JAPAN SOCIETY OF CIVIL ENGINEERS
COASTAL ENGINEERING COMMITTEE

Coastal Engineering Journal, Vol. 59, No. 4 (2017) 1750020 (33 pages)

DOI: 10.1142/S0578563417500206

First Tests on the Symmetrical Breakwater Armor Unit Crablock

M. Salauddin[*,†,¶], A. Broere[‡], J. W. Van der Meer[†],
H. J. Verhagen[‡] and E. Bijl[§]

[*]*Department of Civil Engineering,*
Chittagong University of Engineering and Technology,
Chittagong-4349, Bangladesh

[†]*IHE Delft, Delft, The Netherlands*

[‡]*Delft University of Technology, Delft, The Netherlands*

[§]*CDR International, Rijssen, The Netherlands*

[¶]*mdsalauddin24@gmail.com*

Received 14 November 2016
Accepted 16 November 2017
Published 13 December 2017

Single layer concrete armor systems are being widely used nowadays in the design of rubble mound breakwaters. Recently, a new concrete armor unit has been developed and applied as single layer armor system in the repair works of one damaged breakwater at Al Fujeirah, UAE. It has a symmetrical shape, in contrast to most other units. Modern single layer concrete armor units that exist at this moment have design guidelines in terms of placement, stability and overtopping. However, because of lack of laboratory research and the little experience of using Crablock, no design guidance exists yet for this new single layer block compared to other existing one layer units. Being a new armor unit, the placement was investigated first. Then physical model tests were performed in a wave flume to come up with results on stability and wave overtopping. Furthermore, to determine the interlocking properties of armor units, pull tests were also conducted in this research. The placement tests showed that uniform placement was best achieved with a rectangular grid on a relatively small underlayer of rock. Test results on stability showed that longer waves affected the armor layer a little more, with more rocking and earlier start of damage. Packing density as well as placement pattern showed no influence on wave overtopping. The overtopping tests gave larger overtopping than expected, which might be due to the fairly steep 1:30 foreshore that gave a large ratio of significant wave-height from the time domain and the spectral wave-height.

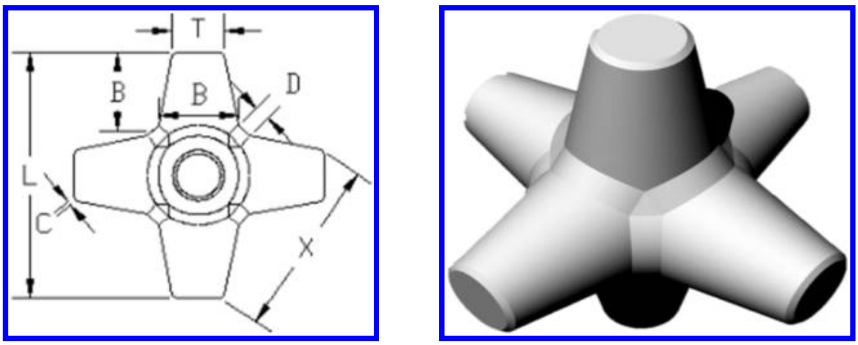
Keywords: Crablock; placement pattern; single layer armor; stability; wave overtopping.

1. Introduction

Generally, coastal structures such as breakwaters are applied for harbors and as similar structures along coasts to protect beaches from the action of waves and currents and to stop siltation in approach channels. Rubble mound breakwaters have often been applied by designers, usually made of rock or concrete armor in double layer systems or in one layer systems. Single layer systems using concrete armor units are being widely used nowadays in the design of coastal protections compared to traditional double layer methods.

A new and symmetrical single layer armor unit, the Crablock, has been designed in the UAE. One breakwater was reconstructed with Crablock after experiencing damage, but very limited testing was performed. After this application, the unit was improved substantially, leading to the shape as given in Fig. 1 and dimensions (prototype) as presented in Table 1. The Crablock unit consists of six symmetrical truncated cones (legs), one for each face of a hypothetical central cube. The geometry of Crablock demonstrates symmetry in the three directions of the development of the block. At present, standard prototype dimensions range from 2.5 ton to 25 ton, see Hendrikse and Heijboer [2014].

Single layer concrete armor units that exist at this moment have design guidelines in terms of placement, stability and overtopping. However, because of lack of laboratory research and the little experience of using Crablock, no design guidance exists yet for this new single layer block compared to other existing one layer units. To design a breakwater with Crablock as one layer system, preliminary guidance on placement of Crablock, stability and wave overtopping is required. This led to



Top view of Crablock Isometric view of Crablock

(a)

Fig. 1. Crablock: A new single layer concrete armor unit.

Table 1. Dimensions of proposed Crablock unit (prototype).

Model	Unit span (mm) L	Arm's base dia (mm) B	Arm's tip dia (mm) B	Arm's length (mm) T	Tip's chamfe R(mm) C	Base's chamfe R(mm) D	X span (mm) X	Volume (cu.m)	Weight (tons)
CB100	1880	599	385	599	34	115	1570	1.0	2.5
CB200	2366	754	484	754	43	145	1977	2.0	5.0
CB300	2712	865	555	865	49	166	2256	3.0	7.5
CB400	2980	950	610	950	54	183	2479	4.0	10.0
CB500	3211	1024	657	1024	58	197	2671	5.0	12.5
CB600	3413	1088	698	1088	62	209	2839	6.0	15.0
CB700	3595	1146	735	1146	65	220	2991	7.0	17.5
CB800	3756	1198	769	1198	68	230	3125	8.0	20.0
CB900	3907	1246	799	1246	71	239	3251	9.0	22.5
CB1000	4049	1291	828	1291	73	248	3369	10.0	25.0

the present investigation which was performed at Delft University of Technology in cooperation with IHE Delft. It has been described in two MSc-theses, Salauddin [2015] and Broere [2015], which forms the basis of this paper.

It is worth mentioning that the symmetrical shape of Crablock makes the unit different from other existing randomly placed single layer units. Therefore, the placement of Crablock armor units is also assumed different compared to other single layer blocks. As the symmetrical shape was a new item, the placement of this unit was investigated first. After the placement tests, physical model tests were performed in a wave flume to come up with stability and wave overtopping results. Furthermore, to determine the interlocking properties of armor units, pull tests were also conducted in this research.

It should be noted that the status of any patent on the Crablock is unclear. There is no worldwide patent, but there might be copy rights in Qatar, Saudi Arabia, UAE, Oman, Bahrain and Kuwait.

2. History of Modern Single Layer Armor Units

The 1950s saw an upsurge interest in developing and using concrete armor for rubble mound breakwaters. Consequently, after the 1950s a large variety of concrete armor units has been invented by various consultants in different countries. As the theme of this research is based on modern single layer concrete armor units, only monolayer systems are discussed in this paper that developed after the failures of the large breakwaters like Sines and Arzeu and that were developed to have very strong interlocking. This first development was the Accropode. The older one layer concrete armor units have been developed as both pattern placed block and randomly oriented blocks, like for example, Cobs, Seabees, Dolos (but mostly applied in two layers), Sheds, Stabits, Hexalegs, Quadripods and others. They will not be treated here.

In the eighties, Sogreah introduced first the randomly placed one layer concrete armor unit, which is known as Accropode [CLI, 2011a]. After the introduction of Accropode, it has been applied on more than 200 breakwaters [CLI, 2011b].

Next to Accropode in the mid 1990s, another randomly oriented one layer concrete armor unit was invented by US Army corps of Engineers [CLI, 2012], the Core-loc. Melby and Turk [1994] argued that Core-loc provides a higher stability with good interlocking and a low cost solution compared to other existing irregularly oriented armor units. However, the Rock Manual [2007] warned that although in comparison to Accropode the hydraulic stability of Core-loc armor unit looks superior, the structural integrity of Core-loc might be lower than the Accropode armor block.

The development of single layer armor units was then followed by the invention of other randomly oriented one layer units, the A-Jack in 1998 by Armortec (although designed as river bank protection), Xbloc in 2003 by Delta Marine Consultants, Accropode II in 2004 by Sogreah, again followed by the Core-loc II in 2006 [Rock Manual, 2007].

Furthermore, in 2005 the Cubipod was developed as one layer with randomly placed units to improve the low hydraulic stability of Cubes, with keeping advantages of high structural strength and easy placement [Gomez-Martin and Medina, 2006].

Recently, the new concrete armor unit Crablock has been invented in UAE and applied as repair in one damaged rubble mound breakwater as monolayer system.

The main reasons behind the popularity of single layer systems are its characteristics like high interlocking, large structural and hydraulic stability and cost efficiency. Van der Meer [1999] suggested that due to high interlocking properties monolayer armor units can better sustain under higher wave-heights compared to conventional double layer armor units. In addition to the stability of structures, a randomly placed one layer armor system provides a better economic solution compared to conventional double layer system by a smaller concrete consumption [Bakker *et al.*, 2003; Muttray *et al.*, 2003; Van Gent *et al.*, 1999]. Furthermore, maintenance in a conventional double layer system may be expected if the design storm is exceeded. One layer systems do not show damage for events exceeding the design conditions and are therefore less vulnerable for maintenance [Muttray and Reedijk, 2009].

Failure of one layer systems show a brittle behavior in contrast to double layer systems [Van der Meer, 1999; Besley and Denechere, 2009; Rock Manual, 2007; Medina and Gómez-Martín, 2012]. This means that the structure is stable to a very high wave-height, but fails quite drastically if a certain wave-height is exceeded. For this reason a safety factor is required between "start of damage" and the design value. The effect is then that wave-heights exceeding the design value still do not show damage, in contrast to double layer systems where a damage curve shows the damage development [Van der Meer, 1999]. But it is very important to establish a correct design value with a safety factor that is large enough. There is of course a tension between a commercially attractive safety factor (a unit with a high design value) and the real safety of the structure [Jensen, 2013]. Furthermore, the use of one layer armor systems might increase the rate of overtopping discharge [Bruce *et al.*, 2009; EurOtop, 2007]. Van Gent *et al.* [1999] mention that various factors like placement pattern, allowable levels of damage and failure systems of armor layers should be treated with care for the application of monolayer systems.

Therefore, it is necessary to understand the behavior of one layer systems in order to use this system properly in the design of rubble mound breakwaters.

3. Technical Background

3.1. *Placement pattern and packing density*

Placement of single layer concrete armor units is difficult and challenging. Moreover, the accuracy and speed of the placement might be affected by harsh conditions during construction and by deep water [Muttray and Reedijk, 2009]. However, to ensure a firm armor cover with good interlocking capacity, the placement of armor blocks has to be precise [Oever, 2006]. The good placement of armor units ensures the stability of single layer armor systems [Muttray *et al.*, 2005]. In addition to hydraulic stability of armor layers, the structural integrity of armor units is also influenced by the placement of single layer armor blocks [Muttray *et al.*, 2005]. To construct a good interlocked armor layer with high hydraulic stability, significant concentration should be paid to the placement of concrete elements. Initial factors governing the placement of Crablock can be determined from a theoretical study, Bonfantini [2014]. This author proposed a first outline for the placement grid of Crablock, being the start of the present research.

Generally, the placement of armor units with random orientation is relatively easier under water compared to strict orientation of units with uniform placement. Nevertheless, it should be noted that some blocks (such as Accropode) get

Rectangular grid

Diamond-Shaped grid

Fig. 2. Uniform placement of Crablock. Note that the units have been placed on a horizontal wooden plate, not on a breakwater slope.

Source: Hendrikse and Heijboer [2014].

their high interlocking by random placement and it is difficult to place them in a regular pattern. The regular placement of armor blocks is esthetically attractive and symmetrical blocks, like Crablock, might be more stable in comparison to random oriented placement. A regular placement on a horizontal plate (just to give two different systems) is shown in Fig. 2. Phelp *et al.* [2012] argued that Crablock armor units with uniform orientations provide compact interlocking between the units. Hendrikse and Heijboer [2014] believed that Crablock armor units can be placed with uniform orientation in both rectangular and diamond shaped grid, see Fig. 2.

Small scale dry placement tests were carried out at the Fluid Mechanics Laboratory of the Faculty of Civil Engineering and Geosciences at Delft University of Technology, Netherlands in cooperation with IHE Delft. The tests were executed with the use of small units.

3.2. *Stability and wave overtopping*

3.2.1. *Stability*

The stability of a breakwater structure is a function between the forcing of the waves and the strength of the structure following from the geometry. The strength of a breakwater armor layer is provided by an interaction between gravity, interlocking, inter-block friction and bottom friction with the underlayer. The contribution of these four mechanisms depends on the shape of the unit, the placement method and packing density. The stability number is usually used to indicate the stability of concrete armor units, which is $H_{sD}/\Delta D_n$, where H_{sD} = the design wave-height, Δ = the relative mass density under water and D_n = the nominal diameter.

3.2.1.1. Damage definition

The stability is related to the starting point of damage and the point of failure. To define damage for rubble mound armor several methods have been used. The most obvious method is based on the extraction of units from the armor layer. The number of units displaced from the structure (extractions) can be expressed as a relative strip displacement. The relative strip displacement N_{od}, is defined as the number of units displaced within a strip of one D_n width, see Eq. (1).

$$N_{\mathrm{od}} = n_d/(B * D_n), \tag{1}$$

where N_d is the number of displaced units from the armor layer, B is the width of breakwater section and D_n is the diameter of the unit.

When settlement and/or movements become too large, the interlocking function between the units can be lost. A damage criterion based on settlement and movements within the armor layer is therefore introduced in the form of a relative settlement method. A threshold level of movement needs to be defined to quantify the exceeding number of units N_{om} and is presented in Eq. (2).

$$N_{\mathrm{om}} = n_m/(B * D_n), \tag{2}$$

where N_m is the number of units that moved or settled exceeding the threshold level.

Although the structural strength of the units cannot be determined from the physical model tests, repeated movements of the units was visually observed and counted. This typical rotational movements are called “rocking”. In reality, rocking can harm the individual units and may lead to damage of the armor layer. Therefore, also a damage criterion for rocking of Crablock units is shown in Eq. (3).

$$N_{\mathrm{or}} = n_r/(B * D_n), \tag{3}$$

where N_r is the number of units that rocked.

3.2.2. *Wave overtopping*

Sea defences to protect coastal flooding, coastal protections to minimize coastal erosion and breakwaters at harbors to ensure safe navigation and mooring of vessels, are often armored with single layer units. Design for allowable overtopping of waves is considered as one of the prime concerns [EurOtop, 2007]. Overtopping of waves mainly occurs due to the low crest height in comparison to wave run-up levels of the largest waves [TAW, 2002]. In that case, the crest freeboard (R_c) is calculated by the difference in elevation between height of the crest and the still water level. In general, wave overtopping is expressed by the term mean overtopping discharge per linear meter of width, q, in terms of m^3/s per m or in l/s per m [EurOtop, 2007].

To be able to use Crablock as a single-layer system on rubble mound breakwaters, preliminary design guidance is also required on wave overtopping over the structure. A limited set of physical model tests was performed on this new armor block by CSIR [2009] in South Africa. However, the wave overtopping discharge Crablock was not measured during those tests. To come up with design guidance on wave overtopping over Crablock slopes, 2D wave flume tests were performed in a wave flume at the Fluid Mechanics Laboratory of Delft University of Technology, Netherlands.

3.2.2.1. Empirical prediction

The general formula [Eq. (4)] used for the estimation of wave overtopping discharge over a coastal structure is [EurOtop, 2007],

$$\frac{q}{\sqrt{\mathrm{g}\mathrm{H}_{\mathrm{m0}}^3}} = \mathrm{a}\exp\left(-b\frac{R_c}{\mathrm{H}_{\mathrm{m0}}}\right). \tag{4}$$

EurOtop [2007] describes empirical equations in detail for the approximation of overtopping over rubble mound slopes. The formulae used in this research are only discussed in short here. Recently, Van der Meer and Bruce [2014] concluded that empirical formulae provided by EurOtop [2007], for breaking waves as well as for non-breaking waves over-estimate wave overtopping for sloping structures with very low or zero crest height. Furthermore, Van der Meer and Bruce [2014] recommended the following formulae [Eqs. (5) and (6)] to predict wave overtopping on slopping structures with zero and positive crest height.

— for breaking waves

$$\frac{q}{\sqrt{\mathrm{gH}_{\mathrm{m0}}^{3}}} = \frac{0.023}{\sqrt{\tan\alpha}} \cdot \gamma_{\mathrm{b}} \cdot \xi_{\mathrm{m-1,0}} \cdot \exp\left[-\left(2.7\frac{R_c}{\xi_{\mathrm{m-1,0}} \cdot \mathrm{H}_{\mathrm{m0}}\gamma_{\mathrm{b}} \cdot \gamma_{\mathrm{f}} \cdot \gamma_{\beta}\gamma_{\mathrm{v}}}\right)^{1.3}\right]. \quad (5)$$

— and for non-breaking waves a maximum value of

$$\frac{q}{\sqrt{\mathrm{gH}_{\mathrm{m0}}^{3}}} = 0.09 \cdot \exp\left[-\left(1.5\frac{R_c}{\mathrm{H}_{\mathrm{m0}} \cdot \gamma_{\mathrm{f}} \cdot \gamma_{\beta}}\right)^{1.3}\right] \quad (6)$$

The term breaking or non-breaking waves relate to the behavior of the waves on the structure slope. Breaking waves are plunging waves and non-breaking waves surge up and down the slope without breaking. Waves at the transition from plunging to surging are called collapsing waves, see also EurOtop [2007]. In the empirical prediction of overtopping, Eq. (5) is applicable for plunging (breaking) waves and Eq. (6) is valid for surging (non-breaking) waves. In reality, waves may also break over the foreshore due to depth limitations. These are often spilling breakers, unless the foreshore is quite steep. Spilling breakers may reach a structure and may then still be quantified as breaking or non-breaking on the structure slope.

4. Placement Tests of Crablocks

4.1. *Test set-up*

To perform small scale dry placement tests a model breakwater was constructed with the use of a rock underlayer, a wooden toe and on a wooden frame. The slope of Crablock armor (wooden frame) has been kept as 1:4/3, similar to Accropode, core-loc and Xbloc in their initial model testing to define design parameters. All the placement tests were carried out with the use of small scale Crablock units in average 0.0637 kg in mass, with 2364 kg/m^3 as mass density and with a nominal diameter of exactly 0.030 m. Two different sizes of underlayer were used to perform the placement tests. Initially, an underlayer of one-tenth of Crablock armor units (0.003–0.009 kg) has been used. But with the use of this relatively large underlayer, a uniform placement of Crablock was hardly reachable. Thus, to get the uniform placement, a relatively smaller underlayer (0.001–0.004 kg) was used to place the armor units, which is about 1/25th of the Crablock weight. Figure 3 gives examples of the test set-up followed for performing the dry placement tests.

Uniform placement using smaller underlayer in a rectangular grid

Random placement using conventional underlayer in a diamond-shaped grid

Fig. 3. Pictures of test set-up for dry placement tests.

4.2. *Testing programme and testing procedure*

Bonfantini [2014] proposed an outline of four placement test series. However, in the present research 14 different test series were performed to observe the placement of Crablock. The reason for choosing 14 different test series instead of four tests by Bonfantini [2014], was to get a good idea about the lower and upper limits of packing density of Crablock armor units. To establish a reliable dataset, each placing method was repeated three times. Thus, in total 42 tests were performed on the placement of Crablock. The first 11 tests were conducted using large underlayer with the mean weight around 1/10th of the armor layer, whereas the last three placement tests were

Table 2. Test programme for dry placement tests.

Test series no.	Placement grid	Designed placement pattern	Underlayer	Designed Hor. placement Dis. (D)	Designed Up. Placement Dis. (D)	Packing density co-efficient, ϕ
1	Rectangular	Uniform	11 to 16 mm	0.71 D	0.57 D	0.71
2	Rectangular	Uniform	11 to 16 mm	0.65 D	0.60 D	0.74
3	Rectangular	Uniform	11 to 16 mm	0.75 D	0.65 D	0.59
4	Rectangular	Uniform	11 to 16 mm	0.80 D	0.60 D	0.60
5	Diamond	Uniform	11 to 16 mm	0.60 D	0.50 D	0.96
6	Diamond	Uniform	11 to 16 mm	0.70 D	0.60 D	0.68
7	Diamond	Uniform	11 to 16 mm	0.80 D	0.65 D	0.55
8	Rectangular	Random	11 to 16 mm	0.71 D	0.57 D	0.71
9	Rectangular	Random	11 to 16 mm	0.65 D	0.60 D	0.74
10	Rectangular	Random	11 to 16 mm	0.75 D	0.65 D	0.59
11	Diamond	Random	11 to 16 mm	0.70 D	0.60 D	0.68
12	Rectangular	Uniform	7 to 11 mm	0.71 D	0.57 D	0.71
13	Rectangular	Uniform	7 to 11 mm	0.65 D	0.60 D	0.74
14	Rectangular	Uniform	7 to 11 mm	0.75 D	0.65 D	0.59

performed with the use of small underlayer material with the mean weight around 1/25th of the armor weight, see Table 2.

It is noted that all the placement tests were carried out without water. Prior to the start of the placing test, underlayer material was placed on top of the slope of the frame. Then, Crablock units were placed as single layer armor according to the designed placing grid. It is worth mentioning that all the units were placed only by hand. At first, the armor units in the first row were positioned by pointing Crablock units in the designed grid position. Afterward, the units were set in the higher upslope based on the designed placement pattern and placing grid. Photographs were captured after placement of the armor units in order to describe the placement of the Crablock visually. The grid coordinates of each individual armor unit in case of both horizontal and upslope direction were measured by using a linear scale.

In which, D is the Height of Crablock unit, ϕ is the Packing density coefficient = Packing density $XD_n{}^2$ and D_n is the nominal diameter of Crablock.

5. Wave Flume Tests

2D flume tests at small scale were carried out at the Fluid Mechanics Laboratory of the Faculty of Civil Engineering and Geosciences at Delft University of Technology, Netherlands, in cooperation with IHE Delft. All tests were executed with the use of small Crablock units with an average mass of 63.7 g.

5.1. *Model set-up*

The model set-up was established by considering the small scale set-up of Accropode [Van der Meer, 1987], the set-up of Xbloc [DMC, 2003] and the set-up of Bruce *et al.* [2009] for rubble mound breakwaters with various types of armor units. The designed model rubble mound breakwater consisted of single layer Crablock armor, an underlayer, core, a toe structure and a crest wall, see Fig. 4. In this experimental research, the slope of the Crablock armor was kept at 1:4/3 similar to Accropode, Core-loc and Xbloc. A crest height of 1.2 times of design wave-height (H_{sD}) was chosen to allow for some overtopping under design conditions. This design significant wave-height has a stability number around 2.8. This clearly indicates that

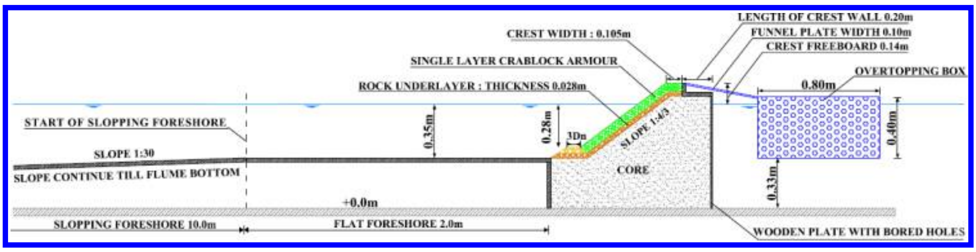


Fig. 4. Cross-section of breakwater with crest height $1.2 \times H_{sD}$; tests 1–8.

wave overtopping over the crest of breakwater will be a lot more for significant wave-heights beyond the design significant wave-height. However, to investigate the influence of the crest height on hydraulic stability and overtopping, a crest height of 1.6X design wave-height (H_{sD}) was also tested, by rebuilding the cross-section. Note that such a crest height may be outside or at the edge of a real breakwater design.

To resemble a sea bathymetry, a foreshore of 1:30 was constructed on the bottom of the flume. The length of the sloping foreshore was 10 m, which gives a depth at the artificial bottom that is 0.33 m less than at the deeper part of the flume. Moreover, a horizontal foreshore of 2 m was considered in front of the structure toe in order to put wave gauges to measure wave-heights at this structure toe.

The design stability number governs the design of the geometry of the cross-section and the test programme [Bruce *et al.*, 2009]. To design the geometry for the tests on Crablock, a stability number of 2.8 was chosen, comparable with Xbloc, Core-loc and Accropode. The design wave-height can then be estimated from the known stability number:

$$\text{Stability number} = H_{sD}/\Delta D_n = 2.8.$$

H_{sD} = Design significant wave-height; Δ = relative mass density = 1.36 and $D_n = 0.030$ m. This gives a design wave-height of $H_{sD} = 0.114$ m.

The water depth at the structure was 0.35 m, that means approximately three times the design wave-height. In order to have water at a depth of 0.35 m at the structure, the water depth at the wave paddle was set at 0.68 m. For most of the tests (test series 1–8), the water depth on top of the toe was 0.28 m, giving a ratio of 0.80 between water depth on top of the toe and in front of the toe.

5.2. *Wave generation and measurements*

The 2D wave flume has a length of approximately 45 m, a width of 0.80 m and a depth of 1.0 m. The theoretical maximum water depth is restricted to 0.90 m to prevent the waves overtopping over the sidewalls of the flume. The sidewalls of the flume are made of glass. A wave generator is available to generate random waves. Furthermore, an active reflection compensation system has been equipped with the wave generator to compensate for reflected waves from the structure. The wave reflection compensation ensures the generation of the desired waves in the flume without the effect of re-reflection at the wave board.

Wave-heights were measured with the use of wave gauges along the flume. Eight wave gauges were used in the wave flume tests. One set with three gauges (numbers 4, 5 and 6) was positioned at the horizontal foreshore of 2 m, close to the structure, in order to determine the incident wave-heights at the structure. The position of wave gauges was determined regarding to the three-wave gauge approach described by Mansard and Funke [1980]. This allows dividing the reflected and incoming waves with the use of the least square method. Furthermore, in order to measure the wave-heights at deep water, another group of three wave gauges (numbers 1, 2 and 3) have been placed far from the structure at a water depth of 0.68 m. One wave gauge was placed at the crest of the breakwater (number 7) to measure the number of overtopping waves. In order to measure the water level in the overtopping box, one water level gauge (number 8) was placed in the overtopping box.

5.3. *Test programme and procedure*

Regarding the literature, the important parameters governing the geometrical design of breakwaters were found to be placement pattern, packing density, crest height and wave steepness in terms of wave-height and wave length [Bonfantini, 2014]. The placing grid, orientation of units and packing density were selected mainly based on the results of the dry placement tests. With considering the important design parameters, laboratory facility and available time for testing, in total 10 test series were performed on stability and wave overtopping of the Crablock armor slope. Moreover, two test series were executed for comparison with wave overtopping, using a smooth (wooden) slope of 1 in 4/3. Also, two test series (tests 13 and 14) were performed without the presence of a structure in order to determine the incident wave-heights in front of the structure, without reflection from the structure in place.

The following two wave steepnesses have been used: $s_{m-1,0} = 0.02$ and 0.04 at deep water, see Table 3. The spectral period $T_{m-1,0}$ was used to calculate the wave steepness as well as the "deep water wavelength": $s_{m-1,0} = 2\pi H_s/(gT_{m-1,0}{}^2)$. One of the major differences of this experimental research with the set-up by Bruce *et al.* [2009] is that in this research a sloping foreshore was used in front of the structure instead of a horizontal foreshore. Due to the sloping foreshore and limited water depth, a spectral wave steepness $s_{m-1,0}$ higher than 0.04 could not be obtained in this experimental research, which was caused by wave breaking. Therefore, the higher wave steepness for this small-scale test has been fixed to $s_{m-1,0} = 0.04$. All tests were performed with increasing wave-heights to examine the behavior of the armor layer and wave overtopping. The maximum significant wave-height assumed for this experimental investigation was 0.20 m at the toe of the structure and 0.25 m at deep water; the design wave-height with a stability number of 2.8 corresponds to 0.114 m. The significant wave-height (H_{m0}) for a test series started with a low significant wave-height of 0.07 m, which continued to increase in each consecutive test till the maximum wave-height of 0.25 m at deep water. The wave periods together with the wave-heights and the wave steepness are presented in Table 4.

Each test consisted of a sequence of approximately 1000 irregular waves of a JONSWAP spectrum with peak enhancement factor, $\gamma = 3.3$. At the start of each test, the wave flume was filled up to the required water level. Then before taking any reading, wave gauges have been fixed according to the designed position and calibrated to avoid error in measurements of wave-heights. To capture the position

Table 3. Test programme for the small scale physical model tests in the wave flume.

Test series no.	Placement grid	Designed placement pattern	Underlayer	Designed Hor. placement dis. (D)	Designed up. placement dis. (D)	Packing density co-efficient, ϕ	Crest freeboard (m)	Deep water wave steepness, $s_{m-1,0}$	Water depth near structure (m)
1	Rectangular	Uniform	7 to 11 mm	0.65 D	0.64 D	0.69	0.140	0.04	0.35
2	Rectangular	Uniform	7 to 11 mm	0.65 D	0.64 D	0.69	0.140	0.02	0.35
3	Diamond	Uniform	11 to 16 mm	0.75 D	0.61 D	0.63	0.140	0.04	0.35
4	Diamond	Uniform	11 to 16 mm	0.75 D	0.61 D	0.63	0.140	0.02	0.35
5	Rectangular	Uniform	7 to 11 mm	0.68 D	0.64 D	0.66	0.140	0.04	0.35
6	Rectangular	Uniform	7 to 11 mm	0.68 D	0.64 D	0.66	0.140	0.02	0.35
7	Rectangular	Uniform	7 to 11 mm	0.71 D	0.64 D	0.63	0.140	0.04	0.35
8	Rectangular	Uniform	7 to 11 mm	0.71 D	0.64 D	0.63	0.140	0.02	0.35
9	Rectangular	Uniform	7 to 11 mm	0.68 D	0.64 D	0.66	0.185	0.04	0.35
10	Rectangular	Uniform	7 to 11 mm	0.68 D	0.64 D	0.66	0.185	0.02	0.35
11	Smooth 1:4/3 slope						0.185	0.04	0.35
12	Smooth 1:4/3 slope						0.185	0.02	0.35
13	Tests without structure						......	0.04	......
14	Tests without structure						......	0.02	......

Table 4. Input wave conditions.

	$T_{m-1,0}$[s]						
$s_{m-1,0}$[-]\H_{m0}[m]	0.07	0.10	0.13	0.16	0.19	0.22	0.25
0.02	1.57	1.88	2.14	2.38	2.59	2.79	2.97
0.04	1.13	1.3	1.45	1.59	1.72	1.84	1.95

of armor units in their initial condition and after a test, photographs were taken before the start and after each test. A video recorder was set up at a fixed position to capture the wave attack on the structure and the behavior of the armor layer during each test run.

Then waves have been generated based on the test wave conditions. The test started with a low wave-height in order to cause the first small settlements and to protect the armor layer from sudden failure. In each test, wave-heights and periods were increased until failure of the armor slope. Once the armor slope or underlayer was damaged due to waves, the armor layer were reconstructed for the next test series. At the end of every step, the water level in the overtopping box was determined to measure the volume of overtopping waves. It should be noted that the number of waves overtopping the structure was calculated from the record of the wave gauge placed at the crest of the breakwater. Photographs were captured at the end of each test. The test set-up and procedure for the 2D wave flume tests on Crablock has been reported more in depth by Salauddin [2015].

6. Pull Tests

6.1. *Model set-up*

To determine the interlocking properties, pull tests have been introduced. The level of interlocking is defined as the interlocking degree. This is the ratio between the extraction force and the individual weight of the unit. The extraction force was measured just after placement of the armor in dry conditions and after exposure of

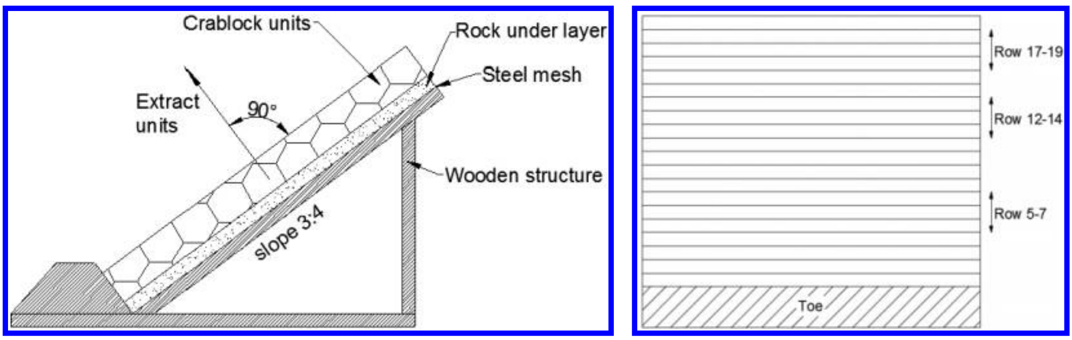


Fig. 5. Test set up of pull tests.

waves in the flume. The pull tests after the flume test on hydraulic stability have been performed to determine the influence of settlement on the interlocking degree. The maximum force needed for the extraction has been used for the interlocking degree. To secure the extraction perpendicular from the slope, a frame was used. For the tests in dry conditions the cross-section presented in Fig. 5 was applied.

6.2. *Testing procedure*

The pull tests, provide extra information to clarify the behavior of the Crablock units. To make a comparison between an armor with and without settlement, it is important to use the same configurations in the dry tests as used by the flume tests. Not all flume tests on hydraulic stability have been used for the pull tests. The Crablock units were extracted from several heights on the slope. This was performed to investigate the influence of the additional weight of the units above the interlocking. At each height on the slope, multiple units were extracted to improve the accuracy. See Broere [2015] for the full description of the procedure.

7. Results and Discussions

7.1. *Placement tests*

7.1.1. *Visual observation and experience of placing*

The placement pattern and the general accuracy of the placement of the armor layer has first been analyzed by visual inspection of the armor units. A summary of the results is given in Table 5.

To scrutinize the placement pattern of Crablock in a rectangular grid, tests 1, 8 and 12 were compared. All the three tests were performed with the same designed horizontal and upslope placement distance. However, it was observed that the small underlayer (test 12) certainly provided a better uniform placement in comparison to a conventional underlayer (test 1) in a similarly designed rectangular grid. It was noticed that a uniform pattern (tests 1 and 12) looked more interlocked compared to a random pattern (test 8). Furthermore, from Table 4 it can be concluded that a pre-defined uniform placement pattern could not be achieved for all cases. Also, a lot of loose units were observed for some tests, which is not allowable in a real situation.

7.1.2. *Measurements on accuracy of placement*

The accuracy of the placement can be analyzed by determining the average deviations of units from the designed grid position. The accuracy of the placement varied with different grids and with different orientation of units. Based on the measured position of the units, the deviation of each individual unit was determined. The average deviation of units has been determined for all the placement test series.

Table 5. Overview of the results of visual inspection in all test series.

Test series no.	Placement grid	Underlayer	Designed hor. placement dis. (D)	Designed up. placement dis. (D)	Designed placement pattern	Obtained placement pattern	Observation
1	Rectangular	11 to 16 mm	0.71 D	0.57 D	Uniform	Not 100% uniform	Interlocked
2	Rectangular	11 to 16 mm	0.65 D	0.60 D	Uniform	Not 100% uniform	Good interlocked
3	Rectangular	11 to 16 mm	0.75 D	0.65 D	Uniform	Not 100% uniform	Loose units
4	Rectangular	11 to 16 mm	0.80 D	0.60 D	Uniform	Not 100% uniform	Lot of loose units
5	Diamond	11 to 16 mm	0.60 D	0.50 D	Uniform	Random	Lot of loose units
6	Diamond	11 to 16 mm	0.70 D	0.60 D	Uniform	Random	Interlocked
7	Diamond	11 to 16 mm	0.80 D	0.65 D	Uniform	Random	Lot of loose units
8	Rectangular	11 to 16 mm	0.71 D	0.57 D	Random	Random	Interlocked
9	Rectangular	11 to 16 mm	0.65 D	0.60 D	Random	Random	Interlocked but too narrow
10	Rectangular	11 to 16 mm	0.75 D	0.65 D	Random	Random	Loose units
11	Diamond	11 to 16 mm	0.70 D	0.60 D	Random	Random	Good interlocked
12	Rectangular	7 to 11 mm	0.71 D	0.57 D	Uniform	Uniform	Interlocked
13	Rectangular	7 to 11 mm	0.65 D	0.60 D	Uniform	Uniform	Good interlocked
14	Rectangular	7 to 11 mm	0.75 D	0.65 D	Uniform	Uniform	Loose units

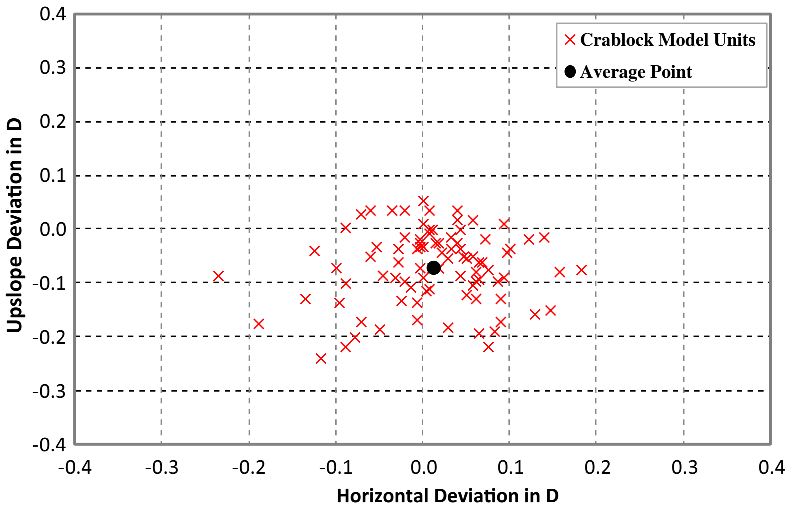


Fig. 6. Deviation of units from their intended position (Test 13).

For placement test series 13 (observation: good interlocking), the deviation of each individual unit from the designed placement grid is shown in Fig. 6 as an example. Figure 6 shows that the average horizontal deviation of the units amounted to 0.01 D and the average upslope deviation of the units to −0.07 D, where deviations to the right and upward have been defined as positive. In this test, relatively small deviations of units have been observed, which indicates that this designed grid is also applicable in prototype situation.

7.1.3. *Packing density*

The average packing density for each test was determined by calculating the mean of the local packing densities of each unit regarding the calculated horizontal and upslope placement distance for each specific unit. The measured horizontal and upslope placement distances diverged from the theoretically predicted value.

Figure 7 shows a comparison between the nominal packing density as designed and the measured one in each individual test series. The test results show that in both the diamond-shaped and rectangular grid, the measured packing density was lower for the randomly oriented armor in comparison to uniformly oriented Crablock armor. Moreover, from the test results it can be concluded that a lower packing density of Crablock was obtained with the use of a diamond-shaped grid. It can also be concluded that the upslope placement distance is often around 0.63 D.

The rogue point of 0.96 (designed packing density coefficient), indicates that for Test 5, model Crablock units were not possible to place uniformly according to the specific designed grid. The theoretically designed grid with recommended placement distances was very small to place the units in position. From the visual inspection, it was noticed that some of the units were not entirely interacted with other units.

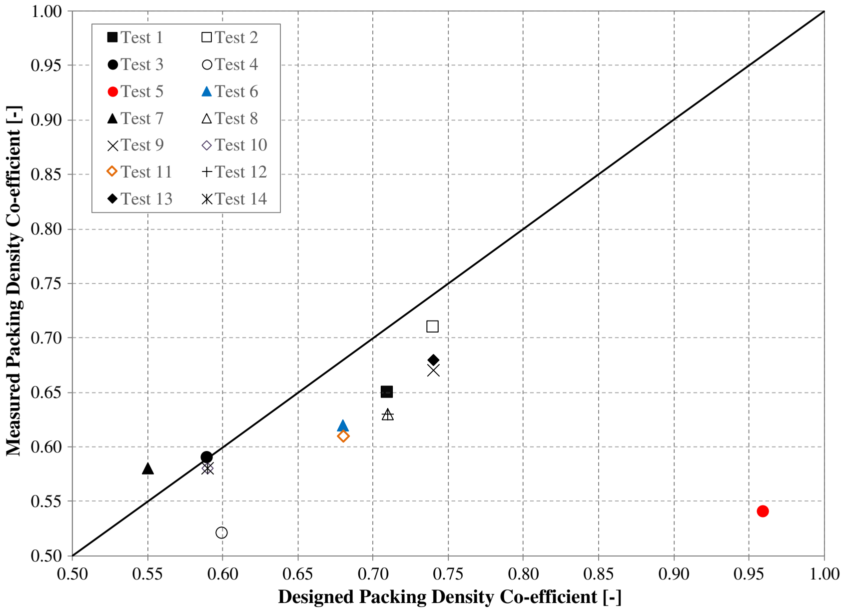


Fig. 7. Designed nominal packing density co-efficient against measured nominal packing density co-efficient.

Moreover, most of the units displaced from their planned grid position with loosing the diamond pattern, see details in Salauddin [2015].

From the above results and discussions, it can be concluded that it is possible to obtain a good interlocked uniform pattern of Crablock armor units with a packing density coefficient of 0.68 on the condition that a relatively small underlayer has to be used. In a diamond-shaped grid, the randomly oriented Crablock units ensure a good interlocked armor with a packing density co-efficient of 0.61. The theoretically designed diamond-shaped grid with uniform placement pattern was hardly possible using a conventional rock underlayer and without fixation of the first row.

7.2. *Wave flume tests*

7.2.1. *Stability*

7.2.1.1. Damage based on displacements

The stability limits for the Crablock may be linked to the stability number, and are given by low or zero values of the relative number of Crablock displaced (extracted) units N_{od}. In all cases, the structure was stable to a very high wave-height, exceeding the set design wave-height by far. Note that start of damage in Fig. 8 never started for a stability number smaller than 2.8. The wave-height in the stability number is given as the average of the highest one-third of the waves ($H_s = H_{1/3}$) and not as the spectral wave-height H_{m0}.

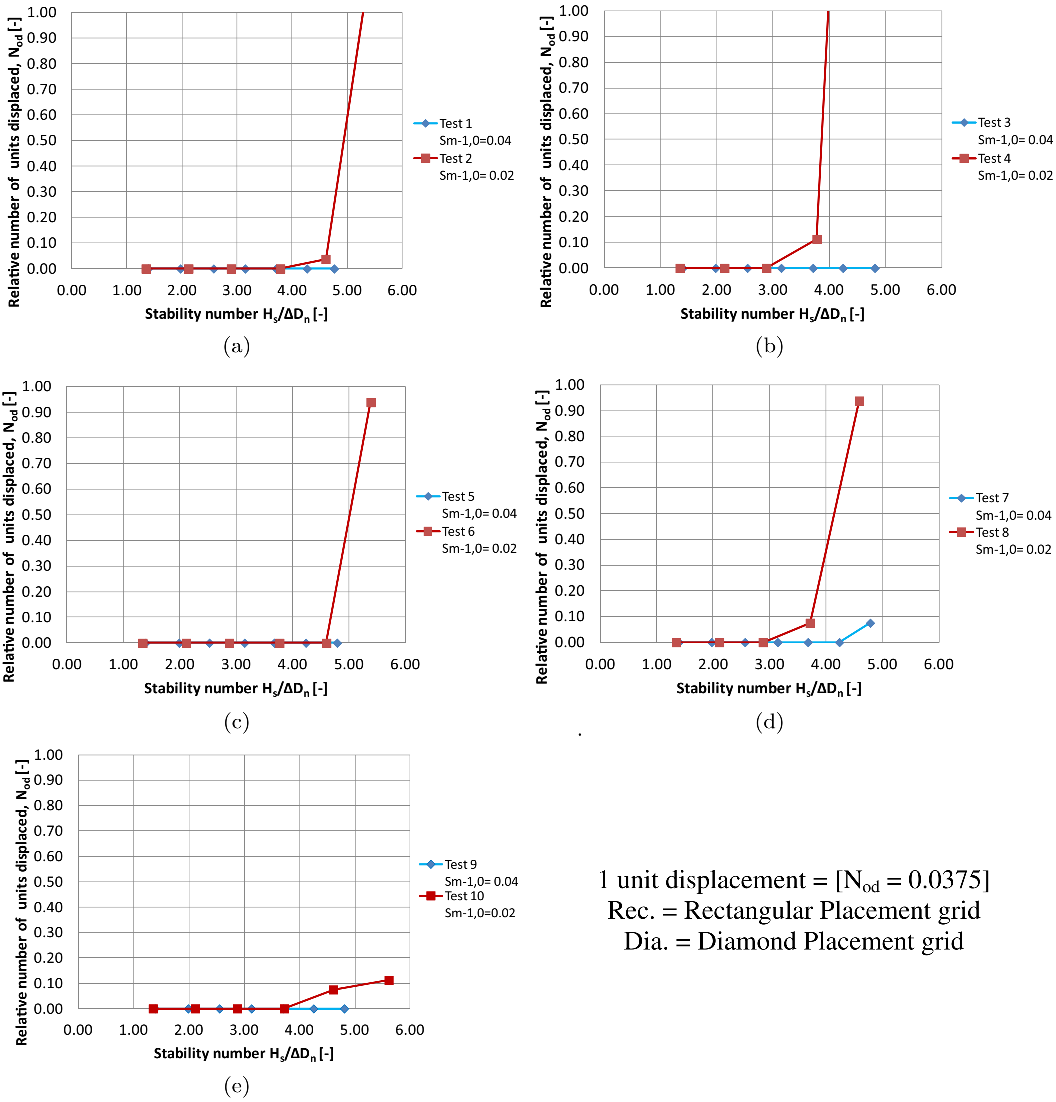


Fig. 8. N_{od} versus stability number $(H_s/\Delta D_n)$ for all tests- (a) Rec. grid with $\phi = 0.69$, (b) Dia. grid with $\phi = 0.63$, (c) Rec. grid with $\phi = 0.66$; (d) Rec. grid with $\phi = 0.63$ and (e) $\phi = 0.66$ with higher crest freeboard $(R_c = 0.185)$.

For the tests with the highest wave steepness $s_{m-1,0} = 0.04$ only slight damage was obtained during the physical model tests performed with a packing density coefficient of $\phi = 0.63$ and a rectangular grid, see Fig. 8. The long waves with a lower wave steepness caused damage (extracted units) to the armor layer for all tests, but of course only for very large wave-heights. The higher crest level experienced the most severe wave attack on the armor slope, while for the normal crest level the highest waves attacked the armor at the transition from slope to horizontal crest. Settlements caused openings between the units on the upper slope and at the horizontal crest, which resulted in the weakest point of the armor layer. The heavy wave attack at the lowest crest level is therefore focussed on the most vulnerable part. This might explain the lower number of displacements found for the higher crest level with $\phi = 0.66$.

7.2.1.2. Damage by displacement

Individual displacements of units were determined by comparing photographs before and after testing and measuring the distance moved or displaced. When concerning a threshold level of displacement within the armor layer $> 0.75D_n$, the tests series conducted with packing density coefficient of 0.63 showed very large movements in an early stage (settlement within the layer, mainly at the upper part). The settlements larger than $0.75D_n$ started around a stability number of 2 for the diamond grid and around stability number of 3 for rectangular grid.

The influence of the crest level on settlement is considerable for the packing density coefficient of 0.66 and the tests with a high crest level resulted in larger settlements. For both steepnesses, the displacements for the normal crest level started around a stability number of 4. Although only this packing density was tested for different crest levels, it might be expected that there is some influence on other packing densities as well. The armor layer executed with a $\phi = 0.69$ did not show any displacement above the chosen threshold levels at all. Note that in all tests there were 22 rows of Crablock units, which in reality for other single layer units like Accropode and Xbloc is considered as an absolute maximum. For more detailed information see Broere [2015].

7.2.1.3. Damage by rocking

Rocking was obtained by visual inspection during testing. For the rocking behavior of Crablock, a criterion of $N_{\text{or}} = 0.2$ was used to eliminate inaccurate placing of the individual armor units. This criterion represents rocking of about five units. The armor layer executed with a packing density coefficient of $\phi = 0.69$ complied this criterion for a stability number of approximately 4. Looking at $\phi = 0.66$, the rocking criterion was exceeded around a stability number of about 3 for both crest levels. In the tests performed with a packing density coefficient of 0.63, rocking was observed from a stability number of 2. So, packing density has a significant influence on rocking of units. The progression of rocking movements against stability number is described in detail by Broere [2015].

7.2.1.4. Excluding packing density coefficient of 0.63

When only considering damage by displacements/extractions, the results obtained from a packing density coefficient of 0.63 were acceptable according to Fig. 8.

Considering the settlement and rocking of the armor layer, a packing density coefficient of 0.63 performed badly. Large settlements and considerable rocking started already during low stability numbers. Next to this, the settlements resulted in some very loose packed units which rolled over the underlayer. Although the units are robust, rolling of units cannot be accepted in reality in order to prevent possible damage to the unit. A packing density coefficient of 0.63 is therefore considered as too loose and was not considered in further analysis. Since the maximum ϕ achievable for the diamond placement grid is 0.63, this placement is considered as not applicable for Crablock armor units.

7.2.1.5. Design stability number

Regarding the results of the analysis on hydraulic stability, start of damage by displacements occurred from a stability number of 4.6, see Fig. 8 for packing density coefficient of $\phi = 0.66$ and $\phi = 0.69$. The wave steepness of 0.04 did not show any damage at all up to the largest possible wave-height with a stability number of 4.8. The lower wave steepness of 0.02 gave two times start of damage at a stability number of 4.6 and once (leading also to large damage) at 5.4. The average value for start of damage becomes then 5.0. The wave-height is then more than 75% larger than the assumed design wave-height.

The settlement of the units with a threshold level set on $> 0.75D_n$ started for the higher crest level to become considerable from a stability number of 4.0. For the lower crest level, the units did not exceed this threshold level during the whole test series. Applying a criterion of $N_{\text{or}} = 0.2$ for rocking, the armor layer executed with a packing density coefficient of 0.69 complied with this criterion for a stability number of approximately 4.0. However, looking at a packing density coefficient of 0.66 the rocking criterion was exceeded around a stability number of about 3.0 for both crest levels.

Single layer units show a brittle failure: up to a large wave-height there is no damage, but if for this very large wave-height damage occurs, it is also close to complete failure. For this reason, a significant safety factor is required to come to a design value. If no damage occurred during the first 1000 waves, it was assumed that more waves were not able to cause significantly more damage. The no-damage criterion is therefore independent of the number of waves.

For Accropode [Van der Meer, 1987], the design stability number was based on a safety factor of 1.5 on the stability number. The average start of damage occurred there for a stability number of 3.7, leading to a design stability number of 2.5 for Accropode, which was accepted by CLI/Sogreah at that time as a design value. Accropode II and Core-locs are a little more stable, which resulted in a design stability number of 2.8. This was also used to design the geometry of the cross-section for the model tests on Crablock. For Xbloc, a safety factor of 1.25 has been chosen, also leading to a design stability number of 2.8.

The stability results on Crablock are better than on Accropode or Xbloc. A safety factor on the average start of damage would give a design stability number of 3.3, significantly higher than for the other known single layer units. However, a stability number of about 3 is also the point where the criteria on rocking ($N_{\text{or}} = 0.2$) was exceeded. The margin between the design stability number and start of rocking is not known for Accropode but for Xbloc a value of 1.1 is applied [DMC, 2003]. This margin of 1.1 may also be applied on Crablock with respect to exceedance of the rocking criteria. A very conservative design value of the stability number is 2.8 and is thereby equal as assumed when preparing the model set-up and is equal to the other single layer units. A less conservative design stability number, but still with a safety factor of 1.5, is a value up to 3.3.

When taking a higher stability number one should realize that the criteria on rocking has to be less strict. This leads to a first approximation for stability as in Eq. (7). More research is required to come to a final design value.

$$\text{Design stability number} = H_{sD}/\Delta D_n = \text{minimum 2.8, maximum 3.3} \qquad (7)$$

7.2.2. *Overtopping*

The mean wave overtopping rate and overtopping percentages over a Crablock armor slope were measured for each test series. In all cases, the incident wave-height at the toe of the structure was considered, where the wave-height was based on the spectrum (H_{m0}), as this is the wave-height that is used in overtopping estimations [EurOtop, 2007].

7.2.2.1. Relative wave overtopping discharges

The resulting relative wave overtopping discharge $q/\sqrt{gH_{m0}^3}$ as a function of the relative crest freeboard (R_c/H_{m0}) is presented in Fig. 9. The graph shows that test series with irregular placement of Crablock result in almost the same overtopping as the other test series with regular placement of Crablock units, for the same wave steepness. To give an example, the comparison of measured wave overtopping in test series 1, 3, 5 and 7 (same wave period) demonstrates that regular placement (test 3) hardly has any influence on overtopping; see Fig. 9. Furthermore, for the tests with the same wave steepness overtopping results did not vary much between the different test series, with the change in packing density, see again Fig. 9. For instance, test series 1, 5 and 7 were performed with a uniform placement pattern with the same configuration, but with a different packing density of armor layer. Based on the test results, it can be concluded that the variation in packing density did not really change the overtopping behavior of these test series.

Figure 10 presents the comparison between the measured dimensionless overtopping discharges over Crablock from the flume tests versus the predictions by the new empirical formula from Van der Meer and Bruce [2014]. Besides an empirical prediction with an assumed roughness factor of $\gamma_f = 0.45$, the reference line for a smooth

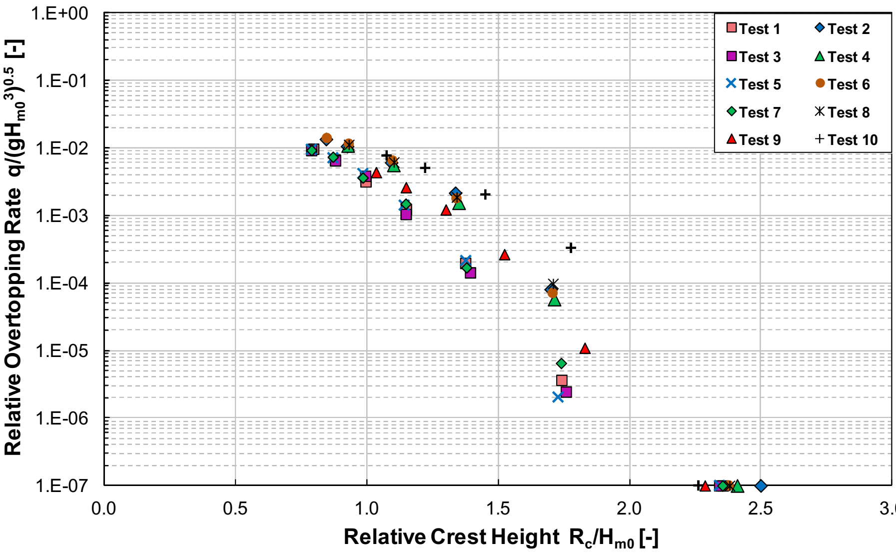


Fig. 9. Relative overtopping discharge as a function of relative freeboard.

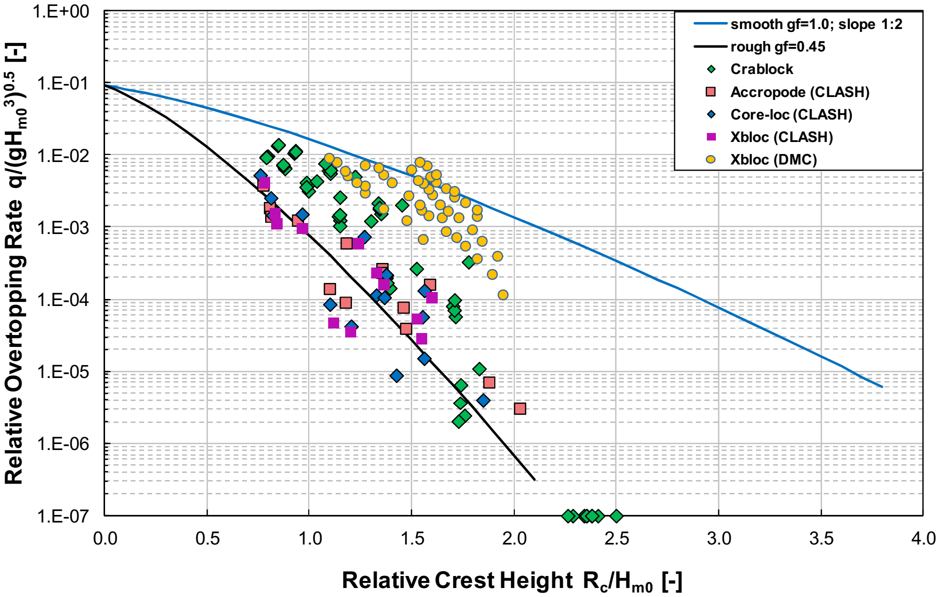


Fig. 10. Test results compared to empirical prediction and other monolayer units.

slope has been drawn with $\gamma_f = 1.0$. Figure 10 also compares the test results with other single layer units extracted from the CLASH [2004] results described by Bruce *et al.* [2009] and from 2D model tests on Xbloc by DMC [2003]. Based on Fig. 10, it is also observed that in almost all the cases the empirical formula ($\gamma_f = 0.45$) underestimates the wave overtopping discharge over Crablock slopes, compared to the test measurements. Also, for high waves the overtopping over Crablock is somewhat larger in comparison to the overtopping over other single layer units, like Accropode, Core-loc and Xbloc [CLASH, 2004]. However, a completely different scenario is observed in case of Xbloc measurements by DMC [2003]. From Fig. 10, it is recognized that overtopping over Xbloc by DMC [2003] is significantly higher compared to the empirical line of rough armor, Bruce *et al.* [2009] and Crablock.

7.2.2.2. Percentage of wave overtopping

Figure 11 shows the measured percentage of overtopping waves with respect to a dimensionless crest height. In this research, the nominal diameter (D_n) of the Crablock was constant, thus the percentage of overtopping waves varied with the significant wave-height (H_{m0}) at the toe and the armor freeboard (A_c). The resulting graph clearly shows that the percentage of overtopping waves increases with the increase of significant wave-height at the toe of breakwater, while it decreases with the increase of crest freeboard. The test results showed that in general the percentage of waves overtopping the structure were a bit higher for longer wave periods than for high wave steepness. For example, from Fig. 11 it is seen that tests with a wave steepness of $s_{m-1,0} = 0.02$ gave higher percentages of overtopping waves compared to the tests with a wave steepness of $s_{m-1,0} = 0.04$.

In Fig. 12, the percentage of waves overtopped over the Crablock armor slope in different test series is compared with the results of CLASH [2004] described by Bruce *et al.* [2009], Xbloc [DMC, 2003] and with the prediction by the empirical formula from EurOtop [2007]. From the resulting graph, it can be concluded that for smaller waves the test results are almost within the range of CLASH [2004], more specifically Bruce *et al.* [2009]. It should be noted that the CLASH [2004] data contained a maximum percentage of overtopping around 30% [EurOtop, 2007]. Therefore, the

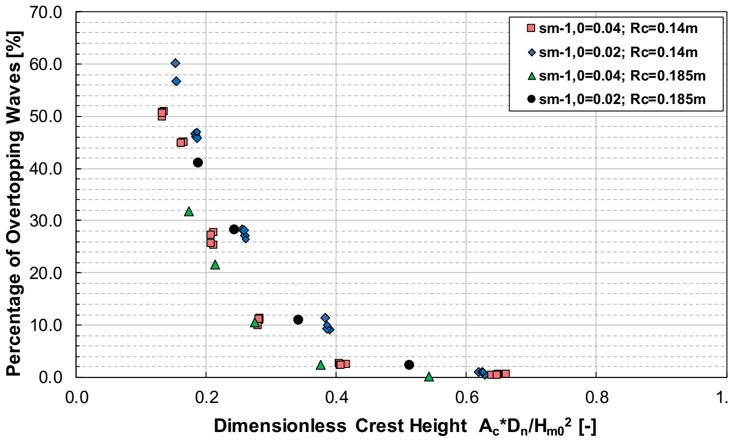


Fig. 11. Percentage of wave overtopping as a function of dimensionless crest freeboard.

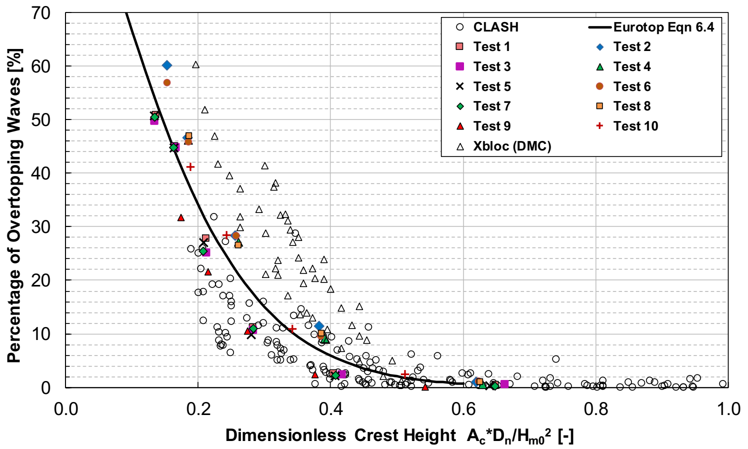


Fig. 12. Test results on percentage of overtopping compared to empirical prediction and other single layer units.

test results on overtopping percentages for higher waves which exceeds 30% are out of the CLASH [2004] range and cannot be compared. Based on Fig. 12, it is also observed that in comparison to long waves. EurOtop [2007] predicts the percentage of overtopping for short waves well. For example, for tests 2, 4, 6 and 8 (long wave period) EurOtop [2007] underestimates the percentage of overtopping to some extent, while the results of tests 1, 3 and 5 (short wave period) are almost on top of EurOtop line.

However, similar to the relative overtopping rate in Figs. 10 and 12 shows that the overtopping percentage over Xbloc by DMC [2003] is also much higher compared to the empirical prediction by EurOtop [2007], results of CLASH [2004], described by Bruce *et al.* [2009] and test results of the Crablock.

The difference in results between the measured overtopping over Crablock units, specific CLASH [2004] data on other concrete units and the empirical predictions might be due to the following reasons:

- CLASH [2004] data described by Bruce *et al.* [2009] are based on 2D experiments which were performed with three wave steepnesses $s_{\mathrm{op}} = 0.02; 0.035$ and 0.05. In the present study, tests were carried out by using two constant wave steepnesses $s_{m-1,0} = 0.02$ and 0.04 ($s_{\mathrm{op}} = 0.015$ and 0.035). This means that all the tests with low wave steepness $s_{\mathrm{op}} = 0.015$ were just outside the range of Bruce *et al.* [2009], which mainly gave higher overtopping compared to those results. For very low steepness, there seems to be a trend that a longer wave period gives substantially more overtopping. But this observation should be combined with the remarks on H_{m0} and $H_{1/3}$ below before a firm conclusion can be made.
- All the experiments in the CLASH [2004] project described by Bruce *et al.* [2009] were performed on a relatively simple standard cross-section without any sloping foreshore in front of the model and with relatively deep water (0.7 m). However,

a sloping foreshore of 10 m in length with a uniform slope of 1:30 was used in this research. The 1:30 slope changed the shape of the waves and the waves at the structure toe showed a clear increase in velocity (eye observation) of the wave crest (near or at breaking). This might also have been the case for the Xbloc research [DMC, 2003], where also a 1:30 foreshore slope was applied.

- It is worth pointing out that all the empirical formulae on overtopping are based on the spectral significant wave-height H_{m0} at the structure. As presented in Fig. 10, the dimensionless wave overtopping for CLASH [2004], Xbloc by DMC [2003] and test results on Crablock are also based on H_{m0} at the toe of the structure. However, in the present research it was observed that for the higher wave-heights with a long period H_{m0} at the structure considerably differed from $H_{1/3}$ at the structure, see details in Salauddin [2015]. The maximum $H_{1/3}/H_{m0}$-ratio for the low steepness become 1.29, which is a very large value. For the higher steepness, the maximum ratio was 1.10. Note that this was not the case for the data from Bruce *et al.* [2009] as it was performed in relatively deep water with respectively short wave periods. Therefore, the use of H_{m0} instead of $H_{1/3}$ also played a role for the difference between Crablock with earlier research and empirical prediction in the above figures. To observe the influence of $H_{1/3}$, Fig. 11 is re-plotted with the use of $H_{1/3}$ instead of H_{m0}, see Fig. 13. Based on a comparison of Figs. 11 and 13 it can be concluded that by using $H_{1/3}$ the variation between Bruce *et al.* [2009] and Crablock is considerably reduced. Also, the test results of Crablock units performed with two different wave steepnesses have now become much closer to each other. It should be noted that $H_{1/3}$ in the following graph is used only for the comparison, all other analysis of overtopping is performed with H_{m0} at the

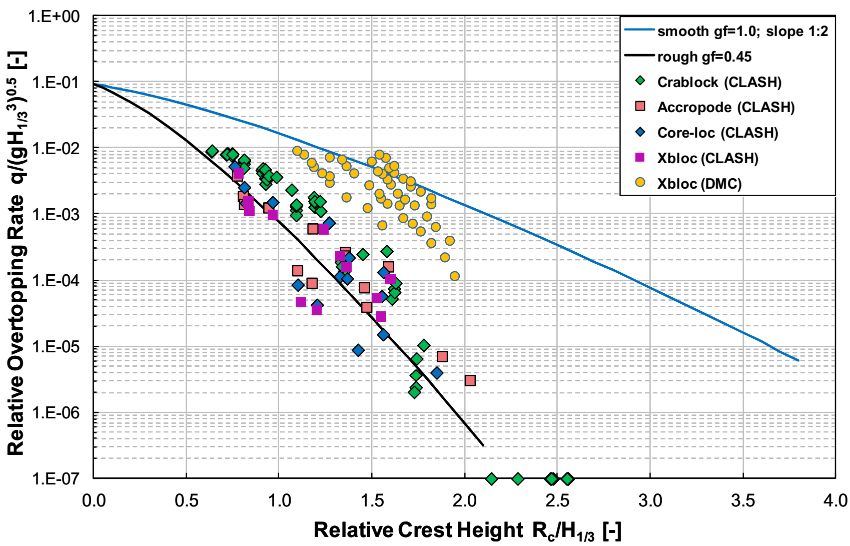


Fig. 13. Test results compared to empirical prediction and other monolayer units (using $H_{1/3}$).

structure. But above results may raise the question whether using H_{m0} instead of $H_{1/3}$ in overtopping prediction formulae, is a good one.

7.2.3. *Pull tests*

For a packing density coefficient of 0.63 the results show (Fig. 14) an increase in interlocking degree after exposure of waves. The vertical lines express the deviations found and the horizontal lines resemble the average values. For the dry test the ratio Force/Weight can be characterized as in the order of 5 for all three locations, while wave exposure increased this value up to 2–3 times. The difference in results after wave attack between the various locations can be explained by large settlements around the SWL and thus a higher packing density. A higher packing density is assumed to obtain a higher interlocking degree.

In the dry test with a packing density coefficient of 0.63, no influence of the extraction location was found. The observed packing was so loose that the units

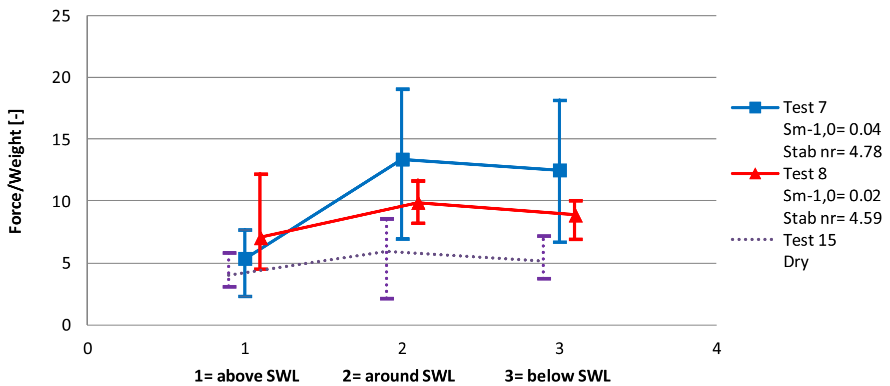


Fig. 14. Overview of average interlocking degree for $\phi = 0.63$.

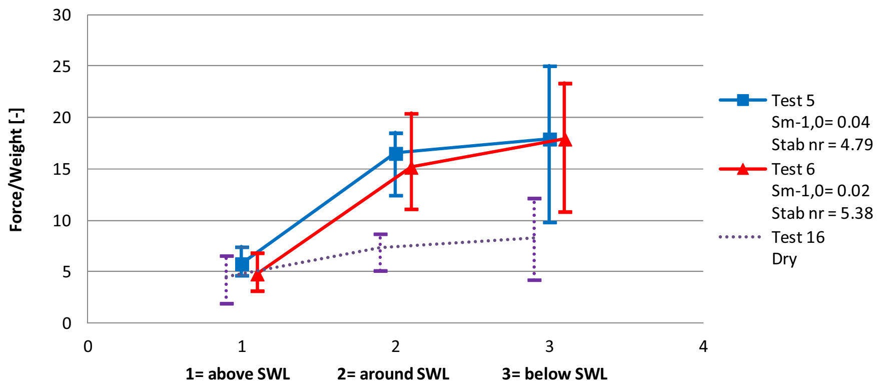


Fig. 15. Overview of average interlocking degree for $\phi = 0.66$.

above did not contribute to the interlocking degree by providing some additional weight. This is another reason to not allow a packing density coefficient of 0.63 for a real design.

The ratio between the interlocking degrees with and without wave exposure for a packing density coefficient of 0.66 is in the order of 3, see Fig. 15. In this case, it can also be assumed that settlement increased the packing density and so the interlocking degree. The interlocking degrees found after wave exposure for Location 2 and 3 were almost equal. However, this comparison is based on armor layers exposed to different wave-heights. Due to the increase of interlocking degree from Location 1 to 2 it can be assumed that the $\phi = 0.66$ provided enough interlocking thus the weight of the units above was affecting the interlocking degree of units located below. The actual packing density is determined after wave exposure to obtain the relation between interlocking degree, packing density and extraction location. This analysis is only done for initial ϕ of 0.63 and 0.66. It is worth mentioning that during test series 1–4 the frame to perform the pull tests in the flume after testing, was not ready yet and therefore pull tests were not performed for these tests.

Figure 16 gives the relation between the packing density and the interlocking degree. For all three extraction locations, the interlocking degree becomes higher with an increasing packing density. It is remarkable that not only the packing density plays a role in the interlocking degree but also the extraction location. For the three extraction locations, the ratio between the increase of packing density and interlocking degree is different as the slope of the trend lines differs. The more additional rows above the extraction location, the larger the influence on interlocking degree. Settlement has therefore a significant influence on the interlocking degree.

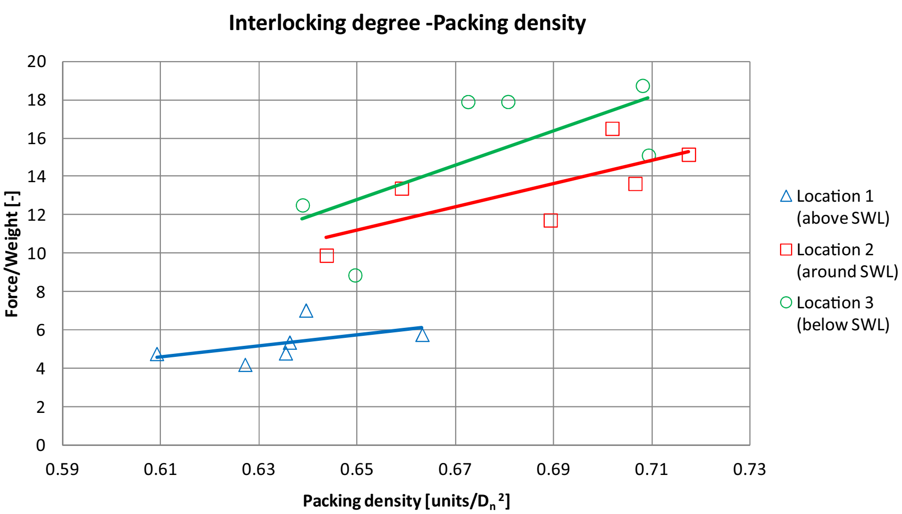


Fig. 16. Overview of interlocking degree corresponding to packing density after wave attack.

8. Conclusions

Based on the results, analysis and observations, the conclusions of the small scale physical tests on the new symmetrical single layer unit Crablock, can be pointed out as follows:

Placement of Crablock:

- A proper uniform pattern of Crablock was difficult to obtain in a rectangular grid with a conventional (large) underlayer. The test results showed that a uniform pattern of Crablock can be achieved in a rectangular grid by using a relatively small and smooth underlayer, which is about 1/25th of the armor layer weight. This is well within the limits for underlayer stability, but one should realize that a smaller underlayer may give less stability during construction when the armor layer has not yet been placed.
- Regular placement of Crablock was hardly achievable in a diamond-shaped grid. It was noticed that in a diamond-shaped grid, a random placement pattern can be achieved with higher accuracy and easily in comparison to a uniform placement pattern.
- For a good interlocked uniform pattern of Crablock armor units, on a relatively small underlayer it was possible to obtain the following measured average values:
  - Horizontal placement distance: 0.66 D and upslope placement distance: 0.63 D with a packing density coefficient $\phi = 0.68$.
- It was observed that in a diamond-shaped grid the randomly oriented Crablock units ensure a good interlocked armor with the following measured average values:
  - Horizontal placement distance: 0.75 D and upslope placement distance: 0.63 D with a packing density coefficient $\phi = 0.61$.

Stability:

- Longer waves affected the armor layer more, gave larger and earlier displacements. But this all occurred for very large wave-heights exceeding the assumed design wave-height significantly (up to 75%). In realistic conditions, this should never occur, of course.
- A high crest level gives large settlements if the design wave-height is exceeded significantly.
- The approximated stability number for design is between 2.8 and 3.3. A value of 2.8 is very conservative because this gives a safety factor of about 1.8 with respect to average start of displacements. A value of 3.3 belongs to a safety factor of 1.5, comparable to Xbloc, Accropode II and Core-loc, but this value is considerably higher than used for other units and should therefore be chosen with care.

Overtopping:

- Two different wave steepnesses were tested in this experimental investigation. It was clear that a very low wave steepness (long wave period) gave higher overtopping compared to a high wave steepness (short wave period). This might be due to the 1:30 foreshore slope that had large influence on the wave attenuation at the toe of the structure.
- Overtopping results showed that there is no influence of placement pattern and packing density on wave overtopping.
- The measured relative wave overtopping over Crablock was found to be slightly higher in comparison to CLASH [2004] results on Accropode, Core-loc and Xbloc as described by Bruce *et al.* [2009]. This variation was mainly observed for the test results with low wave steepness with $s_{m-1,0} = 0.02(s_{\text{op}} = 0.015)$, which was slightly outside of the CLASH [2004] range, described by Bruce *et al.* [2009] with $s_{\text{op}} = 0.02; 0.035$ and 0.05. The use of a sloping foreshore (1:30) and a more depth limited situation instead of a horizontal one as in Bruce *et al.* [2009] might have significant influence on the overtopping behavior. The 1:30 slope changed the shape and height of the waves and the waves at the structure toe showed a clear increase in velocity of the wave crest (near or at breaking). For the low wave steepness there was a clear difference in wave-heights between H_{m0} and $H_{1/3}$ at the structure, almost up to a factor of 1.3. Using $H_{1/3}$ made the differences between test results and predicting formulae much smaller. It may therefore be questioned whether the use of H_{m0} in EurOtop [2007] gives correct results if the values for the two definitions of wave-height deviate substantially.

Pull Tests:

- The results showed no influence of placement pattern on interlocking degree.
- The interlocking degree did not influence the hydraulic stability for packing densities higher than $\phi = 0.63$. The interlocking degree was just sufficient and did not result in differences in hydraulic stability.
- Interlocking degree depends more on the number of rows located above the extraction and on increasing packing density by some settlement. The lower placed units have a higher interlocking degree than the higher placed ones for equal packing densities. An increase in packing density, due to some settlement, results for the lower units in a higher increase in interlocking degree. There is a positive influence of the weight of the units above the extraction.

9. Recommendations for Design

The Crablock is an interesting single layer unit, as it is symmetrical by shape. This means that, in contrast to most other single layer units, a symmetrical placing pattern can be obtained. Some clients like a symmetrical placement more than random placement, see for example the many regular "pitched" rock armor slopes in the Middle East countries. It is for this reason that the unit was chosen for first testing in a wave flume for stability and wave overtopping. The tests are of course not yet conclusive on all possible design aspects.

The unit is very stable if uniformly placed in a rectangular pattern with sufficient packing density. That is the advantage of the outcome of the tests. But it is not easy to design a rectangular and uniform pattern if the length of the armor slope changes (by depth changes) or if there are curves or breakwater roundheads. A solution has not been found for this design aspect yet.

The stable configuration also needs a quite smooth underlayer, smaller than in many conventional designs. A smaller underlayer is less stable under daily conditions during construction and this may become a disadvantage.

Also, the construction of the first row of Crablock is important. A special toe block design, as available for Xbloc, may be a solution, but this has not yet been designed.

The overall recommendation is that it is worthwhile to explore the disadvantages mentioned above more in depth and to find practical solutions for design.

Acknowledgments

The first author of this paper would like to thank the NICHE-081 BGD project, for funding his MSc study at IHE Delft. Special thanks goes to AM Marine Works and CDR international for partly sponsoring the laboratory studies at Delft University of Technology. Furthermore, we would like to place our appreciations to all the members of the support staff of the Hydraulics Laboratory at TU Delft for their assistance during the experiments.

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