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Placement and wave overtopping tests for a new concrete armour unit crablock

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Abstract

Single layer concrete armour systems are being widely used nowadays in the design of rubble mound breakwaters. Recently, a new concrete armour unit has been developed and applied as single layer armour system in the repair works of one damaged breakwater at Al Fujeirah, UAE. It has a symmetrical shape, in contrast to most other units. Single layer concrete armour 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. The main objective of the present research was to come to first guidance. This led to the present investigation on the placement pattern, packing density and wave overtopping. The placement tests showed that uniform placement was best achieved with a rectangular grid on relatively small under layer rock. A random placement was best achieved by a conventional diamond shaped grid. Packing density showed no influence on wave overtopping. In general, the wave overtopping tests gave larger overtopping than expected, which might be due to the fairly steep 1:30 foreshore.

Keywords: Crablock, packing density, placement pattern, single layer armour and wave overtopping.

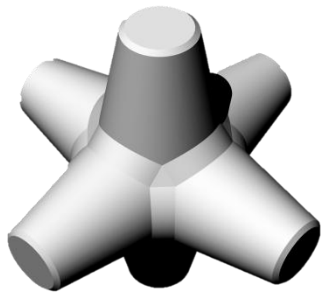
1. Introduction

Breakwaters are expensive coastal structures generally applied for harbours and similar structures along coasts to protect beaches from the action of waves and currents and also to stop siltation in approach channels. Rubble mound breakwaters have been mostly applied by designers among several types of breakwaters, usually made of rock or concrete armour in double layer systems or in single layer systems. One layer systems using concrete armour units are being widely used nowadays in the design of coastal structures, in comparison to conventional double layer armour systems. Crablock, a new concrete armour unit has been developed and applied as single layer armour system in one damaged breakwater at UAE. After this application the unit was improved substantially, leading to the shape as given in Figure 1.

Single layer concrete armour 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. In order to design a breakwater with crablock as one layer system, the preliminary guidance on placement of crablock, stability and wave overtopping is required. This led to the present investigation which was performed at Delft University of Technology in cooperation with UNESCO-IHE.

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 armour 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 this physical model tests were performed in a wave flume to come up with stability and wave overtopping results. Results on stability will be published elsewhere.

Top View of Crablock



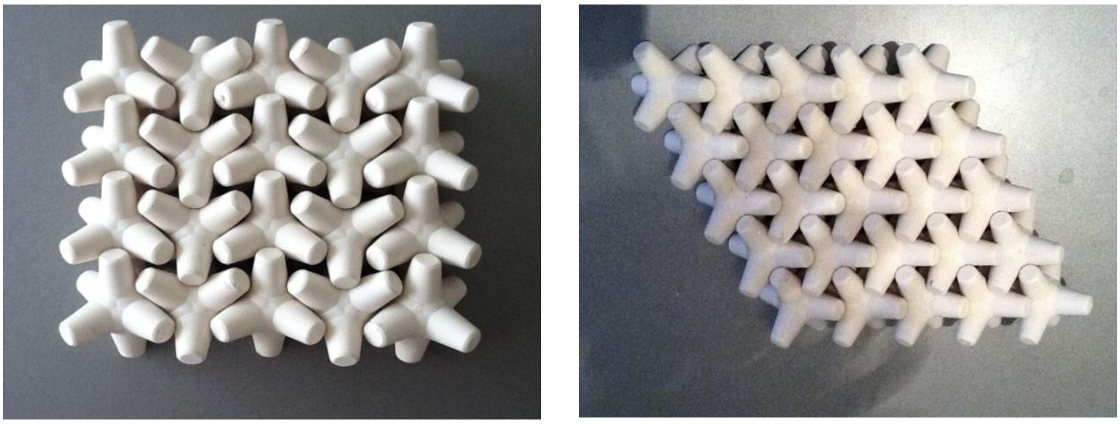
Isometric View of Crablock

Fig. 1. Crablock: a new single layer concrete armour unit (Source: Hendrikse 2014)

2. Placement tests of crablock

In reality, the placement of single layer concrete armour units is difficult and challenging. Moreover, the accuracy and speed of the placement might be affected by the harsh conditions during construction and by deep water (Muttray and Reedijk 2009). However, in order to ensure a firm armour cover with good interlocking capacity the placement of armour blocks has to be precise (Oever 2006). The good placement of armour units ensures the stability of single layer armour system (Muttray et al. 2005). In addition to hydraulic stability of armour layers, the structural integrity of armour units is also influenced by the placement of single layer armour blocks (Muttray et al. 2005). In order to construct a good interlocked armour 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). She proposed a first outline for the placement grid of crablock.

Generally, the placement of armour units with random orientation is relatively easier under water compared to strict orientation of units for uniform placement. Nevertheless, it should be noted that some blocks (like accropode) get their high interlocking by random placement and cannot be placed regularly. The regular placement of armour blocks is aesthetically attractive and for the symmetrical blocks like crablock might be more stable in comparison to irregular placement. A regular placement is shown in Figure 2. Phelp et al. 2012 argued that crablock armour units with uniform orientations provide compact interlocking between the units. Hendrikse and Heijboer 2014 believed that crablock armour units can be placed with uniform orientation in both rectangular and diamond shaped grid, Figure 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 UNESCO-IHE. The tests were executed with the use of small units.

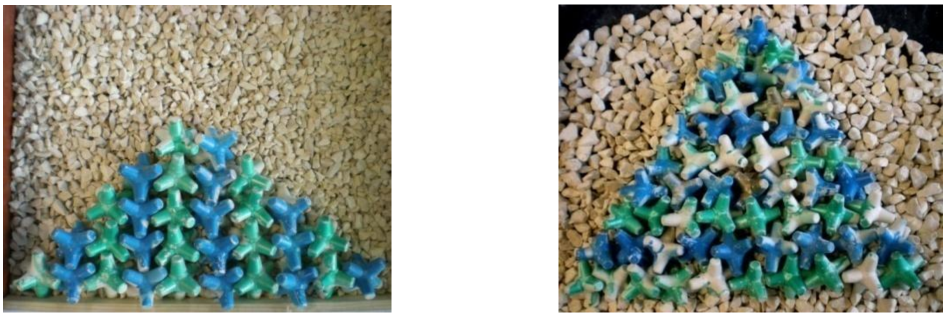


Rectangular grid Diamond -Shaped grid

Fig. 2. Uniform placement of crablock (Source: Hendrikse and Heijboer 2014)

2.1 Test procedure and programme

To perform small scale dry placement tests a model breakwater was constructed with the use of a rock under layer, a wooden toe and on a wooden frame. The slope of crablock armour (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, 2364 kg/m^3 in mass density and a nominal diameter of exactly 0.030 m. Two different sizes of under layers were used to perform the placement tests. Initially an under layer of one-tenth of crablock armour units (0.003-0.009 kg) has been used. But with the use of this relatively large under layer, a uniform placement of crablock was hardly reachable. Thus, to get the uniform placement a relatively smaller under layer (0.001-0.004 kg) was used to place the armour 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 under layer in a rectangular grid Random placement using conventional under layer in a diamond-shaped grid

Fig. 3. Test set-up for dry placement tests

Table 1
Test programme for dry placement tests

Test Series No.	Placement Grid	Orientation	Underlayer	Horizontal Distance	Upslope Distance	Designed PD (per D_n^2)
1	Rectangular	Uniform	11 to 16 mm	0.71D	0.57D	0.71
2	Rectangular	Uniform	11 to 16 mm	0.65D	0.60D	0.74
3	Rectangular	Uniform	11 to 16 mm	0.75D	0.65D	0.59
4	Rectangular	Uniform	11 to 16 mm	0.80D	0.60D	0.60
5	Diamond Shaped	Uniform	11 to 16 mm	0.60D	0.50D	0.96
6	Diamond Shaped	Uniform	11 to 16 mm	0.70D	0.60D	0.68
7	Diamond Shaped	Uniform	11 to 16 mm	0.80D	0.65D	0.55
8	Rectangular	Random	11 to 16 mm	0.71D	0.57D	0.71
9	Rectangular	Random	11 to 16 mm	0.65D	0.60D	0.74
10	Rectangular	Random	11 to 16 mm	0.75D	0.65D	0.59
11	Diamond Shaped	Random	11 to 16 mm	0.70D	0.60D	0.68
12	Rectangular	Uniform	7 to 11 mm	0.71D	0.57D	0.71
13	Rectangular	Uniform	7 to 11 mm	0.65D	0.60D	0.74
14	Rectangular	Uniform	7 to 11 mm	0.75D	0.65D	0.59

Bonfantini 2014 proposed an outline of four placement test series. However, in the present research fourteen different test series were performed to observe the placement of crablock. The reason for choosing fourteen 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 armour units. In order 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 eleven tests were conducted using large under layer, whereas the last three placement tests were performed with the use of small underlayer material (Table 1). It is noted that all the placement tests were carried out without water. Prior to the start of the placing test, under layer was placed on top of the slope of the frame. Then crablock units were placed as single layer armour according to the designed placing grid. It is worth mentioning that all the units were placed only by hand. At first the armour units in the first row were positioned by pointing crablock units in the designed grid position. Afterwards, the units were set in the higher upslope based on the designed placement pattern and placing grid. Photographs were captured after placing armour unit in order to describe the placement of crablock visually. The grid coordinates of each individual armour unit in case of both horizontal and upslope direction were measured by using linear scale.

3. Wave overtopping tests

Sea defences to protect coastal flooding, coastal protections to minimize coastal erosion and breakwaters at harbours to ensure safe navigation and mooring of vessels, are often armoured 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 crest freeboard or free crest height (R_c) is determined 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 discharge per linear metre of width, q, in terms of m^3/s per m or in l/s per m (EurOtop 2007). In order 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. Few physical model testing were performed on this new armour block by CSIR

(2009) at South Africa. However, wave overtopping discharge for the design of crablock armour unit was not measured before. 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.

3.1 Test set-up and programme

The set-up of the cross-section to perform flume tests has been done by considering the small scale model set-up of accropode (Van der Meer, 1987), set up of xbloc (DMC 2003) and set up of (Bruce et al. 2009) for rubble mound breakwaters with various types of armour units. The chosen cross-section of the model rubble mound breakwater consisted of single layer crablock armour, under layer, core, stone protection at toe and a crest wall (Figure 4). In this physical small scale investigation, the slope of crablock armour has been kept as 1:4/3, similar to accropode, core-loc and xbloc. The ratio between freeboard and "design significant wave height" was fixed as 1.2 allowing some waves overtopping during design conditions. This design significant wave height was assumed to have a stability number around 2.8, often used for the other single layer units. In this investigation significant wave heights much larger than the design significant wave heights were generated to observe failure of armour layer. For these conditions massive wave overtopping occurred.

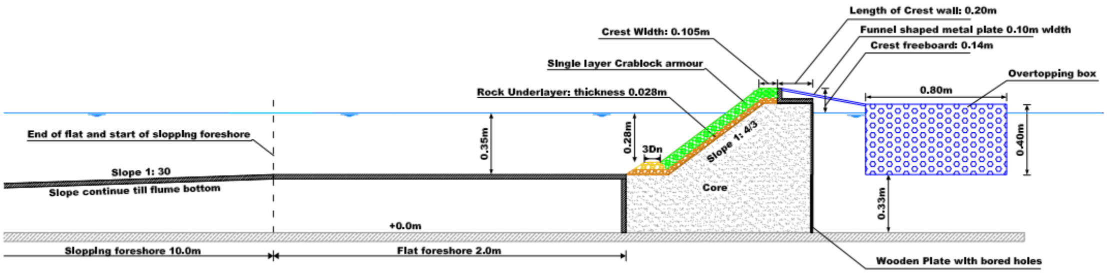


Fig. 4. Cross-section of model breakwater (R_c= 1.2 X Design wave height); tests 1-8

A sloping foreshore has been considered in front of a 2 m horizontal foreshore, with a uniform slope of 1:30. The length of the sloping foreshore was 10 m, starting from the bottom of the flume up to a depth 0.33 m above the bottom (Figure 4). The horizontal foreshore in front of the toe structure has been provided in order to put wave gauges to measure wave heights at similar depth. The design wave height can be estimated from the well-known stability number following the approach used by Bruce et al. 2009. For the crablock armour unit the design wave height was assumed as follows:

$$H_s/\Delta D_n = 2.8$$

Where, H_s = 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.

Based on the understanding of mentioned earlier research and available capacities of the wave flume, the water depth at the structure has been considered as 0.35 m, which means approximately 3 times the design wave height, H_{sD}. In order to have a water depth of 0.35 m at the structure, the water depth at deep water was kept 0.68 m for all the tests.

3.2 Test set-up and programme

Regarding to 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 dry placement tests. With considering the important design parameters, laboratory facility and available time for testing, in total ten test series were performed for the determination stability and wave overtopping of the crablock armour slope.

Moreover, two test series were executed for comparison, 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 actual incident wave heights in front of the structure.

Table 2
Test programme for the small scale physical model tests

Test Series No.	Placement Grid	Orientation	Hor. Vs Up Slope Distance	Packing Density	Crest Free board (m)	Underlayer	Deep Water Wave Steepness, $S_{m-1,0}$	Water Depth near structure (m)
1	Rectangular	Uniform	0.65DX0.64D	$0.69/Dn^2$	0.140	7 to 11 mm	0.04	0.35
2	Rectangular	Uniform	0.65DX0.64D	$0.69/Dn^2$	0.140	7 to 11 mm	0.02	0.35
3	Diamond	Random	0.75DX0.61D	$0.63/Dn^2$	0.140	11 to 16 mm	0.04	0.35
4	Diamond	Random	0.75DX0.61D	$0.63/Dn^2$	0.140	11 to 16 mm	0.02	0.35
5	Rectangular	Uniform	0.68DX0.64D	$0.66/Dn^2$	0.140	7 to 11 mm	0.04	0.35
6	Rectangular	Uniform	0.68DX0.64D	$0.66/Dn^2$	0.140	7 to 11 mm	0.02	0.35
7	Rectangular	Uniform	0.71DX0.64D	$0.63/Dn^2$	0.140	7 to 11 mm	0.04	0.35
8	Rectangular	Uniform	0.71DX0.64D	$0.63/Dn^2$	0.140	7 to 11 mm	0.02	0.35
9	Rectangular	Uniform	0.68DX0.64D	$0.66/Dn^2$	0.185	7 to 11 mm	0.04	0.35
10	Rectangular	Uniform	0.68DX0.64D	$0.66/Dn^2$	0.185	7 to 11 mm	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	Without Structure				---	---	0.04	---
14	Without Structure				---	---	0.02	---

The following two wave steepness's have been used: $s_{m-1,0} = 0.02$ and 0.04 at deep water (Table 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 structure instead of a horizontal foreshore.

Due to the sloping foreshore and limited water depth, spectral wave steepness $s_{m-1,0}$ higher than 0.04 could not be obtained in this experimental research. 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 failure of the armour layer.

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 low significant wave height of 0.07 m, which continued to increase is each consecutive test till the maximum wave height of 0.25 m at deep water.

3.3 *Empirical prediction*

The general formula used for the estimation of wave overtopping discharge over a coastal structure is (EurOtop 2007)

$$\frac{q}{\sqrt{gH_{m0}^{3}}} = a\exp(-b\frac{R_c}{H_{m0}}) \tag{1}$$

(EurOtop 2007) describes empirical equations in details for the approximation of overtopping over rubble mound slopes. The formulas used in this research are only discussed here shortly. Recently, (Van der Meer and Bruce 2014) concluded that empirical formulas provided by (EurOtop 2007), for breaking waves as well as for non-breaking waves over-estimate wave overtopping for slopping structures with very low or zero crest height. Furthermore, (Van der Meer and Bruce 2014) recommended the following formulas (Equation 2 & 3) to predict wave overtopping on slopping structures with zero and positive crest height.

— for breaking waves

$$\frac{q}{\sqrt{gH_{m0}^{3}}} = \frac{0.023}{\sqrt{\tan\alpha}}\cdot\gamma_b\cdot\xi_{m-1,0}\cdot\exp[-\left(2.7\frac{R_c}{\xi_{m-1,0}\cdot H_{m0}\cdot\gamma_b\cdot\gamma_f\cdot\gamma_\beta\cdot\gamma_v}\right)^{1.3}] \tag{2}$$

— and for non-breaking waves a maximum value of

$$\frac{q}{\sqrt{gH_{m0}^{3}}} = 0.09\cdot\exp[-\left(1.5\frac{R_c}{H_{m0}\cdot\gamma_f\cdot\gamma_\beta}\right)^{1.3}] \tag{3}$$

Equation 3 is normally used for steep coastal structures, like breakwaters.

4. Results of dry placement tests

4.1 Visual observation and experience of placing

The placement pattern of the armour layer has mainly been analysed by visual inspection of the armour units. The accuracy of the placement was analysed partly by observing the armour layer visually.

Table 3
Overview of the results of visual inspection in all test series

Test Series No.	Placement Grid	Designed Hor. Dis. (D)	Designed up. Dis. (D)	Designed Placement Pattern	Obtained Placement Pattern	Observation
1	Rectangular	0.71D	0.57D	Uniform	Not 100% Uniform	Interlocked
2	Rectangular	0.65D	0.60D	Uniform	Not 100% Uniform	Good interlocked
3	Rectangular	0.75D	0.65D	Uniform	Not 100% Uniform	Loose units
4	Rectangular	0.80D	0.60D	Uniform	Not 100% Uniform	Lot of loose units
5	Diamond	0.60D	0.50D	Uniform	Random	Lot of loose units
6	Diamond	0.70D	0.60D	Uniform	Random	Interlocked
7	Diamond	0.80D	0.65D	Uniform	Random	Lot of loose units
8	Rectangular	0.71D	0.57D	Random	Random	Interlocked
9	Rectangular	0.65D	0.60D	Random	Random	Interlocked but too narrow
10	Rectangular	0.75D	0.65D	Random	Random	Loose units
11	Diamond	0.70D	0.60D	Random	Random	Good interlocked
12	Rectangular	0.71D	0.57D	Uniform	Uniform	Interlocked
13	Rectangular	0.65D	0.60D	Uniform	Uniform	Good interlocked
14	Rectangular	0.75D	0.65D	Uniform	Uniform	Loose units

For each individual dry placement test, the armour layer was inspected visually to describe the placement of crablock for that specific test. A summary of the results is given in Table 3. To scrutinize the placement pattern of crablock in a rectangular grid, test 1, test 8 and test 12 were compared. All the three test series 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 similar designed rectangular grid. It was noticed that a uniform pattern (test 1 and test 12) looks more interlocked compared to a random pattern (test 8). Furthermore, from Table 3 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, what is not allowable in a real situation.

4.2 Accuracy of placement

The accuracy of the placement can be analysed by determining the average deviation of units from the designed grid position. The accuracy of the placement differed with different grids and also 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. For placement test series 13, the deviation of each individual unit from the designed placement grid is shown in Figure 5 as an example. From Figure 5, the average horizontal deviation of the units is examined 0.01D and the average upslope deviation of the units is determined−0.07D. In this experiment, relatively small deviation of units has been observed which indicates that this designed grid is also applicable in prototype situation.

4.3 Packing density

The average packing density for each particular test was determined by taking the mean of the local packing density of each particular unit regarding to the calculated horizontal and upslope placement distance for each specific unit.

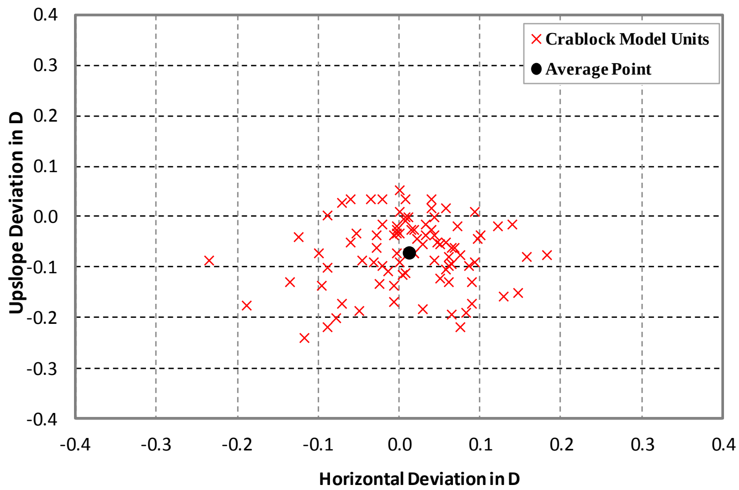


Fig. 5. Deviation of units from its intended position (Test 13)

Because of the deviation of units the measured horizontal and upslope placement distance have been also diverged from the theoretically predicted value. Figure 6 shows a comparison between the nominal packing density as designed and the measured one in each individual test series. The test results showed that in both the diamond-shaped and rectangular grid, the measured packing density was lower for the randomly oriented armour in comparison to uniformly oriented crablock armour. Moreover, from the test results it is seen that lower packing density of crablock was obtained with the use of a diamond-shaped grid. It also looks that the upslope placement distance is often around 0.63 D.

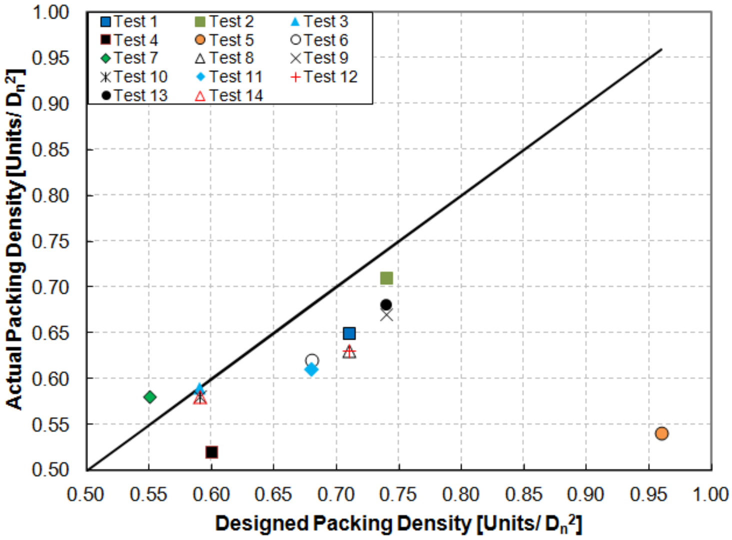


Fig. 6. Designed nominal packing density against measured nominal packing density

From the above results and discussions it can be concluded that a good interlocked uniform pattern of crablock armour units was possible to obtain with a relatively small under layer with a packing density of $0.68/D_n^2$. In a diamond-shaped grid, the randomly oriented crablock units ensures a good interlocked armour with a packing density of $0.61/D_n^2$. The theoretically designed diamond shaped grid with uniform placement pattern was hardly possible using a conventional rock under layer and without fixation of the first row by dedicated toe units (both rotation and location).

5. Results of wave overtopping tests

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

5.1 Relative wave overtopping

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 Figure 7. 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 (Figure 7). Furthermore, for the tests with same wave steepness overtopping results did not vary much between the different test series, with the change in packing density (Figure 7). For instance, test series 1, 5 and 7 performed with uniform placement pattern with the same configuration, except a different packing density of armour layer. Based on the test results it can be concluded that the change in packing density did not really change the overtopping behaviour of these test series. Figure 8 presents the comparison between the measured dimensionless overtopping discharges over crablock from flume tests versus the predictions by the new empirical formula (Equation 3) from (Van der Meer and Bruce 2014). Besides empirical prediction with an assumed roughness factor of γ_f equal to 0.45, another empirical line has been drawn with $\gamma_f = 1.0$ in order to compare the test results with maximum overtopping for a 1:2 smooth slope. Moreover, Figure 8 also compares the test results with other single layer units extracted from the (CLASH 2004) database and from 2D model tests by (DMC 2003).

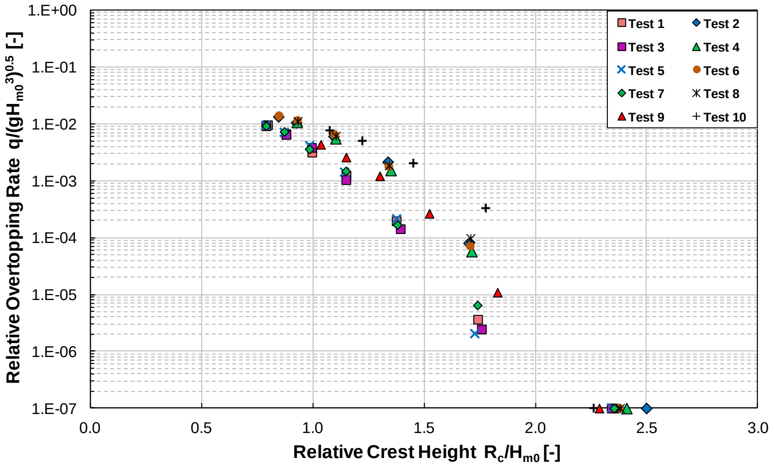


Fig. 7. Relative overtopping discharge as a function of relative freeboard

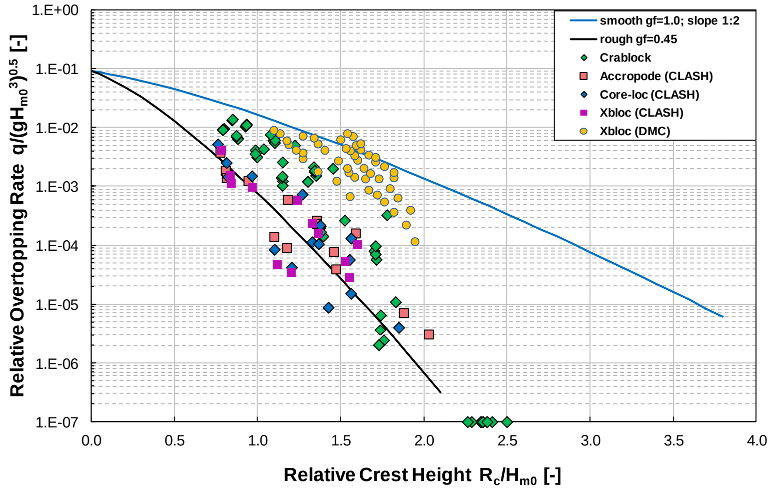


Fig. 8. Test results of crablock compare to empirical prediction and other monolayer units

Based on Figure 8, 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 Figure 8, it is recognised that overtopping over xbloc by (DMC 2003) behaves like a smooth structure which is significantly higher compared to the empirical line of rough armour, (CLASH 2004) and crablock.

5.2 *Percentage of overtopping waves*

Figure 9 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 significant wave height (H_{m0}) at the toe and the armour 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. Furthermore, 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 Figure 9 it is seen that tests with wave steepness of $s_{m-1,0} = 0.02$ gave high percentages of waves overtopping compared to the tests with wave steepness of $s_{m-1,0} = 0.04$.

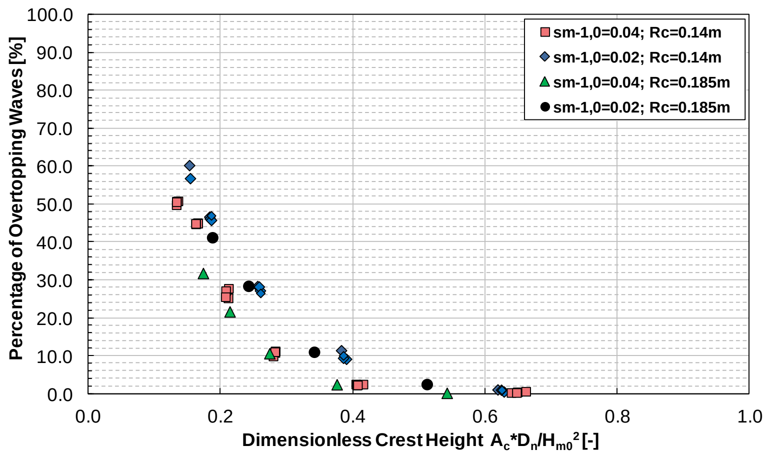


Fig. 9. Percentage of wave overtopping as a function of dimensionless crest freeboard

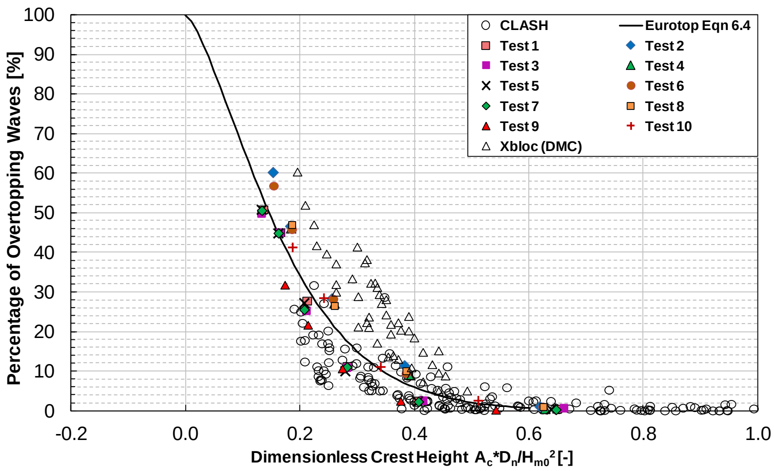


Fig. 10. Test results on percentage of overtopping compare to empirical prediction and other single layer units

In Figure 10, the percentage of waves overtopped over the crablock armour slope in different test series is compared with the results of (CLASH 2004), 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). It should be noted that (CLASH 2004) data contained a maximum percentage of overtopping around 30% (EurOtop 2007).

Therefore, the test results on overtopping percentages for higher waves which exceeds 30% are out of (CLASH 2004) range and cannot be compared with the database. Furthermore, based on Fig. 10 it is also observed that in comparison to long waves (EurOtop 2007) well predict the percentage of overtopping for short waves. For example, for tests 2, 4, 6 and 8 (long wave period) (EurOtop 2007) underestimates the percentage of overtopping to some extent, while the test results of 1, 3 and 5 (short wave period) are almost on top of EurOtop line. However, similar to the relative overtopping rate in Fig. 8, Fig. 10 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) and test results of the crablock.

The difference in results between the measured overtopping over crablock units, (CLASH 2004) data on other concrete units and the empirical predictions might be due to the following reasons.

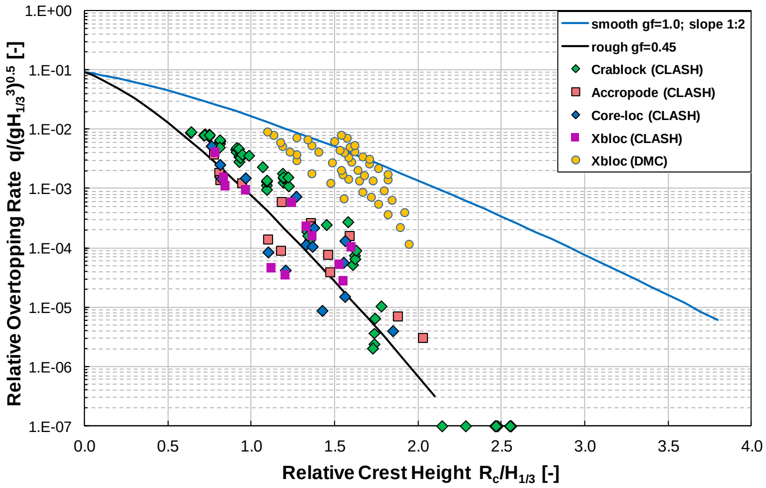


Fig. 11. Test results of crablock compare to empirical prediction and other monolayer units (using $H_{1/3}$)

– (CLASH 2004) data are based on 2D experiments which were performed with the use of three wave steepnesses s_{op} = 0.02; 0.035 and 0.05. Nevertheless, in this study flume tests were carried out by using two constant wave steepnesses $s_{m-1,0}$ = 0.02 and 0.04 (s_{op} = 0.015 and 0.035). That means all the tests with low wave steepness s_{op} = 0.015 were just out of the range of CLASH, which mainly gave higher overtopping compared to (CLASH 2004). 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 were performed in 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 of the wave crest (near or at breaking).

– It is worth pointing out that all the empirical formulas on overtopping are based on spectral significant wave height H_{m0} at structure. As presented in Figure 8, 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 this research it was observed that for higher wave heights with long period H_{m0} at the structure considerably differs from $H_{1/3}$ at the structure, see details in Salauddin, 2015. Note that this was not the case for (CLASH 2004) 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 (CLASH

2004) and empirical prediction. To observe the influence of $H_{1/3}$, Figure 8 is re-plotted with the use of $H_{1/3}$ instead of H_{m0} (Figure 11). Based on comparison of Fig. 8 and Fig. 11, it can be concluded that by using $H_{1/3}$ the variation between (CLASH 2004) and crablock is considerably reduced. Also, the test results of crablock units performed with two different wave steepnesses has 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 structure.

6. Conclusion

Based on the results, analysis and observations, the conclusions of these small scale physical tests can be pointed out as following:

6.1 Placement of crablock

– It was found that crablock armour units can be placed in both a uniform and a random pattern. Furthermore, it was also observed that a rectangular grid as well as a diamond-shaped grid is applicable for the placement of crablock as single layer armour units.

– A proper uniform pattern of crablock was difficult to obtain in a rectangular grid with a conventional (large) under layer. However, the test results showed that a uniform pattern of crablock can be achieved in a rectangular grid by using a relatively small and smooth under layer, which is about 1/25th of the armour layer weight.

– Regular placement of crablock was hardly achievable in a diamond-shaped grid. Nevertheless, it was clearly noticed that in a diamond shaped grid, a random placement pattern can be achieved with higher accuracy and easily in comparison to uniform placement pattern.

– A good interlocked uniform pattern of crablock armour units was possible to obtain on a relatively small under layer with the following measured average values: Horizontal distance: 0.66 D and upslope distance: 0.63 D with packing density of $0.68/D_n^2$

– It was observed that in a diamond-shaped grid, the randomly oriented crablock units ensures a good interlocked armour with the following measured average values: Horizontal distance: 0.75 D and upslope distance: 0.63 D with packing density of $0.61/D_n^2$

6.2 Wave overtopping

Two different wave steepnesses were tested in this experimental investigation. Regarding to the test results, it was clear that low wave steepness (long wave period) gave higher overtopping compared to 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 on wave overtopping. The test results with similar configuration except a different packing density proved that the overtopping behaviour does not really change with a change in packing density.

– In this experimental investigation, most of the test series were performed with the use of a crest freeboard 1.2 times the design wave height. Only two test series were conducted with a much higher crest freeboard, 1.6 times the design wave height. However, based on the test results it was monitored that different crest heights give unexpectedly deviation in dimensionless results.

– The relative wave overtopping over crablock obtained in different test series was compared with the empirical prediction provided by (Van der Meer and Bruce 2014). It was found that the empirical equation with assuming γ_f of 0.45 underestimated the measured wave overtopping over crablock slopes.
– The measured relative wave overtopping discharge over crablock was found slightly higher in comparison to (CLASH 2004) results on accropode, core-loc and xbloc. This variation was mainly observed for the test results with low wave steepness $s_{m-1,0}$= 0.02 (s_{op} = 0.015) which was slightly out of the CLASH (2004) range (s_{op} = 0.02; 0.035 and 0.05).The use of a sloping foreshore (1:30) instead of a horizontal one as in (CLASH 2004) might also influence the overtopping behaviour. The 1:30 slope changed the shape 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 H_{m0} and $H_{1/3}$ at the structure. Using $H_{1/3}$ made the differences between test results and predicting formulas much smaller.
– The comparison between the test results on overtopping percentages and prediction by (EurOtop 2007) proved that the percentage of overtopping waves over crablock can be well predicted by using an empirical formula. The percentage of overtopping obtained from the test results were also compared with (CLASH 2004) results. Based on the comparison, it was noticed that for smaller waves the test results are within the range of (CLASH 2004) results.
– It was observed that the wave overtopping over crablock is significantly lower compared to the wave overtopping over xbloc measured by (DMC 2003). It is worth mentioning that here xbloc and crablock had the same foreshore (1:30) in the test.

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