Malaysian Journal of Civil Engineering 27(3):382-396 (2015)

THEORETICAL AND EXPERIMENTAL STUDY ON THE PLACEMENT OF A NEW CONCRETE ARMOUR BLOCK

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Abstract: Crablock, a new concrete armour unit has been developed and applied as single layer armour system in one damaged breakwater at UAE. Single layer concrete armour units that exist at this moment have fixed placement pattern mostly random along with designed placing grids and packing densities. 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. It is worth mentioning that the crablock unit is still under development therefore no design guidance exists at present for this new concrete armour block. To come up with preliminary design guidance for the placement of crablock, an experimental research has been done, which is the subject of this paper. In this laboratory study, in total fourteen placement test series were performed to familiar the placement pattern of crablock as single layer system. In order to establish a reliable dataset, three repetition tests were performed for each test series thus in total 42 tests were conducted on the placement of crablock. This paper describes small scale model placement tests to examine the placement pattern of crablock and also provides a comparison between theoretically designed and actual (measured) placement grid. Based on test results it was observed that crablock armour units can be placed in both uniform and random pattern. Uniform placement of crablock was achievable in a rectangular grid using a relatively small and smooth under layer (1/25th of the size of the armour layer). However, test results showed that a random placement can be best achieved using a conventional diamond shaped grid. Finally, from the placement tests two preferred placing patterns were appeared, a regular pattern in a rectangular grid using a relatively small under layer and a random pattern in a diamond shaped grid using a conventional under layer.

Keywords: *Breakwater, packing density, placement grid, placement pattern and single layer armour.*

1.0 Introduction

Breakwaters are expensive coastal structures generally applied for harbours and similar structures along coasts to protect the beaches, dunes from the action of waves, currents and also to stop siltation in the approach channel (SPM, 1984). Rubble mound breakwaters have been mostly applied by designers among several types of breakwaters, usually made with the use of rock armour 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.

In reality, the placement of single layer concrete armour units is difficult and challenging. Moreover, the precision and speed of the placement might be affected by the harsh conditions and by deep water (Muttray and Reedijk, 2009). However, in order to ensure a firm armour cover with excellent 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 are also influenced by the placement of monolayer armour blocks (Muttray *et al.*, 2005). Therefore, in order to make sure a good interlocked armour layer with high hydraulic stability, immense concentration should be paid in the placement of concrete elements. Single layer concrete armour units that exist at this moment have fixed placement pattern mostly random along with designed placing grids and packing densities. 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. It is worth mentioning that the crablock unit is still under development therefore no design guidance exists at present for this new concrete armour block. To come up with preliminary design guidance for the placement of crablock, an experimental research has been done, which is the subject of this paper. This paper describes small scale model tests to examine the placement pattern of crablock and also provides a comparison between theoretically designed and actual (measured) placement grid.

2.0 Placement Grid and Placement Pattern

Generally, the single layer armour units are placed in a predefined grid position. The designed grid plays a significant role to place the armour units properly and to ensure proper interlocking between the units. The deviation of units from the designed position might influence the interlocking capacity of the armour layer. Therefore, to place the armour units accurately, placement grids should be well designed in line with reality. The horizontal and upslope placement distance are the main design parameters to design a placement grid. It is already mentioned that design guidance on the placement of crablock does not exist yet. Nevertheless, different factors governing the placement of crablock can still be determined from the theoretical study. Based on the theoretical study on the placement pattern of existing single layer blocks, Bonfantini (2014) proposed an outline for the placement grid of crablock.

CSIR (2009) performed 2D wave flume tests using crablock armour blocks and argued that the grid placement distance 0.71× D in horizontal direction and 0.57× D in vertical direction provided the best placement pattern for randomly oriented crablock armour units. In that research, D was referred to as height of crablock armour unit. Based on this study, Bonfantini (2014) designed a standard rectangular grid with possible theoretical placement of crablock units, see Figure . The achievable packing density observed with this standard rectangular grid is $0.71/D_n^{\ 2}$, D_n is the nominal diameter of crablock.

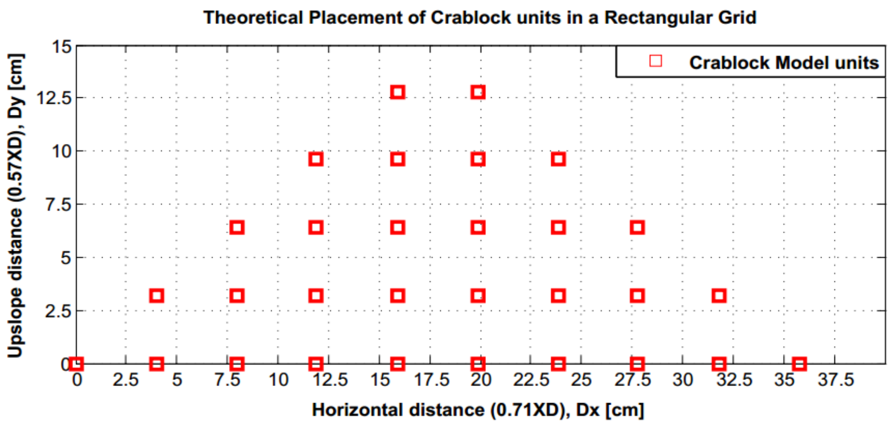


Figure 1: Plan of a theoretically designed rectangular grid (D_x = 0.71D and D_y = 0.57D) [Source: Bonfantini (2014)]

Moreover, the armour units can also be placed in a diamond shaped grid pattern. For example, Oever (2006) designed a diamond shaped grid to place the xbloc armour units. For the placement of crablock units Bonfantini (2014) suggested a diamond shaped grid pattern. In that study Bonfantini (2014) thought that crablock can be placed in a diamond-shaped grid with the minimum horizontal distance 0.6 D and the minimum upslope distance 0.5 D, D is the height of crablock unit. From the horizontal and upslope placement distances the packing density was proposed to $0.94/D_n^{\ 2}$ by researcher. Figure shows the planned diamond shaped grid with possible theoretical placement of crablock units by Bonfantini (2014).

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 regular. The regular placement of armour block is aesthetically attractive and for the symmetrical blocks like crablock might be more stable in comparison to irregular placement. Phelp *et al*. (2012) argued that crablock armour units with uniform orientations provides compact interlocked 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.

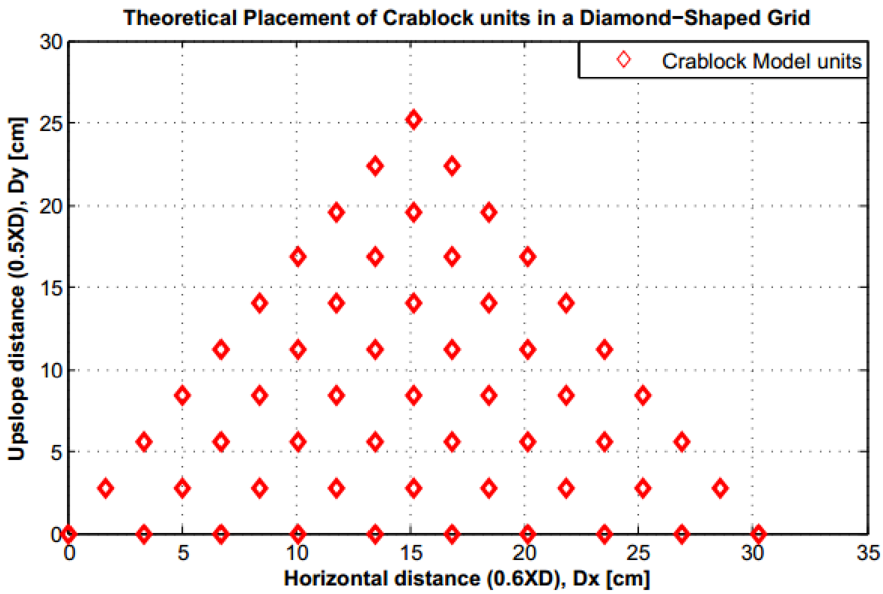
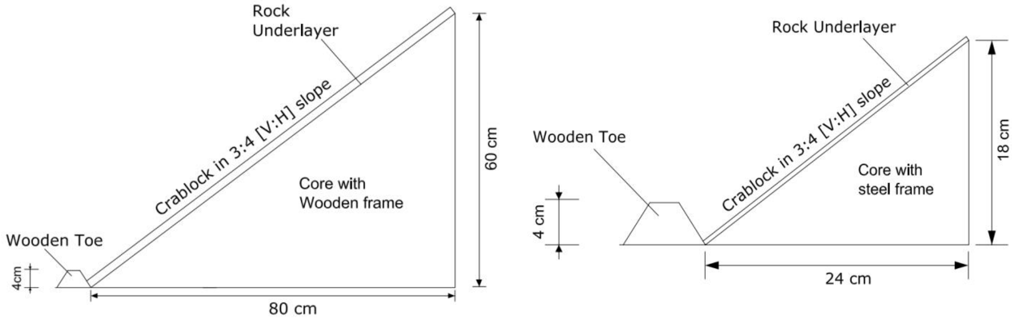


Figure 2: Plan of a theoretically designed diamond grid ($D_x = 0.60D$ and $D_y = 0.50D$) [Source: Bonfantini (2014)]

3.0 Laboratory Set-Up and Testing Procedure

The small scale dry placement tests were performed at the Fluid Mechanics Laboratory of the Faculty of Civil Engineering and Geosciences at Delft University of Technology, Netherlands. At the beginning, to perform small scale dry placement tests a model breakwater was constructed with the use of rock under layer, wooden toe and a wooden frame, see Figure 3. 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 nominal diameter of around 0.03 m. Two different size of under layers were used to perform placement tests, see Figure 4. Initially an underlayer of one-tenth of crablock armour units (0.003-0.009 kg) has been used for the placement tests. Nevertheless, with the use of this large underlayer uniform placement of crablock was almost not reachable. Thus, to get the uniform placement a relatively smaller under layer (0.001-0.004 kg) was used to place the armour units.



(a) (b)

Figure 3: Profile of the model breakwater using (a) large frame used for tests 1-11 and (b) Small frame used for tests 12-14

(a) (b)

Figure 4: Picture of (a) conventional (large) underlayer and (b) small underlayer

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 have a good idea about the lower and upper limit of placement density of crablock armour units. In order to establish a reliable dataset, three repetition tests have been performed for each test series 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, see Table 1. It should be noted that all the placement tests were carried out only above water. Prior to the start of test, underlayer was placed on top of the armour slope. Then crablock units started to place 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 scale. See Salauddin (2015) for the full test set up and testing procedure.

Table1: 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	0.71 D	0.57 D	$0.71/D_n^2$
2	Rectangular	Uniform	11 to 16 mm	0.65 D	0.60 D	$0.74/D_n^2$
3	Rectangular	Uniform	11 to 16 mm	0.75 D	0.65 D	$0.59/D_n^2$
4	Rectangular	Uniform	11 to 16 mm	0.80 D	0.60 D	$0.60/D_n^2$
5	Diamond-shaped	Uniform	11 to 16 mm	0.60 D	0.50 D	$0.96/D_n^2$
6	Diamond-shaped	Uniform	11 to 16 mm	0.70 D	0.60 D	$0.68/D_n^2$
7	Diamond-shaped	Uniform	11 to 16 mm	0.80 D	0.65 D	$0.55/D_n^2$
8	Rectangular	Random	11 to 16 mm	0.71 D	0.57 D	$0.71/D_n^2$
9	Rectangular	Random	11 to 16 mm	0.65 D	0.60 D	$0.74/D_n^2$
10	Rectangular	Random	11 to 16 mm	0.75 D	0.65 D	$0.59/D_n^2$
11	Diamond-shaped	Random	11 to 16 mm	0.70 D	0.60 D	$0.68/D_n^2$
12	Rectangular	Uniform	7 to 11 mm	0.71 D	0.57 D	$0.71/D_n^2$
13	Rectangular	Uniform	7 to 11 mm	0.65 D	0.60 D	$0.74/D_n^2$
14	Rectangular	Uniform	7 to 11 mm	0.75 D	0.65 D	$0.59/D_n^2$

4.0 Results and Discussion

4.1 Visual Observation and Experience of Placing

The placement pattern of armour layer is mainly remarked by the visual inspection of armour units. Also, the accuracy of the placement can be little bit assumed by observing the armour layer visually. For each individual dry placement test, armour layer was inspected visually to describe the placement of crablock for that specific test. In this paper only four test series (out of fourteen) have been described based on visual inspection.

4.1.1 Test 1: Rectangular Grid with Uniform Placement

The main aim of this specific test was to verify the theoretical packing density of crablock. A picture of the placement test number one in test series one (Test 1.1) is presented in Figure 5. From the visual inspection, it is observed that some of the units have uniform orientation whereas some of the units could not be placed with intended regular orientation. For instance, in the picture the yellow line together with red dots shows that not all the units have same orientations also not even in the same line. However, the units indicated by blue line are maintained similar orientations in a column. Furthermore, it is remarkably inspected from the photograph that all the units are interlocked with surrounding units.

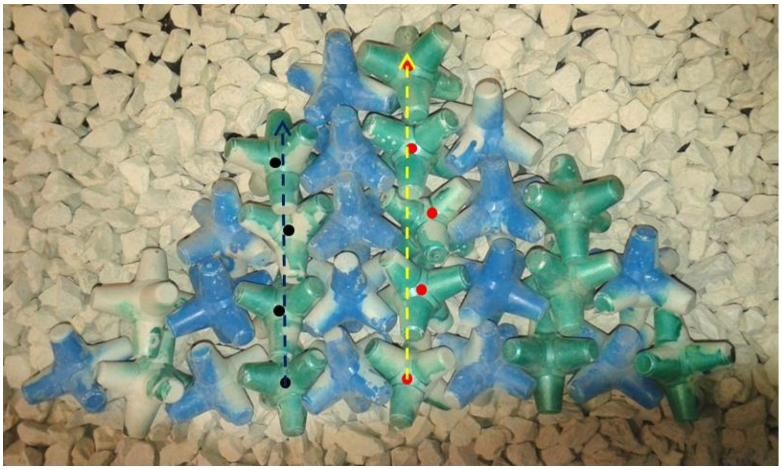


Figure 5: Picture of placement test number one in test series one (Test 1.1)

4.1.2 Test 6: Diamond-Shaped Grid with Uniform Placement

Figure 6: Picture of placement test number two in test series six (Test 6.2)

The aim of this test was to find the possibility of uniform placement of crablock units in a diamond shaped grid with horizontal placement distance of 0.70 times the height of crablock and upslope placement distance assumed 0.60 times the height of crablock model unit. The picture of the placement test number two in test series six (6.2) is attached in Figure 6. The image says that a proper uniform placement pattern could not be achieved in this test even though units are interlocked with surrounding units. All the units were placed with regular rotation according to the designed grid position. But, it is remarkably noted from the image that some of the units do not have uniform orientation. Moreover, some of the units are not in the same line with neighbouring units of same row. The model units in the row indicated by red dots in the following photograph do not have uniform orientation and also are not in the same line.

4.1.3 Test 8: Rectangular Grid with Random Placement

The purpose of this test was to verify the recommended theoretical packing density by Bonfantini (2014) in a rectangular grid with random orientation of units. Similar to the placement test one, this test was also performed in a same rectangular grid and also with same nominal packing density, only the orientations of the units were random for this test. The placement of units with random orientation was relatively easier and quick in comparison to previous all tests with uniform orientation. A photograph of placement test number three in test series eight (Test 8.3) is printed in Figure 7, to describe the test from visual observation. Based on visual inspection and experience of placing, it was inspected that all the units were more or less interacted with nearby units that means no loose units were observed in this placement test. However, the photograph (Figure 8) says that some units misplaced from their defined position in the vertical line (column) and horizontal line (row). For instance, the red line in the following image is indicating the straight column line and red dots are showing the position of units supposed to be that line. This observation clearly illustrates that most of the units in that particular column has moved from their designed position. Therefore, the accuracy of the placement of units might be less using this designed grid.

4.1.4 Test 12: Rectangular Grid with Uniform Placement Using Smaller Under Layer

The specific aim of this test was to examine the uniform placement pattern of crablock armour units in a smaller under layer. In this experiment, the horizontal and upslope placement distance were used as same as the placement test series one and eight. However, in this experiment under layer was relatively small in size compared to previous tests. At the time of placement of units, it was noticed that uniform placement of armour units in a smaller under layer is relatively easy. Also, during the tests it was examined that even though almost all the units could be placed according to their design horizontal spacing but suggested upslope distance was quite short for most of the units. Based on the visual inspection, it is detected that a proper uniform pattern of crablock was achieved in this test, see Figure 8. To cite an example, units indicated by the red dots in the following picture reveals that all the units in that specific vertical line have same orientation and also position of almost all the units are in the line. Moreover, it is also identified that all the armour units are attached with neighbouring units which ensures good interlocking of armour layer.

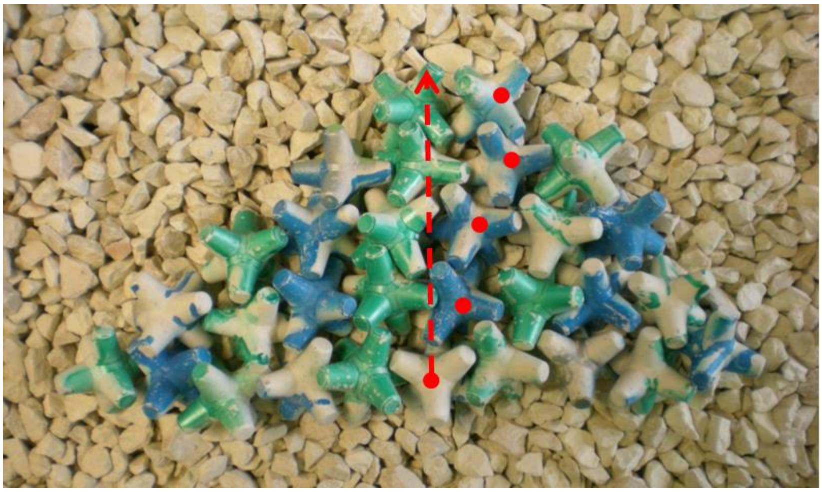


Figure 7: Picture of placement test number three in test series eight (Test 8.3)

Figure 8: Picture of placement test number one in test series twelve (Test 12.1)

The different placement patterns in a designed grid for different tests can be compared regarding to the visual inspection. For example, the following observations are made about the placement of crablock by comparing the tests regarding to visual observation. To scrutinize the placement pattern of crablock in a rectangular grid, Figure 5, Figure7 and Figure 8 are compared based on visual inspection. All the three test series (Test1, Test8 and Tes12) were performed with the same designed horizontal and upslope placement distance. However, it was observed that small underlayer (Test 12) certainly provides better uniform placement in comparison to conventional underlayer (Test 1) in a same designed rectangular grid. Also, it was noticed from the mentioned figures that regular pattern (Figure 5 & Figure 8) looks more interlocked compared to a random pattern (Figure 7).

Table 2: Overview of visual inspection observed 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	0.71 D	0.57 D	Uniform	Not 100% Uniform	interlocked
2	Rectangular	0.65 D	0.60 D	Uniform	Not 100% Uniform	good interlocked
3	Rectangular	0.75 D	0.65 D	Uniform	Not 100% Uniform	loose units
4	Rectangular	0.80 D	0.60 D	Uniform	Not 100% Uniform	lot of loose units
5	Diamond	0.60 D	050 D	Uniform	Random	lot of loose units
6	Diamond	0.70 D	0.60 D	Uniform	Random	interlocked
7	Diamond	0.80 D	0.65 D	Uniform	Random	lot of loose units
8	Rectangular	0.71 D	0.57 D	Random	Random	interlocked
9	Rectangular	0.65 D	0.60 D	Random	Random	interlocked but too narrow
10	Rectangular	0.75 D	0.65 D	Random	Random	loose units
11	Diamond	0.70 D	0.60 D	Random	Random	good interlocked
12	Rectangular	0.71 D	0.57 D	Uniform	Uniform	interlocked
13	Rectangular	0.65 D	0.60 D	Uniform	Uniform	good interlocked
14	Rectangular	0.75 D	0.65 D	Uniform	Uniform	loose units

Furthermore, in order to get a complete view, visual inspection of all the tests are printed in Table 2. From the following table, it can be realized that theoretically designed uniform placement pattern could not be achieved for all cases. Also, a lot of loose units were observed for some tests which are not allowable in real situation.

4.2 Accuracy of Placement

The accuracy of the placement can be predicted by determining the average deviation of units from the designed grid position. Based on the measured position of units, the deviation of each individual unit can be determined. For example, for the placement test series 13, the deviation of each individual unit from the designed placement grid is printed in Figure 9. In this research, the average deviation of units has been determined for all the placement test series. The accuracy of the placement differed with different grids and also with different orientation of units. In Table 3, the measured average deviations of units in together with standard deviation are presented for all the test series. From Table 3, it is inspected that in general the accuracy of placement in a rectangular grid with uniform placed crablock is larger than the rectangular grid with randomly placed crablock units. For example, the average total deviation of units in test 2 is calculated as 0.1 D which is much smaller than the average total deviation of units 0.26 D found in test 8. However, the different scenario is examined for the diamond shaped grid. For instance, the total average deviations of units monitored in test 5, 6 & 7 with uniform placement are greater than the total average deviations of units forecasted in test 11 with random placement.

Table 3: Overview of deviation of units observed in all test series

Test Series No	Avg. Dev. of X (D)	Std. Dev. of X (D)	Avg. Dev. of Y (D)	Std. Dev. of Y (D)	Total Avg. Dev. (D)	Total Std. Dev. (D)
1	0.11	0.14	-0.13	0.12	0.21	0.14
2	-0.01	0.07	-0.07	0.08	0.1	0.07
3	-0.003	0.15	-0.14	0.14	0.22	0.11
4	0.05	0.16	0.03	0.24	0.25	0.16
5	-0.78	0.48	-0.67	0.43	1.11	0.5
6	-0.12	0.25	-0.12	0.23	0.34	0.17
7	0.22	0.19	-0.09	0.18	0.32	0.17
8	0.01	0.18	-0.19	0.14	0.26	0.14
9	-0.03	0.1	-0.08	0.1	0.14	0.09
10	0.1	0.17	-0.13	0.11	0.23	0.11
11	-0.15	0.17	-0.2	0.15	0.3	0.15
12	0.04	0.05	-0.14	0.11	0.16	0.11
13	0.01	0.07	-0.07	0.07	0.1	0.06
14	-0.01	0.05	-0.07	0.08	0.1	0.06

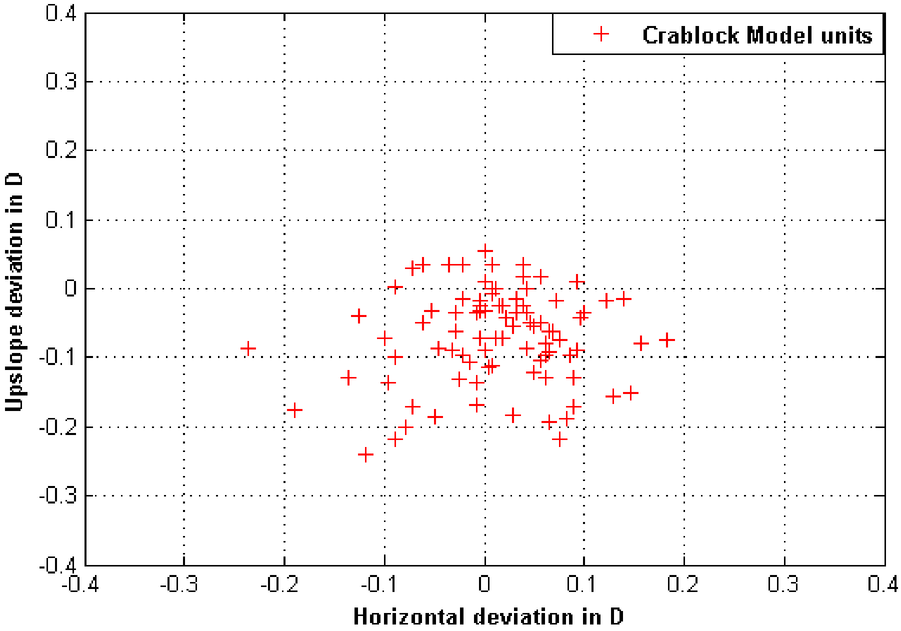


Figure 9: Deviation of units from its intended position

4.3 Packing Density

The average packing density for each particular test was determined by taking mean of local packing density of each particular unit regarding to the calculated horizontal and upslope placement distance for each specific unit. Because of the deviation of units the measured horizontal and upslope placement distance have been also diverged from the theoretically predicted value, see Table 4. As a consequence the calculated packing density also differed from the designed value. Figure 10 shows a comparison between the theoretically designed nominal packing density and measured nominal packing density in each individual test series. The test results showed that in both diamond-shaped and rectangular grid, measured packing density was lower for the randomly oriented armour in comparison to uniformly oriented crablock armour.

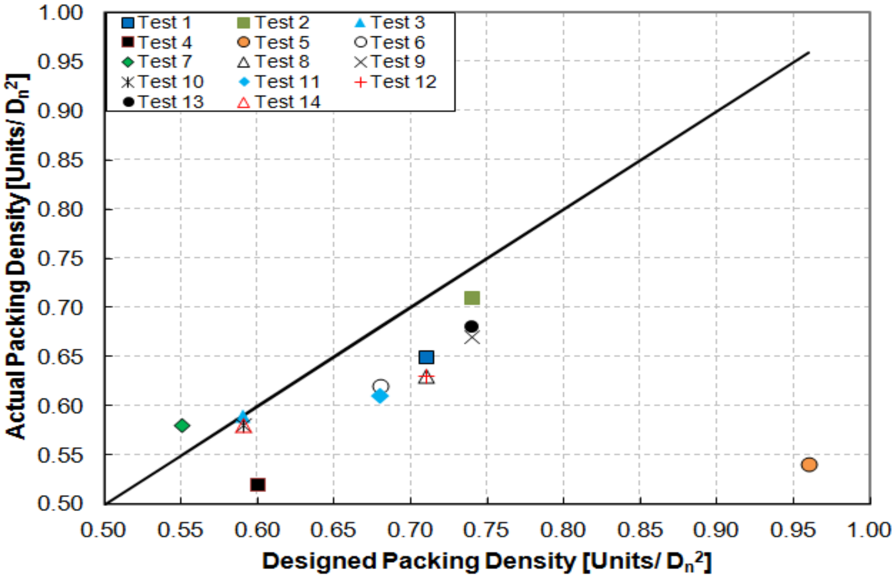


Figure 10: Theoretically designed against measured nominal packing density

Table 4: Overview of designed and measured packing density in all test series

Test Series No	Designed Hor. Placement Dis.	Measured Hor. Placement Dis.	Designed Up. Placement Dis.	Measured Up. Placement Dis.	Designed Packing Density	Measured Packing Density
1	0.71 D	0.69 D	0.57 D	0.64 D	$0.71/D_n^2$	$0.65/D_n^2$
2	0.65 D	0.65 D	0.60 D	0.63 D	$0.74/D_n^2$	$0.71/D_n^2$
3	0.75 D	0.76 D	0.65 D	0.64 D	$0.59/D_n^2$	$0.59/D_n^2$
4	0.80 D	0.79 D	0.60 D	0.70 D	$0.60/D_n^2$	$0.52/D_n^2$
5	0.60 D	0.83 D	0.50 D	0.64 D	$0.96/D_n^2$	$0.54/D_n^2$
6	0.70 D	0.76 D	0.60 D	0.61 D	$0.68/D_n^2$	$0.62/D_n^2$
7	0.80 D	0.82 D	0.65 D	0.61 D	$0.55/D_n^2$	$0.58/D_n^2$
8	0.71 D	0.71 D	0.57 D	0.64 D	$0.71/D_n^2$	$0.63/D_n^2$
9	0.65 D	0.66 D	0.60 D	0.64 D	$0.74/D_n^2$	$0.67/D_n^2$
10	0.75 D	0.74 D	0.65 D	0.67 D	$0.59/D_n^2$	$0.58/D_n^2$
11	0.70 D	0.75 D	0.60 D	0.63 D	$0.68/D_n^2$	$0.61/D_n^2$
12	0.71 D	0.71 D	0.57 D	0.64 D	$0.71/D_n^2$	$0.63/D_n^2$
13	0.65 D	0.66 D	0.60 D	0.63 D	$0.74/D_n^2$	$0.68/D_n^2$
14	0.75 D	0.75 D	0.65 D	0.66 D	$0.59/D_n^2$	$0.58/D_n^2$

Based on the visual inspection, accuracy of placement and comparison between theoretically designed and measuerd packing density, outputs of test series 13 and test series 11 were found satisfactory. A good interlocked uniform pattern of crablock armour units was obtained in a rectagular grid using a relatively small underlayer with a packing density of $0.68/D_n^2$ (test series 13). And in case of a diamond-shaped grid, it was seen that a random placement can be best achieved using a conventional diamond shaped grid with a packing density of $0.61/D_n^2$ (test series 11).

5.0 Conclusions

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

i. It was found that crablock armour units can be placed in both uniform and 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 system.

ii. A uniform pattern of crablock was difficult to obtain in a rectangular grid with conventional (large) underlayer. Nevertheless, it should be noted that tests using a conventional underlayer were performed without the fixation of the first row due to the difficulties in placement with model crablock units. If this can be fixated by designing dedicated toe units (both in rotation and location) it may perform better. Still, the large underlayer makes it difficult to place uniformly.

iii. Nevertheless, the test results showed that regular pattern of crablock can be achieved in a rectangular grid by using relatively small and smooth underlayer.

iv. A good interlocked uniform pattern was obtained with the following measured values: Horizontal distance: 0.66 D and upslope distance: 0.63 D with packing density of $0.68/D_n^2$

v. All the tests in a diamond-shaped placing grid were conducted using a conventional large underlayer. The test results showed that uniform placement of crablock was hardly achievable in a diamond-shaped grid using a conventional large underlayer.

vi. However, it was clearly noticed that in a diamond shaped grid, random placement pattern can be achieved with higher accuracy and easily in comparison to uniform placement pattern. A good interlocked random pattern was achieved with the following measured values: Horizontal distance: 0.75 D and upslope distance: 0.63 D with packing density of $0.61/D_n^2$

vii. Based on the test results, it was also recognized that with the use of random pattern lower packing density can be obtained compared to uniform pattern of crablock, where still on visual inspection the slope with armour units looks good.

6.0 Acknowledgements

First author of this paper would like to acknowledge NICHE-081 BGD project, for funding his MSc study at UNESCO-IHE. Special thank goes to AM Marine Works and CDR international for sponsoring the laboratory studies at Delft University of Technology.

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