A New Symmetrical Unit for Breakwater Armour: First Tests

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ABSTRACT

A new and symmetrical single layer armour unit, the crablock, has been designed in the UAE. One breakwater was reconstructed with crablock, but very limited testing had been performed. Just to become more acquainted with this new unit, pre-competitive research at a university has been performed, which is the subject of this paper. Being a new armour 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. Moreover, to determine the interlocking properties of armour units, pull tests were also conducted in this research. Those results are not part of this paper. Test results on stability showed that the longer waves affected the armour layer a little more, with larger movements and earlier displacements. 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.

KEYWORDS: Crablock, Interlocking, Stability, Wave Overtopping, armour unit.

1. INTRODUCTION

A small number of single layer armour units have been developed after the introduction of the accropode more than thirty years ago: core-loc, xbloc and accropode II. Sometimes the A-Jack has been used in breakwater projects with a mass unit not exceeding 4 t. The cubipod was the latest development in the single layer armour units, although this unit does not get its strength so much from interlocking, which is the case for all the others.

A new and symmetrical single layer armour unit, the crablock, has been designed in the UAE. One breakwater was reconstructed with crablock after experiencing damage, but very limited testing had been performed. Just to become more acquainted with this new unit, pre-competitive research by a cooperation of two universities has been performed, which is the subject of this paper. As the unit is symmetrical, it is possible to place the units in a regular way, this in contrast to most other units, which use a random pattern. This was a new aspect in breakwater armour design and 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. Moreover, to determine the interlocking properties of armour units pull tests were also conducted in this research (but not described in this paper).

2. 2D 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 UNESCO-IHE. All tests were executed with the use of small crablock units with an average mass of 63.7 g.

2.1 Model Set-Up

The model set-up was designed 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 armour units. The designed and constructed model of the rubble mound breakwater consists of single layer crablock armour, under layer, core, stone protection at toe and a crest wall, see Figure 1. In this experimental investigation, the slope of crablock armour was kept as 1:4/3 similar to accropode, core-loc and xbloc. A crest height of 1.2 times the design wave height (H_{sD}) was chosen to allow some overtopping. This indicates, however, that wave overtopping over the crest of breakwater will be a lot more for significant wave heights far beyond the design significant wave height, which was part of the test program. However, a crest height of 1.6 x H_{sD} was also tested.

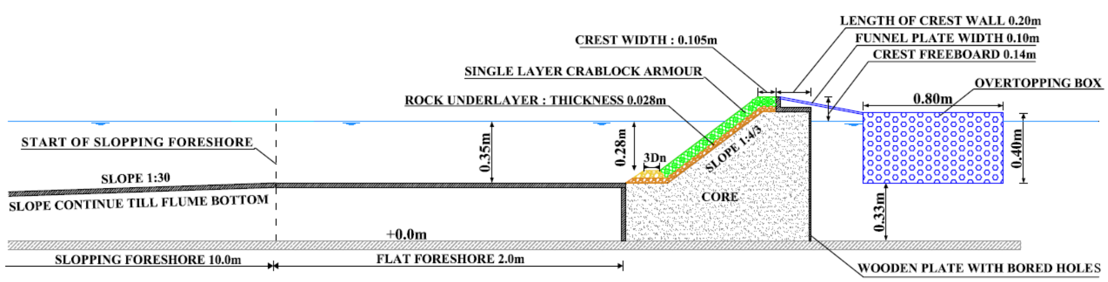

Figure 1: Cross-section of breakwater with crest height 1.2 X H_{sD}; tests 1-8

A sloping foreshore of 1:30 was considered in front of a small horizontal foreshore on which the model was constructed. The length of the sloping foreshore was 10 m, covering a depth difference 0.33 m. Moreover, a horizontal length of 2 m before the toe structure was constructed in order to put wave gauges to measure wave heights near the structure toe. Initially, the design stability number for crablock was chosen as 2.8 comparable with xbloc, core-loc and accropode II in order to define the design significant wave height. The design wave height can be estimated from the known stability number following the approach used by Bruce, et al. (2009), see Equation 1. This gives a design wave height of H_{sD} = 0.114 m.

$$\text{Stability number} = H_{sD}/\Delta D_n = 2.8 \tag{1}$$

Here, H_{sD} = design significant wave height; Δ = relative mass density = 1.36 and nominal diameter D_n = 0.030 m.

The water depth at structure was considered 0.35 m, which means 3 times the design wave height. In order to have a water depth 0.35 m at the structure, the water depth at deep water was kept 0.68 m.

2.2 Test Programme and Procedure

The placement pattern, packing density, crest height and wave steepness in terms of wave height and wave length are considered as the most important parameters that govern the geometrical design of breakwaters (Bonfantini, 2014). Regarding to the results of dry placement tests, the geometrical set-up of each individual test, like placement grid, orientation of units and suitable packing density, were selected for the flume tests. In total ten test series were performed for the determination of stability and wave overtopping of the crablock armour slope. Furthermore, two test series were executed for comparison, using a smooth (wooden) slope of 1 in 4/3. Moreover, 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.

Two wave steepnesses have been used: $s_{m-1,0} = 0.02$ and 0.04 at deep water, see Table 1, where $s_{m-1,0}$ is the spectral wave height based on the spectral period, $T_{m-1,0}$. One of the major differences of this experimental research with the set up by Bruce *et al.* (2009) is that here a sloping foreshore was used in front of structure instead of a horizontal foreshore with relatively deep water. 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.

Each test has been conducted following the individual test programme, see Table 1. 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. Moreover, cameras and video recorder were set up at a fixed position to capture photographs and video. In order to capture the position of armour units in the initial condition photographs were taken before starting of each test. Afterwards, waves have been generated based on the test wave conditions. The test was started with a lower wave height in order to protect the armour layer from sudden failure. In each sub-test wave heights and periods were measured until failure of the armour slope. Once the armour slope or under layer was damaged due to waves, the armour and under layer were reconstructed for the next test series. See Salauddin, 2015 for the full description of the test procedure.

Table 1: Test programme for the small scale flume tests

Test Series No.	Placement Grid	Orientation	Hor. Vs Upslope distance	Packing Density	Crest Freeboard (m)	Underlayer	Deep water Wave Steepness, $S_{m-1,0}$	Water depth near structure (m)
1	Rectangular	Uniform	0.65Dx0.64D	$0.69/D_n^2$	0.140	7 to 11 mm	0.04	0.35
2	Rectangular	Uniform	0.65Dx0.64D	$0.69/D_n^2$	0.140	7 to 11 mm	0.02	0.35
3	Diamond	Random	0.75Dx0.61D	$0.63/D_n^2$	0.140	11 to 16 mm	0.04	0.35
4	Diamond	Random	0.75Dx0.61D	$0.63/D_n^2$	0.140	11 to 16 mm	0.02	0.35
5	Rectangular	Uniform	0.68Dx0.64D	$0.66/D_n^2$	0.140	7 to 11 mm	0.04	0.35
6	Rectangular	Uniform	0.68Dx0.64D	$0.66/D_n^2$	0.140	7 to 11 mm	0.02	0.35
7	Rectangular	Uniform	0.71Dx0.64D	$0.63/D_n^2$	0.140	7 to 11 mm	0.04	0.35
8	Rectangular	Uniform	0.71Dx0.64D	$0.63/D_n^2$	0.140	7 to 11 mm	0.02	0.35
9	Rectangular	Uniform	0.68Dx0.64D	$0.66/D_n^2$	0.185	7 to 11 mm	0.04	0.35
10	Rectangular	Uniform	0.68Dx0.64D	$0.66/D_n^2$	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	-----

3. RESULTS AND DISCUSSIONS

3.1.1 Stability

<u>Damage based on displacements</u>

The stability of the crablock armour units is based on the stability number and relative number of 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 Figure 3 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}.

For the tests with wave steepness $s_{m-1,0} = 0.04$, the short waves, only a slight damage was obtained during the physical model tests performed with packing density $0.63/D_n^2$ and rectangular grid, see Figure 3. The long waves caused damage (extracted units) to the armour layer for all tests, but of course only for the very large wave heights. The higher crest level experienced the most severe wave attack focussed on the armour slope while, for the normal crest level the highest waves attacked the armour at the transition from slope to horizontal crest. Settlements caused openings between the units on the upper slope and the horizontal crest, which resulted in the weakest point of the armour layer. The heavy wave attack at the normal 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 packing density $0.66/D_n^2$.

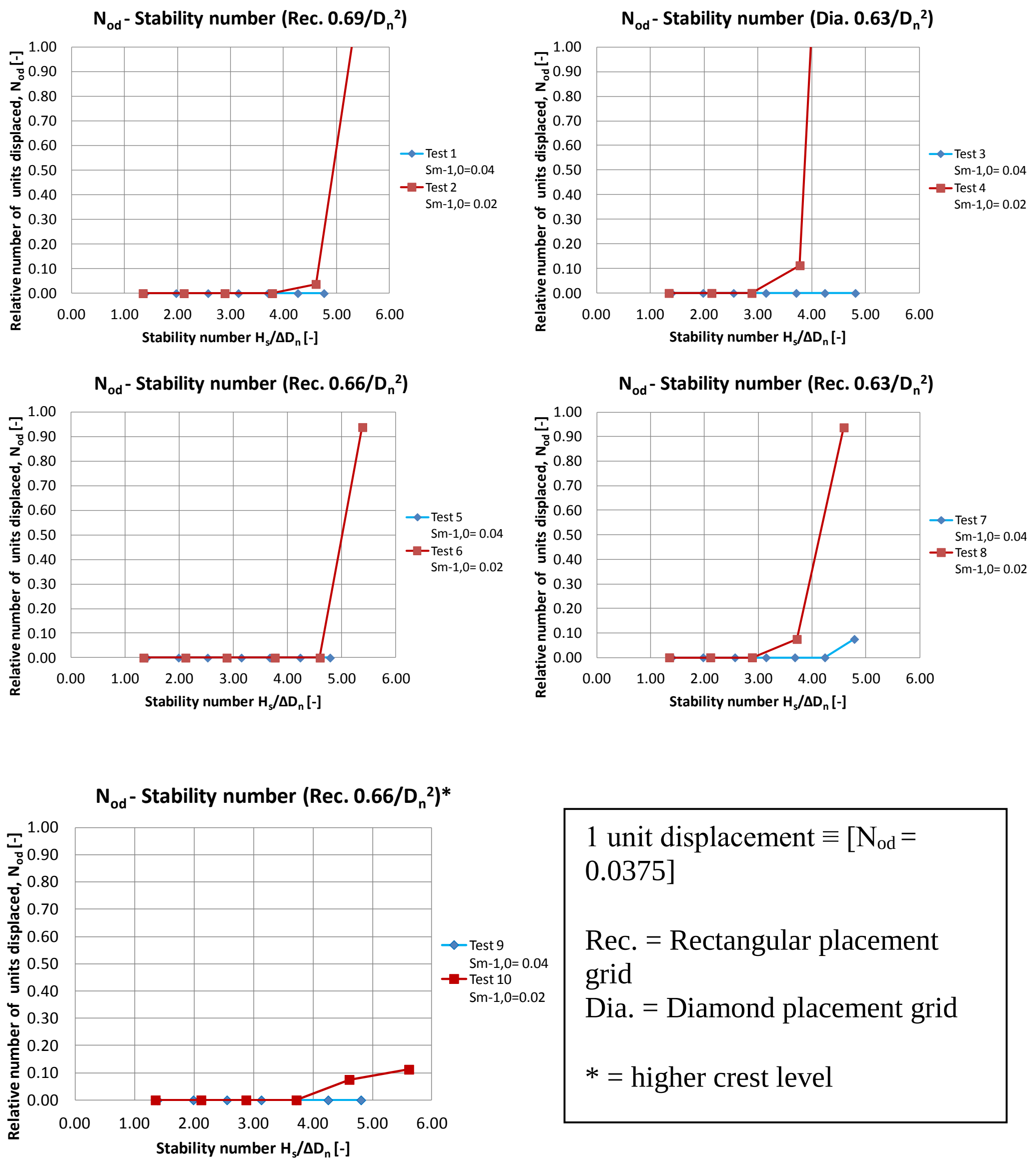

Figure 3: Damage curves N_{od} versus $H_s/\Delta D_n$ for all tests

Damage by movements

Individual movements of units was determined by comparing photographs before and after testing and measuring the distance moved. When concerning a threshold level of movements within the armour layer >$0.75D_n$, the tests series conducted with packing density $0.63/D_n^2$ showed very large movements in an early stage. The movements 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 is considerable for the packing density of $0.66/D_n^2$ and the tests with a high crest level resulted in larger movements. For both steepnesses the movements 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 armour layer executed with a packing density $0.69/D_n^2$ did not show any movement above the chosen threshold levels at all. For more detailed information see Broere, 2015.

Damage by rocking

Rocking was obtained by visual inspection during testing. For analysing the rocking behaviour of Crablock, a criterion of N_{or}= 0.2 is used to eliminate inaccurate placing of the individual armour units. This criterion represents rocking of about five units. The armour layer executed with packing density $0.69/D_n^2$ complied this criteria for a stability number of approximately 4. Looking at a packing density of $0.66/D_n^2$, the rocking criterion was exceeded around a stability number of about 3 for both crest levels. In the tests performed with a packing density of $0.63/D_n^2$ rocking was observed from a stability number of 2.

Exclude packing density of $0.63/D_n^2$

When only considering damage by displacements/extraction, the results obtained from a packing density $0.63/D_n^2$, were hopeful according to Fig. 3. Considering the individual movements and rocking of the armour layer, a packing density $0.63/D_n^2$ performed very bad. Large movements and considerable rocking started already during low stability numbers. Next to this, the movements resulted in some very loose packed units which rolled over the under layer. Although the units are robust, rolling of units cannot be accepted in order to prevent possible damage to the unit.

A packing density of $0.63/D_n^2$ is therefore considered as too loose and was not taken into account in the further analysis. Since the maximum packing density achievable for the diamond placement grid is $0.63/D_n^2$, this placement is considered as not applicable for Crablock armour units.

Design stability number

Regarding the results of the analysis on the hydraulic stability, start of damage by displacements occurred from a stability number of 4.6, see Fig. 3 for packing densities $0.66/D_n^2$ and $0.69/D_n^2$. The wave steepness of 0.04 did not show any damage at all 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 movements of the units with the threshold level set on $>0.75D_n$ started for the higher crest level to become considerable from a stability number of 4.0. For normal crest level, the units did not exceed the threshold level for the whole test series. Applying a criteria of maximal N_{or}= 0.2 for rocking, the armour layer executed with packing density $0.69/D_n^2$ complied this criteria for a stability number of approximately 4.0. However, looking to packing density $0.66/D_n^2$, the rocking criteria 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 safety factor is required to come to a design value. If no damage occurred during the first 1000 waves, more waves were not able to cause damage. The no-damage criterion is therefore independent of the number of waves.

For accropode (Delft Hydraulics, 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. Accropode II and corelocs are a little more stable, which resulted in a design stability number of 2.8. This was also used to design the model tests for the crablock. For xbloc a stability number 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_{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 realise that the criteria on rocking has to be less strict. This leads to a first approximation for stability as in Equation 2. More research is required to come to a final design value.

$$\text{Design stability number} = H_{sD}/\Delta D_n = \text{minimum } 2.8\text{, maximum } 3.3 \qquad (2)$$

3.2.2 Overtopping

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).

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 Figure 4. 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 Figure 4. 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 Figure 4. For instance, test series 1, 5 and 7 performed with a 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.

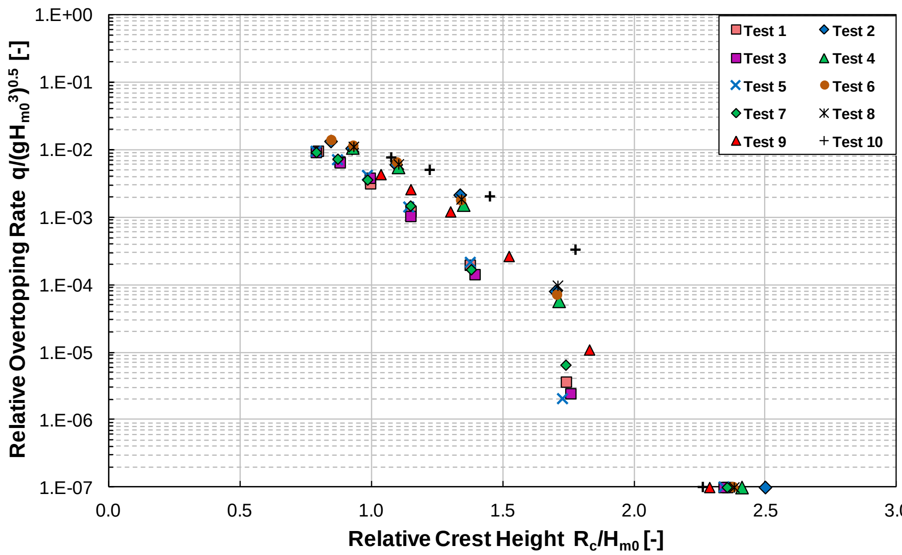

Figure 4: Relative overtopping discharge as a function of relative freeboard

Figure 5 presents the comparison between the measured dimensionless overtopping discharges over crablock from flume tests versus the predictions by the new empirical formula 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 5 also compares the test results with other single layer units extracted from the CLASH (2004) database and from 2D model tests on xbloc by DMC (2003). Based on Figure 5, 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 5, 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.

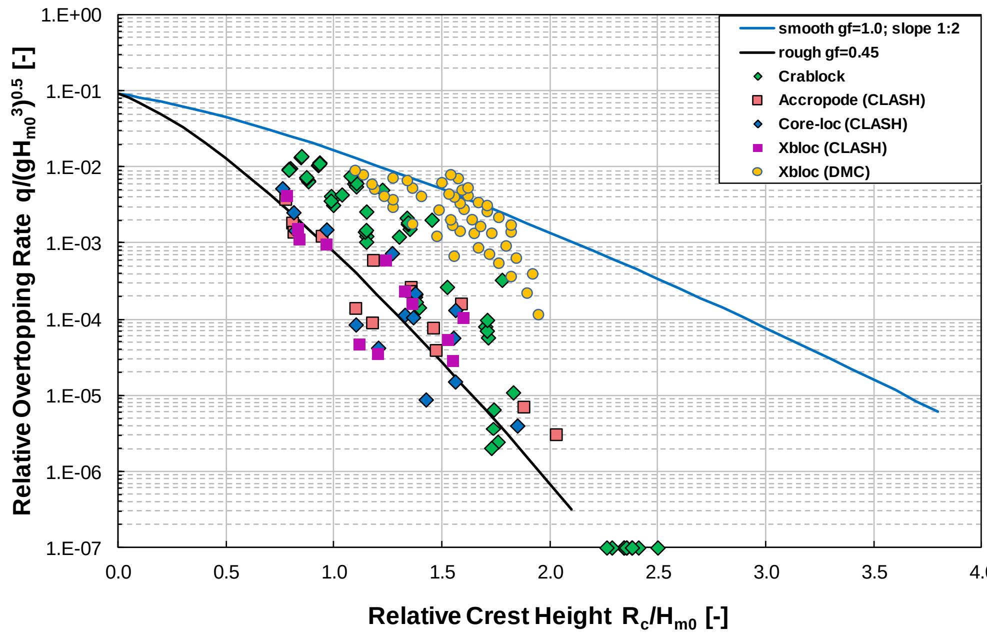

Figure 5: Test results compare to empirical prediction and other monolayer units

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:

- 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). This might also have been the case for the xbloc research (DMC, 2003), where also a 1:30 foreshore slope was applied.

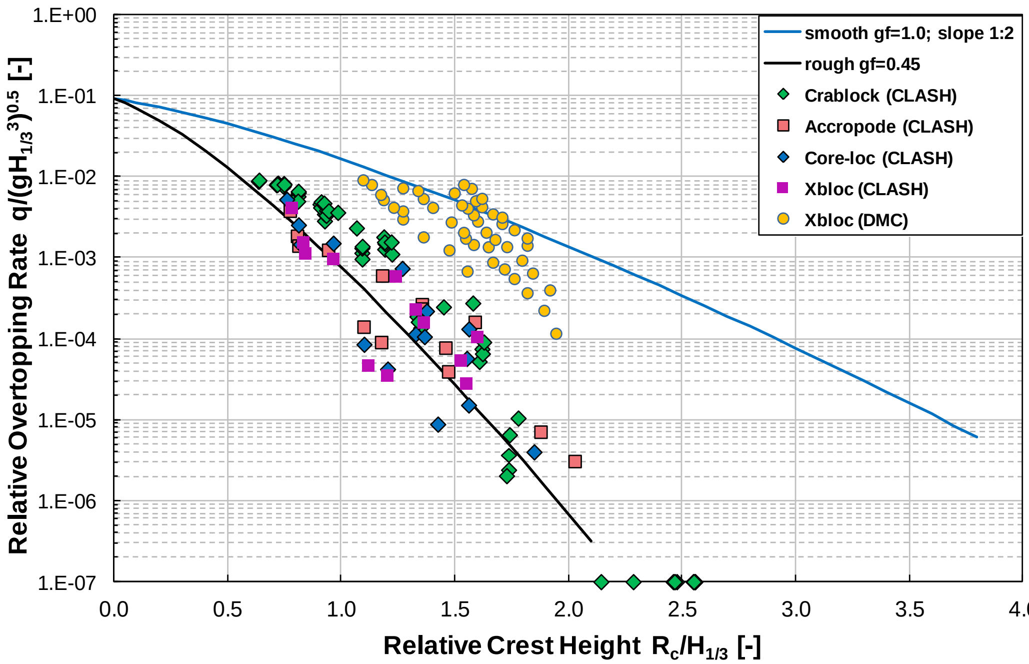

Fig. 6: Test results compared to empirical prediction and other monolayer units (using $H_{1/3}$)

- 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 Figure 5, 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 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 in above figures. To observe the influence of $H_{1/3}$, Figure 5 is re-plotted with the use of $H_{1/3}$ instead of H_{m0}, see Figure 6. Based on a comparison of Figure 5 and Figure 6, 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 the 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.

4. 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:

Stability:

- Longer waves affected the armour layer more, gave larger movements and earlier displacements. But this all occurred for very large wave heights, exceeding the design wave height significantly (up to 50%)
- A high crest level gives large movements if the design wave height is exceeded significantly.
- The approximated stability number 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, 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. Regarding to the test results, it was clear that very 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 and packing density on wave overtopping.

- The measured relative wave overtopping 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 formulae much smaller.

5. ACKNOWLEDGEMENTS

The first author of this paper would like to thank the NICHE-081 BGD project, for funding his MSc study at UNESCO-IHE. Special thank 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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