Conference Paper, Published Version

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Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) -
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_011

Hydraulic Stability and Practical Application of XblocPlus Breakwater Armouring

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Abstract: XblocPlus is a new type of interlocking single layer armour unit which is placed with uniform block orientation and stable due to interlocking. The combination of uniform block orientation and stability due to interlocking distinguishes XblocPlus from other single layer armour units. The new armour unit arose out of DMC's desire to develop a block which allows crane operators to place faster without assessing the optimum block orientation for each unit. The hydraulic stability of the XblocPlus breakwater armour unit was tested in 2D and 3D hydraulic model tests. Test results of a 3D model test with curved breakwater sections and transitions between Xbloc and XblocPlus are described in this paper. The XblocPlus units were stable on a straight and a curved breakwater section for normal and oblique waves with steepness of s=0.02 and s=0.04 for stability numbers up to Hs/(ΔDn)= 3.5 which is 140% of the design stability number of XblocPlus.

Keywords: Breakwater, concrete armour units, hydraulic stability, XblocPlus, armour layer, design, construction

1 Introduction

Single layer interlocking concrete armour units have widely been used since the 1980's due to their cost effectiveness. These armour units such as the Xbloc and Accropode^{TM} are placed with randomly varying orientations and are stable due to interlocking. They can be used in deep water and for severe wave conditions. The main advantages of these units are 1) high hydraulic stability; 2) efficient material use; 3) flexibility to follow an uneven seabed.

Uniformly placed armour blocks have been used for decades as well, although less frequent. These units are stable due to friction and rely on a solid, stiff breakwater toe. Uniform blocks are therefore mostly applied in shallow water depths, preferably where the toe can be built in the dry. They are less suitable to accommodate geotechnical settlements and are typically used for low to moderate design wave heights. The main advantages of these units are 1) aesthetic appearance of the structure and 2) fast placement process.

During the execution of Xbloc projects over the past fifteen years, DMC noticed the desire for a *uniformly placed, interlocking block*. This block combines the advantages of random placed single layer blocks with the advantages of uniform blocks. In 2018, fifteen years after the introduction of the original Xbloc, DMC therefore introduced the XblocPlus, which is uniformly placed, but stable due to interlocking.

The three block types are shown in Figure 1.

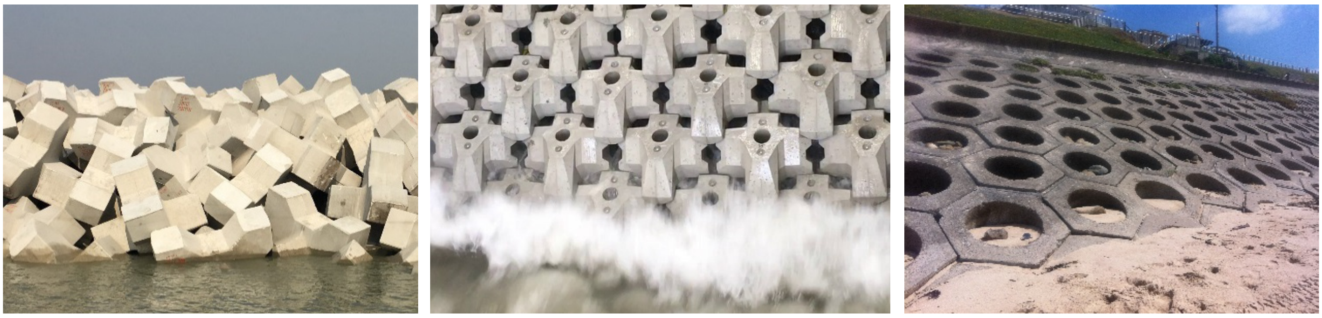

Fig. 1. Xbloc (left): Random placed interlocking, XblocPlus (middle): Uniformly placed interlocking, Seabee (right): Uniformly placed friction

2 Development of the XblocPlus

Single layer interlocking armour units like Xbloc, Accropode™ and Coreloc® are placed with randomly varying orientation to achieve the required porosity and interlocking. If the units are placed in a more regular pattern, the packing density increases and the reduced porosity of the armour layer may cause larger wave overtopping (Muttray et al., 2005). An example of random placement of Xbloc and regular placement of Xbloc can be seen in Figure 2.

Fig. 2. Xbloc Armour unit placed with random orientation (left) & uniformly (right)

During the past fifteen years, DMC noticed that, although it is undesirable with Xbloc, many crane operators have a preference for regular block placement as it simplifies the placement operation. This was the main trigger for the development of XblocPlus, which focused on efficient material use, construction speed, construction safety and of course on hydraulic stability and overtopping.

XblocPlus is placed on a predefined staggered grid, just like Xbloc. The XblocPlus units are resting on the slope and on two units of the next lower row. They are stabilized by two units of the next higher row. Thus, the XblocPlus interlocking is very similar to other single layer armour units. However, the armour unit orientation of XblocPlus does not vary; all units are placed with the same orientation. Therefore, the contact points between units are known and the behavior of the armour layer becomes more predictive (Jacobs et al., 2018). The quality and stability of the armour layer become more homogeneous. This differs from all other single layer, interlocking armouring systems.

The XblocPlus development started from the Xbloc shape which was adapted in steps towards the XblocPlus shape with a hole, which reduces water pressure under the blocks and increases stability. The contact points were optimised for interlocking and flexibility. The development of the block shape can be seen in Figure 3. During the development stages numerous testing procedures were carried out to develop and validate the XblocPlus armour units hydraulic performance and constructability, the test results presented in this paper refer to the final XblocPlus armour unit shape.

Fig. 3. XblocPlus Armour unit shape development timeline

3 Hydraulic Performance of XblocPlus

During the development stages the hydraulic performance of the XblocPlus was tested through numerous 2D & 3D scale model tests. Hydraulic stability of XblocPlus (slope angle 1:2, 2:3 and 3:4) were tested in 2017 and 2018 in the hydraulic laboratory of DMC (Utrecht, NL). Hydraulic stability of XblocPlus under oblique wave attack (slope angle 3:4, wave angles 0° to 60°) was tested in 2017 in 3D model tests at Ludwig Franzius Institute (University Hannover, Germany). These tests are described in Reedijk et al. (2018) and are summarized in Section 3.1 below.

Fig. 4. Large scale tests in the Delta Flume (courtesy Deltares)

Project specific model tests have been carried out for the renovation and upgrading of the Afsluitdijk, a major dam and causeway in The Netherlands. For this project the unit is also referred to as Levvel-bloc, named after the construction consortium. These Afsluitdijk tests have been carried out at small scales at DMC's laboratory (Utrecht, NL) and in the Schelde Flume - Deltares (Delft, NL).

Furthermore large scale test have been carried out in the Delta Flume – Deltares (Delft, NL). These test are described by Klein Breteler et al. (2019). An impression of the tests is shown in Figure 4.

Additional 3D model tests were performed in 2018 at Ludwig Franzius Institute (University Hannover, Germany). The objective of these tests was to investigate 1) the hydraulic stability of XblocPlus in curved sections and 2) at an interface between Xbloc and XblocPlus. These tests are described in Section 3.2 and 3.3 below.

3.1 *Summary of Hydraulic Stability XblocPlus*

The numerous model tests carried with the final XblocPlus shape in various 2D and 3D physical model tests are summarized in Figure 5 with the Xbloc model test results from 2001-2002 included as reference.

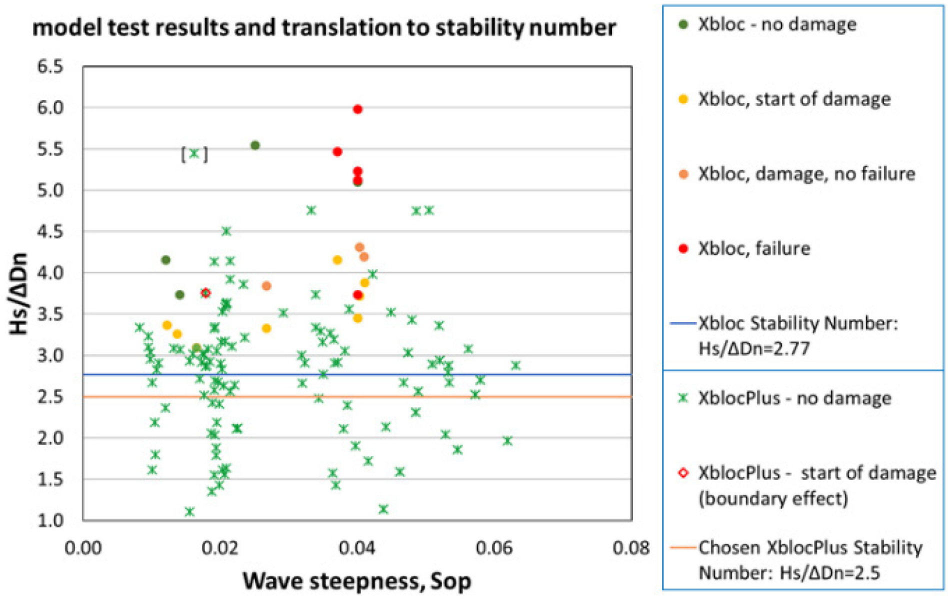

Fig. 5. Graph displaying the model test results for both the XblocPlus & Xbloc armour units and the translation to stability number.

Figure 5 contains information for straight breakwater sections. DMC has concluded that the stability of XblocPlus is very high in comparison with Xbloc as no damage was observed even for a stability number of Hs/(ΔDn)= 5.5 and no rocking was observed in all these tests. This is a significant difference with randomly placed blocks like Xbloc and Accropode™ where rocking units are usually observed in model tests during design or overload conditions. As no rocking is observed the risk of armour units breaking in a severe storm is reduced.

Despite the fact that the stability observed in the model tests conducted so far is very high, DMC has chosen to apply a design stability number of Hs/(ΔDn)= 2.5. When comparing Xbloc (Hs/(ΔDn)= 2.77) and XblocPlus on a breakwater slope with identical wave height, there is an additional safety margin in the XblocPlus size. At the same time it also leads to a significant reduction in the number of blocks to cast and place and therefore this choice leads to increased stability as well as to increased construction speed.

3.2 *Setup of 3D Model Test in Hannover 2018 tests*

The test setup for the Hannover 2018 tests for curved sections and Xbloc-XblocPlus transitions can be seen in Figure 6. The length of the test sections was a 6.26m straight section, adjacent to a curved shape with an angle of 30° followed by a second 3.9m long straight section.

The core was made of 8-16 mm stones and 12-16mm stones were applied as underlayer. The toe consisted of 12-16 mm stones. The front slope had a steepness of 3:4 and was armoured with XblocPlus & Xbloc. The rear slope had a steepness of 2:3 and was armoured with 40-125mm rock armour.

The northern breakwater head (in Figure 6) along with the first 1.0m of the front amour layer were built up by Xbloc units with a weight of 49g (density 2367 kg/m^3). Next to this, a transition section Xbloc – XblocPlus was constructed followed by a straight Xbloc plus section, a 30° curved XblocPlus section and a transition from XblocPlus to rock. The XblocPlus units were 58.4 gram with a mass density of 2360 kg/m^3.
The radius at the toe of the XblocPlus armour is 3.20m with an arc length of 1.68m in which 26 model units were placed in the first row. This is a larger unit to unit distance (called Dx) than the Dx that is applied for normal straight XblocPlus section. This increased Dx is applied in order to create space to apply the XblocPlus units on the curved section as the Dx decreases in the higher rows on the slope. The breakwater has a height of 15 rows of XblocPlus units at the curved section.

The southern end of the breakwater consists of an interface between XblocPlus units and rubble armour of Dn=0.044m. The southern breakwater head is constructed with rubble armour Dn=0.039m.

Settlements and displacement of armour units were analysed from photos before and after the tests.

The design wave height of the applied Xbloc model units is Hs=10.4 cm based on a stability number of Ns = Hs/(ΔDn) of 2.77. The design wave height for the XblocPlus armour units is Hs=9.8 cm, based on a stability number Ns = Hs/(ΔDn) of 2.5. The design wave height of 9.8 cm is used as basis for the model tests. Stability tests were performed with stepwise increasing wave height and constant wave steepness. The planned initial wave height was 80%; wave heights were intended to be increased by increments of 20% to about 140% (percentages refer to the design wave height, Hs of 9.8 cm). However, when the calibration of the incident wave conditions to the point was conducted, wave heights of 120% and 140% could not be reached due to intensive wave breaking over the shallow foreshore. Therefore, for the 120% and 140% tests it was decided to raise the still water level by 0.04m to gain the larger wave heights at the target point. Stability tests and overtopping tests were conducted with wave directions 0° (head-on waves), 15° and 30°. JONSWAP wave spectra were applied; the test duration was >1,000 individual waves. Test series were conducted with a wave steepness of 0.02 and 0.04.

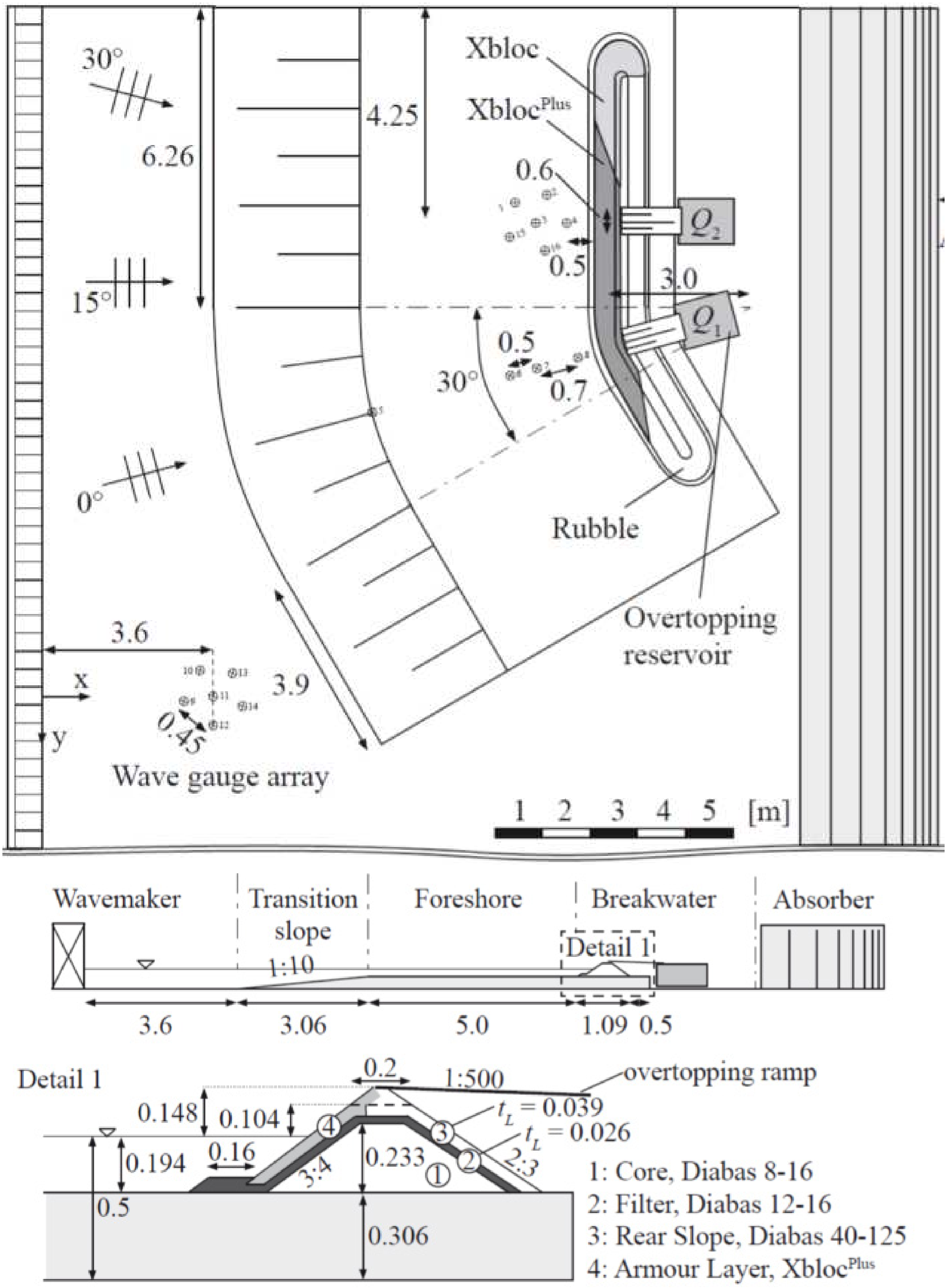

Fig. 6. 3D test setup plan and section views

Fig. 7. Impressions of model construction

Fig. 8. Breakwater model in 3D tests, Curved section and XblocPlus / Xbloc Interface

3.3 Results of 3D Model Test

Three types of armour layer damage are usually considered in physical model tests.

- Displacement of units;
- Settlements of the armour layer which leads to compaction of the armour layer under water and opening up of the armour layer above the water line;
- Rocking of armour units which in prototype may lead to unit breakage.

Displacements

During the 140% design wave height with long waves (s=0.02) the rock armour on the crest and rear side of the breakwater was damaged and subsequently a number of XblocPlus units in the top row were moved backwards. This displacement is a result of the rock armour instability and is not considered as damage to the front armour.

Apart from this case, no displacement was observed which means that the XblocPlus units were stable for all wave steepnesses (s=0.02 and s=0.04) for all wave directions (0°, 15° and 30°) for wave heights from 80% until 140% of the design wave height of the model blocks. This applies for the XblocPlus units on the straight section and the curved section and also for the Xbloc – XblocPlus transition.

Settlements

Due to the nature of the XblocPlus layer, no significant settlements can occur if the rock toe is stable throughout the tests. During the tests, no settlements were observed.

Rocking

Although in general no rocking is observed in XblocPlus model test, there was one unit close to the toe observed rocking during these test. Out of the 2000 model units placed in the model this is 0.05%. This is expected to be caused either by the placement of the unit itself and its surrounding units or by a slight movement of the rock toe.

Influence of wave direction

No influence was found of the wave direction.

Influence of wave steepness

Apart from the fact that the long waves created damage to the crest and rear armour which led to displacement of some armour units at the top of the front armour, there was no damage and therefore a possible influence of wave steepness on the stability of the XblocPlus units could not be determined.

Transition XblocPlus - Rock

The XblocPlus units were stable at this transition in all tests, but it was observed that especially during the first tests, even with moderate wave heights, stones were displaced from the rock armour layer and fell onto the XblocPlus layer. In prototype this can lead to breakage of armour units which should be prevented. The main cause of the rock displacements is that the rock armour (layer thickness 7.5cm) and the XblocPlus armour (layer thickness 3.9cm) were placed on the same under layer profile. As a result the top layer of the rock armour lacked support from the XblocPlus layer at the transition. For the transition XblocPlus to rock armour, it is therefore important to place the rock layer deeper than the XblocPlus layer in order to create a smooth outer surface and a good support for the rock armour.

Fig. 9. Rock displacement at transition XblocPlus - Rock

Fig. 10. Breakwater model in 3D tests, XblocPlus / Rock Interface and Curved section

4 Constructability Aspects of XblocPlus

Expected performance of XblocPlus in practical applications is derived from comparison with other armour units in scale models and from placement trials performed, and for model testing/placement trials on uneven underlayers. The first project with XblocPlus armour units, The Afsluitdijk project will begin construction in 2019.

4.1 Concrete Consumption

The volume of concrete consumed in protecting a given area of breakwater slope for a given design wave height is similar to that of Xbloc, hence about 10% lower than for other single layer interlocking armour units such as Accorpode-II™.

This is shown in Figure 11, which compares graphically the XblocPlus, Xbloc and Accropode-II™ number of units and total concrete volume on a breakwater slope of 80 m width and 10 m length (in upslope direction), for a given design wave height (of Hs=5.3m) that requires a unit size of 4 m^3 for XblocPlus and 3 m^3 for Xbloc and Accropode-II™.

This indicates that significant savings can be achieved as the number of Xbloc units is 35% higher than XblocPlus, and the number of Accropode-II™ units is 44% higher.

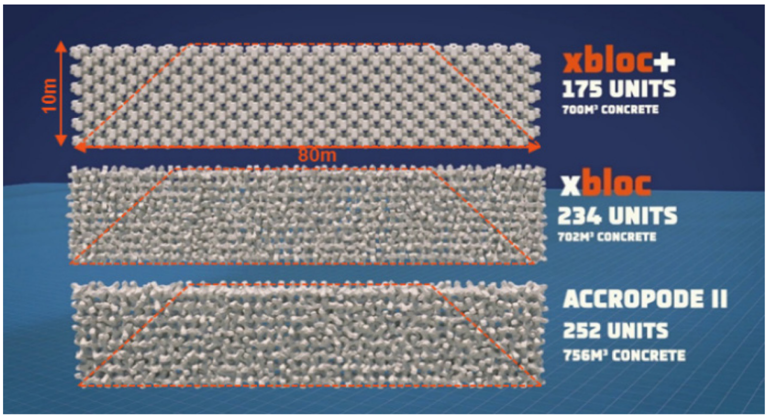

Fig. 11. Scale comparison of 4 m^3 XblocPlus units, 3 m^3 Xbloc & 3 m^3 Accropode-II™

The amount of concrete consumed with XblocPlus is equal to Xbloc and 10% less than Accropode-II™. XblocPlus uses 0.83 m^3/m^2, Xbloc 0.83 m^3/m^2 and Accropode-II™ uses 0.916 m^3/m^2 based on the design tables of these units.

It should be noted that due to the uniform placement pattern of XblocPlus, it is impossible to place the units at a higher packing density than theoretical.

For units such as Xbloc and Accropode-II™ as-built packing densities can be higher than theoretical due to e.g. too uniform placement. XblocPlus makes material quantities more predictable.

4.2 Placement of XblocPlus

Conventional placement of single layer armour units is done by excavator or crawler crane, with a sling and quick release hook, guided by GPS coordinates. XblocPlus units can be placed easily, quickly and accurately with a specially developed hydraulic gripper. This is possible due to the hole in the centre of the XblocPlus units, which serves as a lifting point for the hydraulic gripper. (apart from reducing the water pressure under the block, which increases the stability).
The first placement trials within the Afsluitdijk Project (The Netherlands), were performed with this lifting configuration in 2018 (Figure 12). Another significant advantage of this placement arrangement is that no workers are needed outside on the breakwater to wrap a sling around the blocks to be placed. This improves the safety and cost efficiency of the placement processes of armour units on the breakwater.

Fig. 12. Placement of 2.5 m^3 XblocPlus

4.3 Underlayer Tolerances Effect on XblocPlus

Investigations and physical model testing have been carried out to determine the effect of underlayer irregularities and unevenness for XblocPlus placement and its hydraulic stability (Berg, 2018).

Numerous underlayer slopes were investigated with varying levels of smoothness, involving concave and convex shapes and slopes with an S profile. With small deviations in the underlayer surface having little effect on the hydraulic stability whilst larger deviations in the underlayer, such as S-profiled underlayers having a greater effect on the hydraulic stability. Based on physical tests conducted with this poor profiling the results indicate that the hydraulic stability number $Hs/(\Delta Dn)=2.5$ still applied to the block is applicable based on test results. (Berg, 2018)

It was concluded from the research that the tolerances in the underlayer for the XblocPlus can be equal to the tolerances for Xbloc (0.5 Dn50), When it comes to badly profiled rock, an example of XblocPlus units placed on a badly profiled underlayer is shown in Figure 13. During this scale trial a rock underlayer representing a grading of 0.3-1.0 ton which is typical for a XblocPlus unit of 2.5 m^3 was dumped onto a 3:4 slope and not profiled. XblocPlus units of 2.5m^3 in size were placed on top of this uneven profile on coordinates. All blocks were inspected on interlocking by pulling them from the layer and it was concluded that all units were in fact interlocking. Furthermore it is important to realize that row 1 and 2 are typically covered by a rock toe berm giving additional protection against the waves. From row 3 upwards the units are in a good interlocking grid which shows that even with a very poorly profiled under layer, XblocPlus can be placed in a good grid (although this is not an invitation for contractors not to profile the rock under layer before placing XblocPlus units).

Fig. 13. Placement of XblocPlus units on an under layer significantly exceeding construction tolerances

5 Conclusion

The XblocPlus Armour unit is a uniformly placed interlocking armour unit. Through the numerous 2D and 3D physical model testing regimes carried out during the development of this unit it has been demonstrated that a stability number of $H_s/(\Delta D_n) = 2.5$ can be adopted for design. The hydraulic stability of straight / curved XblocPlus armoured slopes, along with transition zones between Xbloc Plus and Xbloc / Rock was tested in 3D hydraulic model tests. The model tests have demonstrated that the actual hydraulic stability exceeds the stability number of XblocPlus $N_s = H_s/(\Delta D_n)$ of 2.5. Even in overload conditions with 20% and 40% exceedance of the design wave height virtually no damage was observed. The model test series did not show any significant damage, therefore a possible effect of wave steepness or wave direction on XblocPlus stability could not be determined.

The hole in the centre of the armour unit not only increases its hydraulic stability but acts as a lifting point for the specially developed hydraulic gripper to efficiently place the XblocPlus units. Through testing and trial placements, the ability for the XblocPlus unit to maintain its hydraulic stability and remain interlocked on uneven or irregular underlayers has been demonstrated.

XblocPlus is being applied on 2 projects at the beginning of 2019. The first is the Afsluitdijk Project, a 30 km long major barrier in The Netherlands, the second is the Porto Albania Marina Project in Albania. Future publications will include the construction experience with and prototype performance of the new unit.

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