three Crablock units will be used in a single layer.

The cross-sections proposed for the tests are shown from Figure 6-2 to Figure 6-7. The circles represented in figures indicate the size of the model units (diameter = L) and the distances between the center of the circles indicate for the rectangular grid the upslope prescribed in preliminary tests ($D_y = 0{,}57\ L$) and for diamond-shaped grid the minimum upslope distance between units, that will result from the placement tests. For the drawings it was assumed the theoretical upslope distance ($D_y = 0{,}5\ L$).

The structural parameters which will vary from test to test are represented in red for each cross-section. They are: the depth of the water, the freeboard, the number of rows and the upslope distance, according to the considered placing pattern.

In Figure 6-2 the proposed cross-section for Test series 1 and 2 is represented:

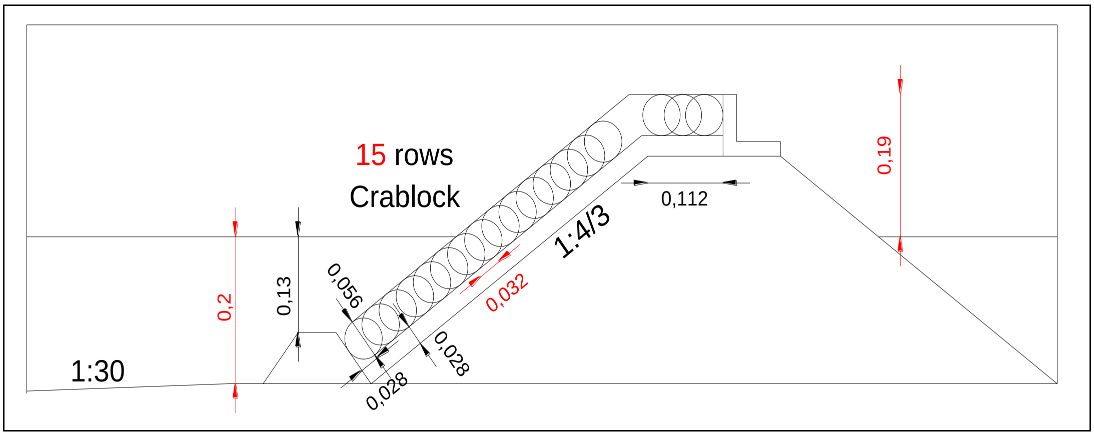

Figure 6-2 Cross-section for Test 1 and Test 2 [measures in m]

For Test series 1 and 2 the rectangular grid will be investigated. In Test 1 the uniform pattern will be used while for Test 2 the units will be placed randomly. The number of rows will be 15, the water depth at the toe will be 0,20 m. The crest height will measure 0,19 m.

In Figure 6-3 the proposed cross-section for Test series 3 and 4 is represented:

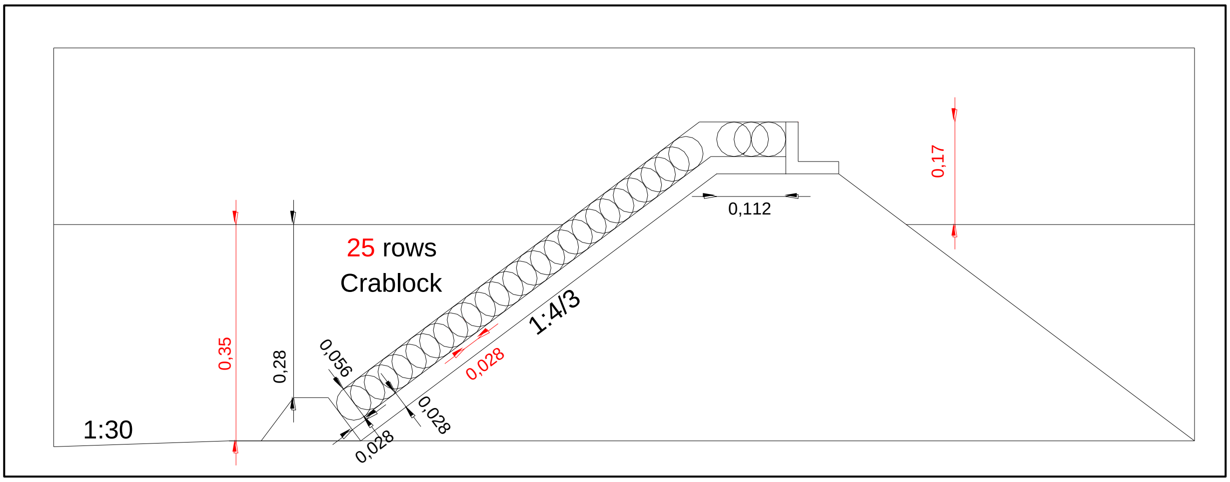

Figure 6-3 Cross-section for Test 3 and Test 4 [measures in m]

For Test series 3 and 4 the diamond-shaped grid will be investigated. In Test 3 the uniform pattern will be used while for Test 4 the units will be placed randomly. The number of rows will be 25, the water depth at the toe will be 0,35 m. The crest height will measure 0,17 m.

In Figure 6-4 in the proposed cross-section for Test series 5 and 6 is represented:

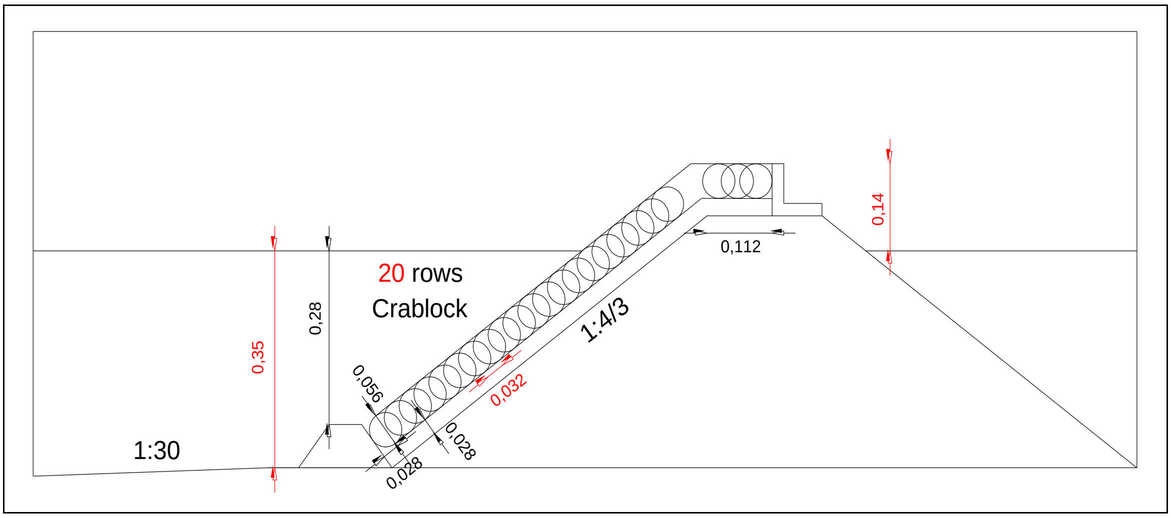

Figure 6-4 Cross-section for Test 5 and Test 6 [measures in m]

For Test series 5 and 6 the rectangular grid will be investigated. In Test 5 the uniform pattern will be used while for Test 6 the units will be placed randomly. The number of rows will be 20, the water depth at the toe will be 0,35 m. The crest height will measure 0,14 m.

In Figure 6-5 the proposed cross-section for Test series 7 and 8 is represented:

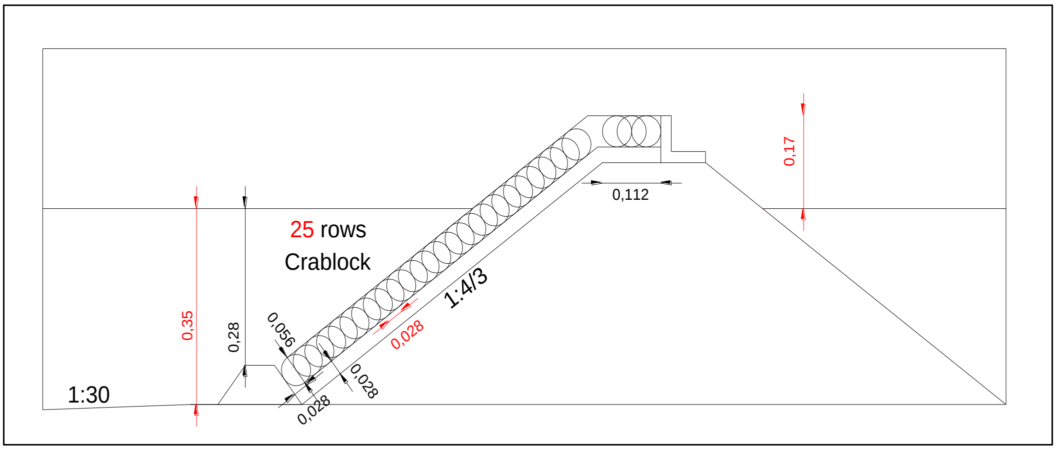

Figure 6-5 Cross-section for Test 7 and Test 8 [measures in m]

For Test series 7 and 8 the diamond-shaped grid will be investigated. In Test 7 the uniform pattern will be used while for Test 8 the units will be placed randomly. The number of rows will be 25, the water depth at the toe will be 0,35 m. The crest height will measure 0,17 m.

In Figure 6-6 the proposed cross-section for Test series 9 is represented:

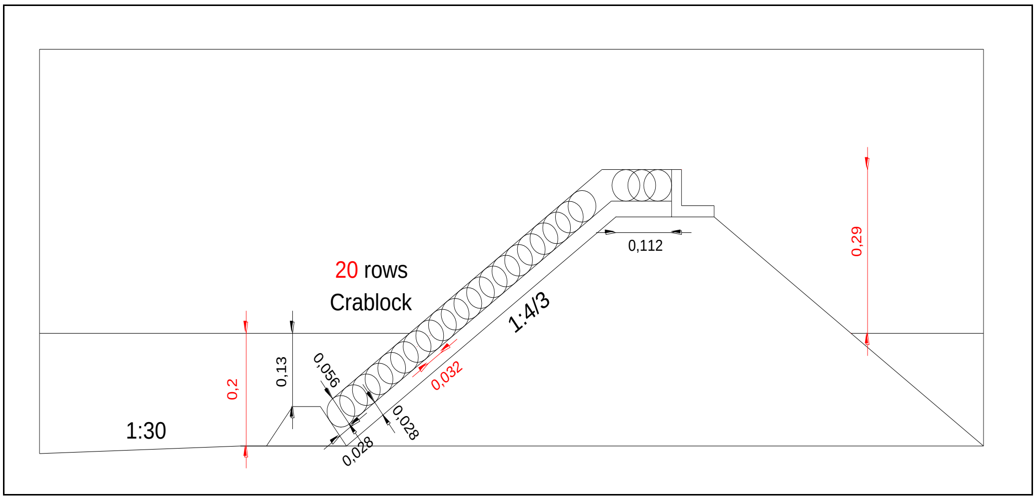

Figure 6-6 Cross-section for Test 9[measures in m]

For Test series 9 the rectangular grid will be investigated and the units will be placed randomly. The number of rows will be 20, the water depth at the toe will be 0,20 m. The crest height will measure 0,29 m.

In Figure 6-7 the proposed cross-section for Test series 10 is represented:

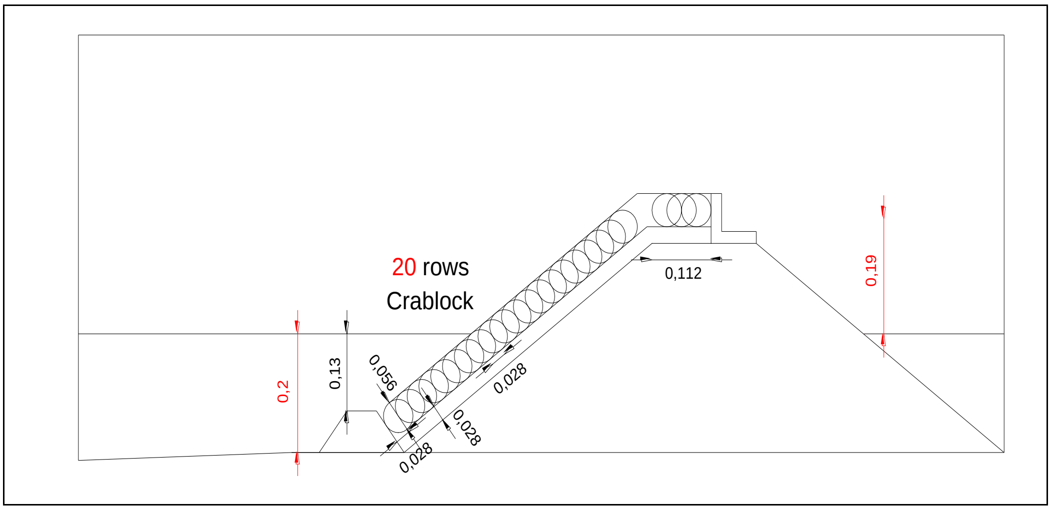

Figure 6-7 Cross-section for Test 10[measures in m]

For Test series 10 the diamond-shaped grid will be investigated and the units will be placed randomly. The number of rows will be 20, the water depth at the toe will be 0,20 m. The crest height will measure 0,19 m.

6.1.1.1 How the height of the crest vary with the number of the rows

In Figure 6-8 the crest height as function of the number of rows is represented for rectangular grid. Note that in proposed investigation no tests with 25 rows in rectangular grid will be considered.

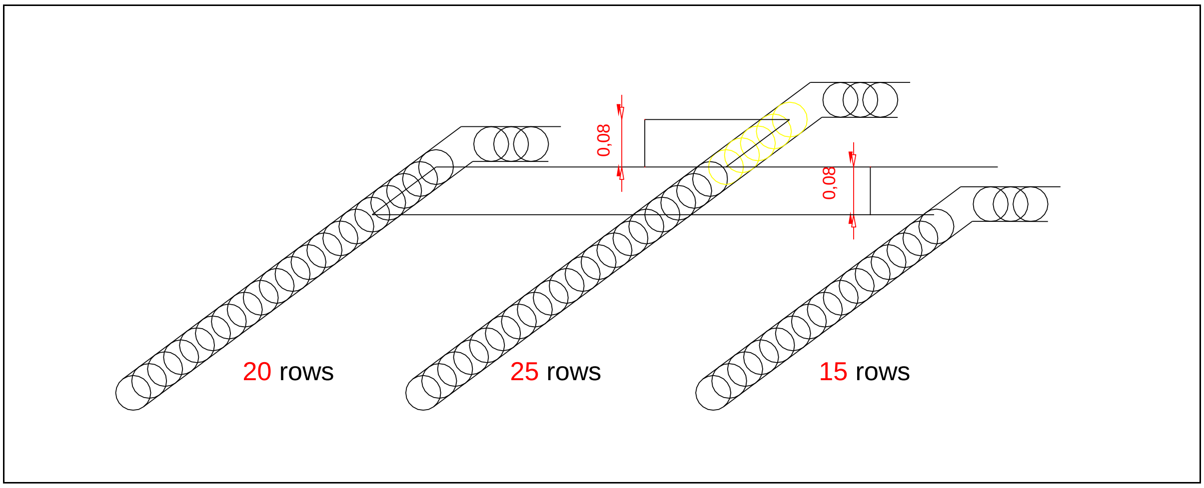

Figure 6-8 Crest height in function of the number of rows for rectangular pattern (measures in m)

In Figure 6-9 the crest height as function of the number of rows is represented for diamond-shaped grid. Note that in proposed investigation no tests with 15 rows in diamond-shaped grid will be considered.

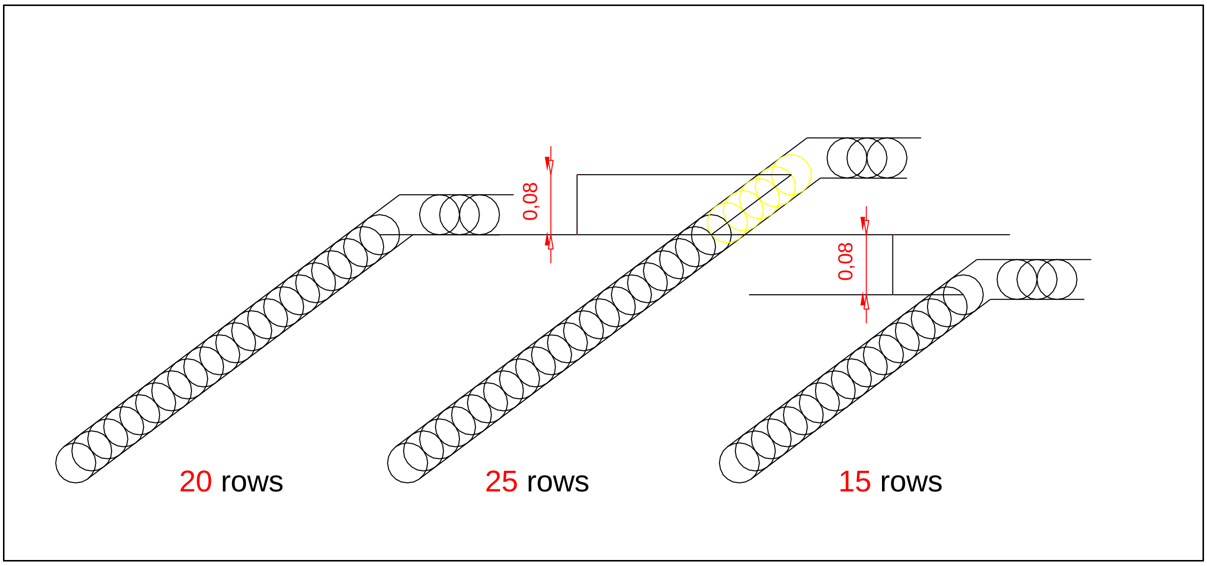

Figure 6-9 Crest height in function of the number of rows for diamond-shaped pattern (measures in m)

6.1.2 Material properties

The properties of the various materials are summarized in Table 11.

Table 11 Properties of the various materials

Properties of the materials in modelCrablock	Layer thickness [mm]	Mass [g]	Sizes [mm] L/D_{n50}	Density [kg/m^3]
Armour layer	56	64	56	2413,45
Under layer	28	3,2 – 6,4	14	2740
Core	_	0 - 0,32	4,9	2650
Toe protection	70	3,2 – 6,4	14	2740

6.1.3 Placement of armour units

Crablock armour units will be placed in horizontal rows. In rectangular grid the unit of the subsequent row will find a position on the unit of the previous row while in diamond-shaped grid the unit of the subsequent row will find a position in between 2 units of the unit of the previous row.

The distances between the center of gravity of the units within 1 row and in between 2 rows will be predefined. The orientation of the units will be either varied randomly (random placement) or predefined (uniform placement). Both rectangular and diamond-shaped grid will be tested.

Five test series will consider the rectangular grid and the other five test series the diamond-shaped grid. For 4 test series the armour units will be uniformly placed. Six test series will be performed with randomly placed armour units.

The number of Crablock armour units that will be placed in the tests series is presented in Table 12.

Table 12 Number of placed units

Test	Rows number on slope	Number of units per row	Total number of units	Grid	Pattern
1	15	33	495	Rectangular	Uniform
2	15	33	495	Rectangular	Random
3	25	33-32	813	Diamond-shaped	Uniform
4	25	33-32	813	Diamond-shaped	Random
5	20	31	620	Rectangular	Uniform
6	20	31	620	Rectangular	Random
7	25	31-30	763	Diamond-shaped	Uniform
8	25	31-30	763	Diamond-shaped	Random
9	20	30	600	Rectangular	Random
10	20	29-30	590	Diamond-shaped	Random

As the dimensions of the slope will be known, the placements distances and packing densities relative to the unit size can be calculated.

In general the flume has a width of 1 m. By dividing this length for the nominal diameter of the Crablock $1m = 33{,}3 * Dn$. In rectangular grid the number of units per rows will be constant for every row, while in diamond-shaped grid an alternate number of units per row is proposed. Note that as the model units are very little in dimension, to cover a width of 1 meter in 25 rows more than 800 units will be needed for some tests series.

6.1.4 Test programme

The test programme has been decided referring to the test programme performed on Xbloc [6].

A total number of ten test series will be executed. A number of individual sub-tests will be conducted within every test series with increasing wave height in order to determine limiting conditions for the Crablock armour layer stability. For each test series constant water level and wave steepness will be fixed.

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

The wave height, and so the wave period , will be measured stepwise until the slope failure or the limits of the wave generator will be reached. The tests will be stopped when the under layer will be damaged. After each test series the armour layer will be removed and under layer and armour layer will be reconstructed.

The same definitions of settlement, damage and failure used in the Xbloc investigation will be used [6]. The definitions are reported below:

- 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 proposed wave conditions for the test series on Crablock are summarized in Table 13:

Table 13 Proposed wave conditions for the test series on Crablock

Test	Grid	Pattern	Steepness	Water depth at toe [m]
1	Rectangular	Uniform	0,02	0,20
2	Rectangular	Random	0,06	0,20
3	Diamond-shaped	Uniform	0,02	0,35
4	Diamond-shaped	Random	0,06	0,35
5	Rectangular	Uniform	0,02	0,35
6	Rectangular	Random	0,06	0,35
7	Diamond-shaped	Uniform	0,02	0,35
8	Diamond-shaped	Random	0,06	0,35
9	Rectangular	Random	0,06	0,20
10	Diamond-shaped	Random	0,06	0,20

Results of these tests will be elaborated in order to find the damage development during the tests (damage curves) to obtain the relation between the damage and the wave height. The overtopping discharge and percentage of overtopping waves can be calculated. An impression of the settlement of the armour units will be got from the pictures. Influence on the hydraulic stability of the packing density, placing pattern, wave steepness, the height of the crest can be plotted and discussed, as for Accropode and Xbloc was done.

The stability formula should be, also, derived for Crablock. In the end a comparison with other existing single layer armour units can be done.

The reason why only two wave steepnesses will be investigate is that the variables are packing density, placing pattern, number of rows, crest height and wave steepness: if we want 4 wave steepnesses, we can do only two different set-ups, for example a random and a regular placement (they will be the two best from the dry tests). Then only one water depth/number of rows/crest height remains. If we have only two wave steepnesses, than there is a little more freedom.

7 Conclusions

7.1 General

Only the investigation of Accropode and Xbloc were compared. Good information on Accropode were available, as Professor J.W. provided the report "Stability Formula for breakwaters armored with Accropode" [Van der Meer, J.W., 1987]. Good information, also, were available on Xbloc, as the website of DMC gives the design guidance for the Xbloc. The comparison resulted in delineation of the most important both structural and environmental parameters to look at for Crablock. The parameters are:

- the placing pattern;
- the packing density;
- the height of the crest as result of variable number of rows on the slope;
- the slope angle and relative settlement;
- the wave steepness, as function of the wave height and the wave length.

The comparison, also, resulted in setting model investigations in the first series, both in dry and in a wave flume. Proposed model Tests are:

- 4 dry placement test series to check the proposed packing density for Crablock in preliminary tests on rectangular grid (PD=0,70/Dn2) and to check the proposed packing density as resulted of theoretical observations on diamond-shaped grid (PD=0,94/Dn2);
- 10 Hydraulic stability tests in a wave flume.

7.2 Recommendations

7.2.1 Recommendations for placement tests

- To validate the theoretical placement grid and to determine the placement accuracy, placement tests on Xbloc were performed with large scale model Xbloc units of 5 kg, which corresponds to approximately 1:10 scale (on dimensions) for a typical breakwater application. This large scale is required to simulate the behaviour of the units during placement in prototype (i.e. sling techniques and interaction between units). As only small scale Crablock units of 64 gr will be available, this directive will not be followed for Crablock placement tests. Anyway it was decided to prescribe the placement tests in order to practice in placing the units on the slope before the hydraulic stability tests.

- In placement tests only dry testing conditions have been prescribed. It could be appropriate in future developments to consider placement in submerged conditions for Crablock, as have been done for Xbloc.
- Although the recommended technique for the "Dry placement tests" is placing by hand, it should be kept in mind that different types of placement techniques could be used for the same placement tests in laboratory. Anyway in order to optimize time it was felt appropriate to place units by hand testing all the proposed patterns: both rectangular and diamond-shaped grid in both uniform and random pattern.
- About the two uniform patterns proposed, the prototype armour block should be placed on the slope in a predetermined orientation through a suitable equipment and a quality control system.

7.2.2 Recommendations for placement procedure

The most common way of placing of prototype concrete armour units is by using a crawler crane or hydraulic excavator provided with a sling or chain in which the armour unit can be lifted into place.

Crawler cranes are relatively slow compared to excavators for placing armour blocks. However, they can carry heavy loads and span much larger distances. This is the only suitable option when placement distance is an issue.

The larger the crane, the more difficult it is to handle. Because of this, long booms should only be considered when they are strictly necessary. Mechanical shovels/excavator are used increasingly to place small blocks on the most accessible rows. Placing is usually much faster than with a crawler crane but is generally severely limited in terms of load and radius of action. Hydraulic and mechanical systems are used to release the block from the sling. Hydraulic excavator in relation to a crawler crane has, also, lower operating costs [5].

For small sized Crablock units a hydraulic excavator can be used instead of a crawler crane for the placement of armour units.

So, an improvement could be to look at larger hydraulic excavators that are able to work with units, say up to 20 t. That would really save costs by speeding up construction. Excavators also do not need the contribution of the divers in placing the units. Information is available in berm breakwater construction, where rock 20-35 t are placed by excavator, optimizing length and location of placing.

7.2.3 Recommendations for hydraulic stability tests

- 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.
- In the test set-up it was suggested to oversize the toe. This to exclude the influence of a failing toe structure on the stability of the armour layer. Nevertheless the toe is very important for the structure as if it fails, probably the whole structure will fail. The standard toe consists of natural rock of the armour unit in a trapezoidal cross-section shape; but when the armour layer is extended down to the seabed it is also possible to use a natural rock toe in a parallelogram cross-section shape, as shown in Figure 7-1.

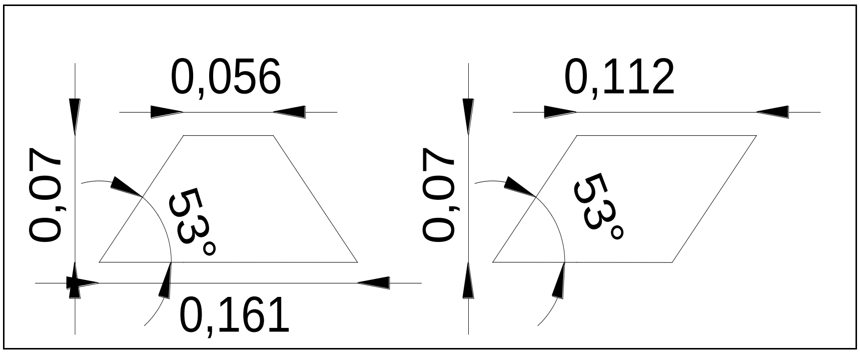

Figure 7-1 Toe proposed for this study vs toe proposed for future developments

Further model tests could investigate different toe options, such as using a heavier conventional CRAblock row as toe, or using a single row of larger rock. An improvement could be to design a new Crablock unit to perform better in hard environmental conditions, as was done for Xbloc.

Further improvements could be the introduction of a filter layer under the toe, to prevent the problems related to a breakwater built on a sand sea bed and the study of a Crablock submerged breakwater.

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