WAVE OVERTOPPING REDUCTION BY MODULAR CONCRETE ARMOUR UNITS

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This paper describes a new armour unit called XP-Overtop which is applied together with XblocPlus armour units in a modular armour layer in order to reduce wave overtopping. This unit is placed close to the crest of the structure. Physical model tests have been performed to study the hydraulic stability and the overtopping reduction of the XP-Overtop as a function of the relative freeboard. Based on the model tests performed, the following conclusions can be drawn: 1) XP-Overtop generates substantial overtopping reduction which increases with increasing relative freeboard; 2) because of the limited effectiveness and hydraulic stability for a low relative freeboard, it is not recommended to apply XP-Overtop for structures with a relative freeboard below $R_c/Hm0=1$; 3) the roughness factor γf for a structure with XP-Overtop is a function of the relative freeboard and varies between $\gamma f=0.42$ and $\gamma f=0.41$; 4) XP-Overtop enables a designer to reduce the crest level of a structure; 5) this reduction translates to significant reductions in the construction materials, costs and CO2 emissions.

Keywords: rubble-mound breakwater; concrete armour; wave overtopping

INTRODUCTION

The seaward armour layer of breakwaters and shore protections is typically made of one kind of armouring (e.g. armour rock or concrete armour units) which is applied from the toe of the structure all the way to the crest. The choice for a certain type of armouring is driven by the hydraulic stability of the structure hence by the wave loads which are maximum close to the still water level. The crest level of the structure is determined by the overtopping requirements which are influenced by the relative freeboard and also by the hydraulic roughness of the chosen material and the wave conditions and water levels. A thin armour layer with a high hydraulic stability can be efficient in terms of concrete quantities but may result in a higher crest level if the armour type has a low hydraulic roughness. A higher crest level leads to increased core material quantities.

In this paper a new armour unit named XP-Overtop is presented which is a modular option that can be applied on XblocPlus structures. This block is an adjusted XblocPlus which reflects part of the wave run-up. Two rows of these units are placed near the crest of a structure where the wave loads are lower. These two rows add roughness high on the slope and reduce the wave overtopping without changing the properties of the armour layer further down on the slope. On top of the 2nd row of XP-Overtop one or two rows of XblocPlus are placed to stabilize the exposed XP-Overtop units. By using the XP-Overtop unit, the advantages of the XblocPlus with regard to the high hydraulic stability and low concrete consumption can be combined with a lower crest level and reduced core material quantities.

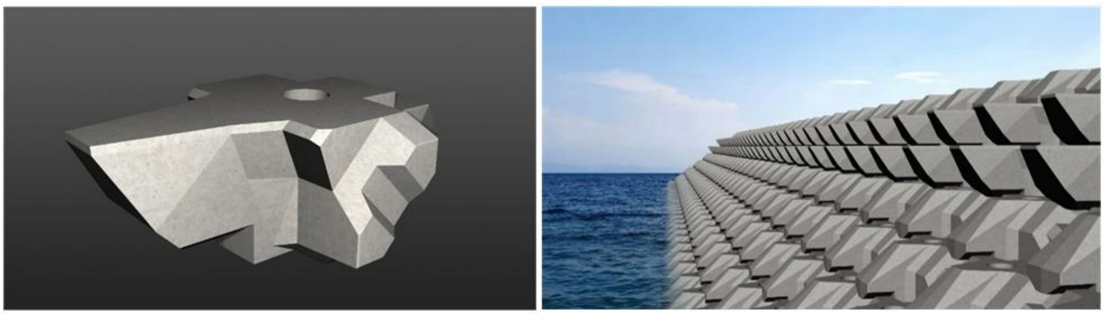

Figure 1. XP-Overtop (left) and armour slope made of XblocPlus with 2 rows of XP-Overtop (right).

The idea of the XP-Overtop unit is based on recurves which are applied on caissons and crown wall structures. From these structures it is known that the relative freeboard has a significant impact on the effectiveness to reduce wave overtopping and that wave forces on recurves can be large. Due to the shape of the XP-Overtop (Figure 1) this unit is more exposed to the overtopping waves than an XblocPlus unit. However, since it is placed near the crest of relatively high structures the wave forces are lower than close to the waterline. At this high elevation the run-up tongue is thin in relation to the protrusions of the armour block, and the wave overtopping is reduced effectively.

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In the EUROTOP Manual (EUROTOP, 2018) the effect of a recurve on a vertical breakwater is distinguished for 3 zones: for $R_c/H_{m0}\leq 0.5$ the recurve has little or no influence; for $0.5< R_c/H_{m0}\leq 1.0$ the recurve has increasing effect for increasing freeboards and for $R_c/H_{m0}>1.0$ the recurve has maximum effect. These 3 zones are visualized in Figure 2. For XP-Overtop a similar influence is expected.

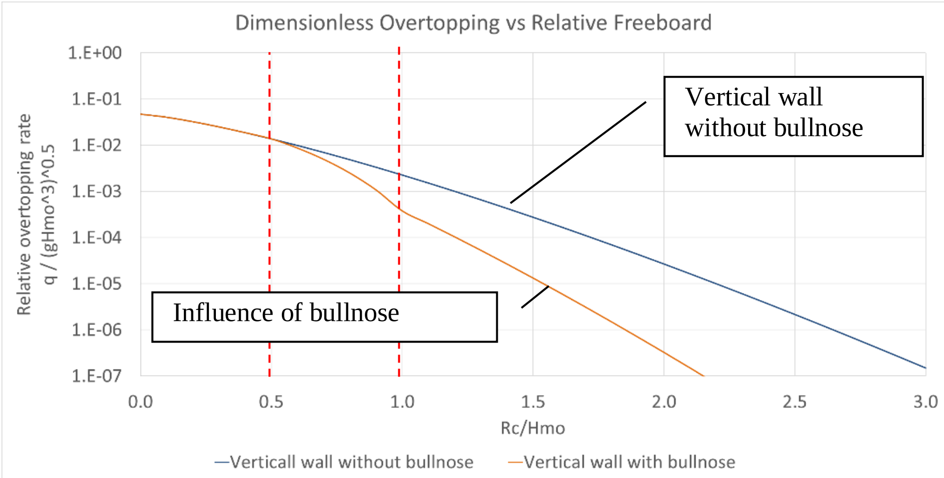

Figure 2. Influence of bullnose on overtopping over vertical wall as function of relative freeboard (from Eurotop2018)

PHYSICAL MODEL TESTS

The stability and effectiveness of XP-overtop were investigated by testing a breakwater model with only XblocPlus and the same breakwater model with XP-Overtop near the crest (Figure 3). These tests were performed in DMC's wave flume in Gouda – The Netherlands.

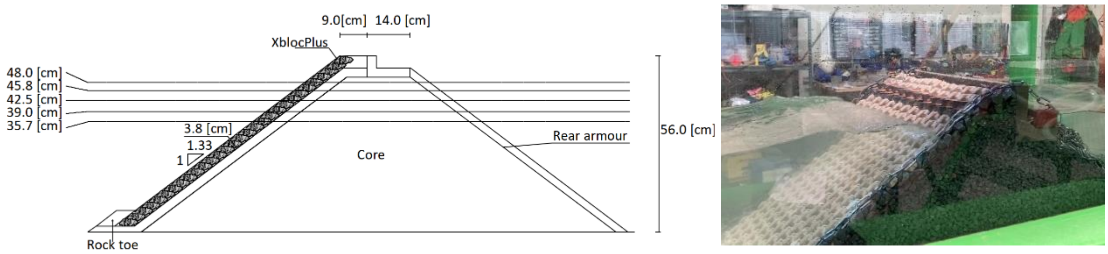

Figure 3. Cross section of physical model tests

The 2 main objectives of the test were 1) to test the hydraulic stability of the XP-Overtop unit for varying freeboards and 2) to test the overtopping reduction as a function of the relative freeboard. The model XblocPlus units have a weight of 58 grams, a density of 2360kg/m^3, a D_n of 2.9cm and a design wave height of $H_{m0,D}$ = 9.9cm (which corresponds to the design stability number $H_{m0}/\Delta D_n$ = 2.5). The stability tests were performed for wave heights between 75% and 160% of the design wave height of the XblocPlus model units. The overtopping tests were performed for wave height of 75% and 100% of the design wave height. No higher waves were included in the overtopping tests as the waves become too large in that case in relation to the thickness of the armour layer. This is in line with the CLASH model test where overtopping tests were performed for wave heights of 50%, 75% and 100% of the design wave height of the model blocks (Bruce et al., 2006). Overtopping was measured at the top of a crown wall at the same level as the top of the armour layer. The tests were performed using two wave steepness's of 0.02 and 0.04, for a relative freeboard (R_c/H_{m0}) between 0.75 - 2.0. The crest height of the breakwater and the tested water depths at the toe are shown in Figure 3. The tests were performed with a horizontal foreshore. The test duration was 1,000 waves per run, using a JONSWAP spectrum with a gamma of 3.3. The DMC flume is equipped with active reflection compensation.

HYDRAULIC STABILITY OF XP-OVERTOP UNITS

For crest levels of R_c/H_{m0}=1 and higher, no damage was observed up to wave heights of 160% of the design wave height of the XblocPlus model units. For a relative freeboard of R_c/H_{m0}=0.75 no damage was observed for waves up to 110%, but start of damage was observed at 120% of the design wave height. The fact that the XP-Overtop units are less stable than the normal XblocPlus units for this low relative freeboard can be explained by the fact that for this freeboard, the XP-Overtop units are placed only marginally above still water level, hence at an elevation where the wave loads are high. As the XP-Overtop units are substantially less stable than the normal XblocPlus units for this tests, it is recommended to apply XP-Overtop only for a freeboard of R_c/H_{m0}=1 and higher.

Table 1. Summary of hydraulic stability tests

Rc/H_{m0}	No Damage	Start of Damage
0.75	110% of $H_{m0,D}$	120% of $H_{m0,D}$
1.00	160% of $H_{m0,D}$	-
1.33	160% of $H_{m0,D}$	-

OVERTOPPING REDUCTION

The overtopping measurements (dimensionless discharge) are plotted in Figure 4 against the relative freeboard R_c/H_{m0}. It can be seen that the XP-Overtop leads to a reduction in overtopping discharge and that this reduction becomes larger for larger relative freeboards. The actual overtopping reduction (ratio of overtopping rates with and without XP-Overtop units) is plotted in Figure 5. For a relative freeboard of 1, the reduction is around 30% and this increases towards 65% for a relative freeboard of 2.

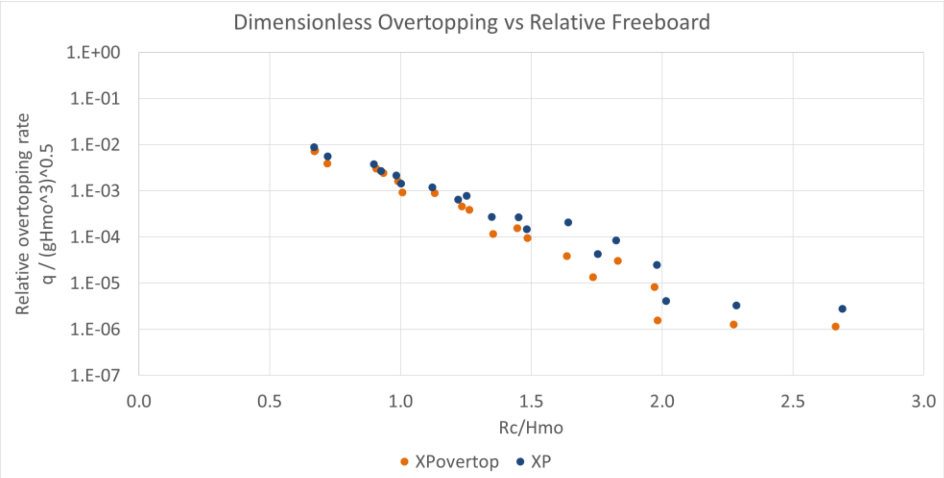

Figure 4. Dimensionless overtopping results with and without XP-Overtop

In Figure 5, three green dots are included which are measurements that were performed by Oceanide from Toulon - France in 2020 during project specific model tests. It can be seen that these measurements are in line with the 2022 model tests in DMC's wave flume.

The data points for the two highest relative freeboards (R_c/H_{m0} of 2.3 and 2.7) are considered less relevant as the overtopping volumes measured were extremely low (less than 10ml during the 1,000 wave test run) hence the absolute difference between the tests becomes insignificant.

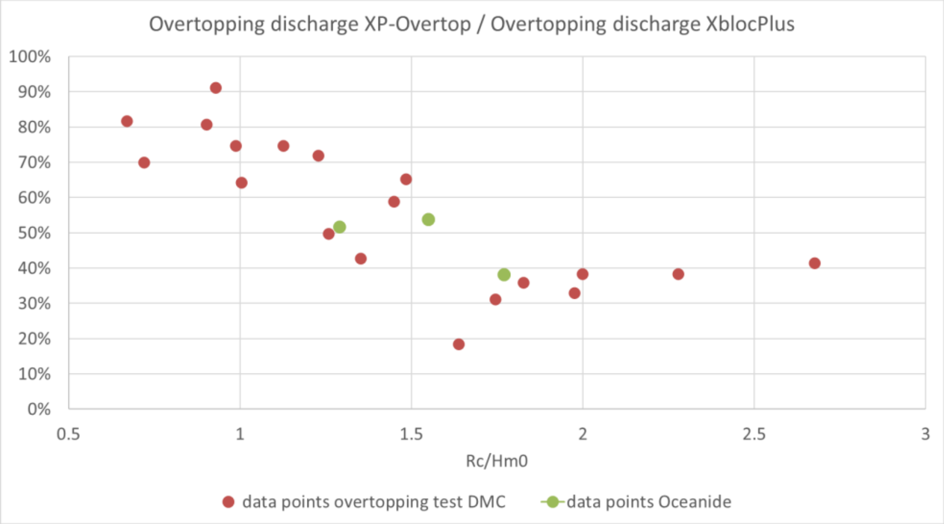

Figure 5. Ratio overtopping with and without XP-Overtop

ROUGHNESS COEFFICIENT XP-OVERTOP

An armour layer with normal XblocPlus has a roughness factor of γf=0.45 (Reedijk, 2018). The combination of XblocPlus with XP-Overtop cannot be described by an adjusted γf since the effect is influenced significantly by the relative freeboard. Based on the test results shown in Figure 4, the following roughness coefficient is proposed for the combination of XblocPlus with 2 rows of XP-Overtop (see Figure 6):

- $\gamma f = 0.42$ for $R_c/H_{m0} < 1$; *(NB: XP-Overtop is not recommended below a relative freeboard of 1)*
- $\gamma f = 0.43 - 0.01\ R_c/H_{m0}$ for $1 \leq R_c/H_{m0} \leq 2$;
- $\gamma f = 0.41$ for $R_c/H_{m0} > 2$

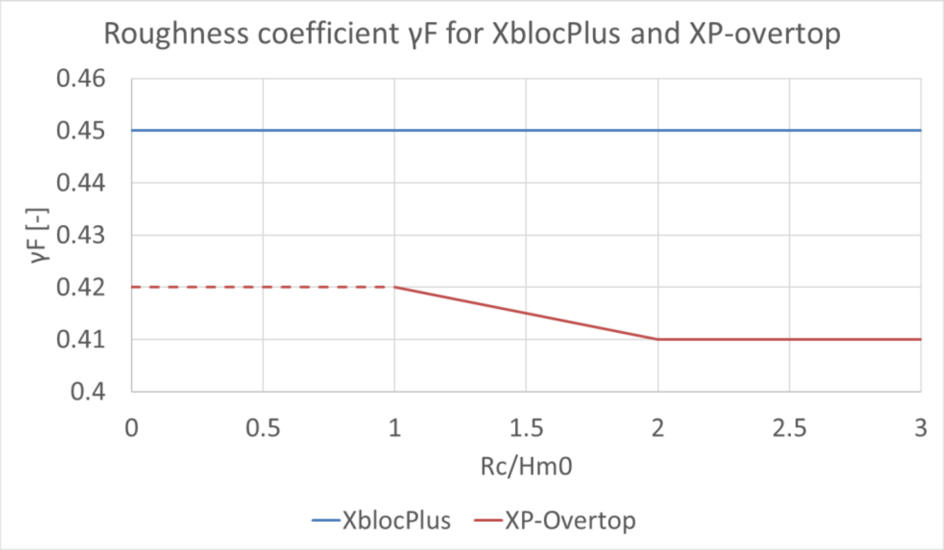

Figure 6. Roughness coefficient for XblocPlus and proposed roughness coefficient for XP-Overtop

A comparison between the overtopping measurements and an overtopping prediction using Equation 6.5 from Eurotop 2018 with the proposed roughness coefficients is shown in Figure 7 and Figure 8. It can be seen that the proposed roughness coefficients give a good match between the theoretical overtopping predictions and the overtopping measurements.

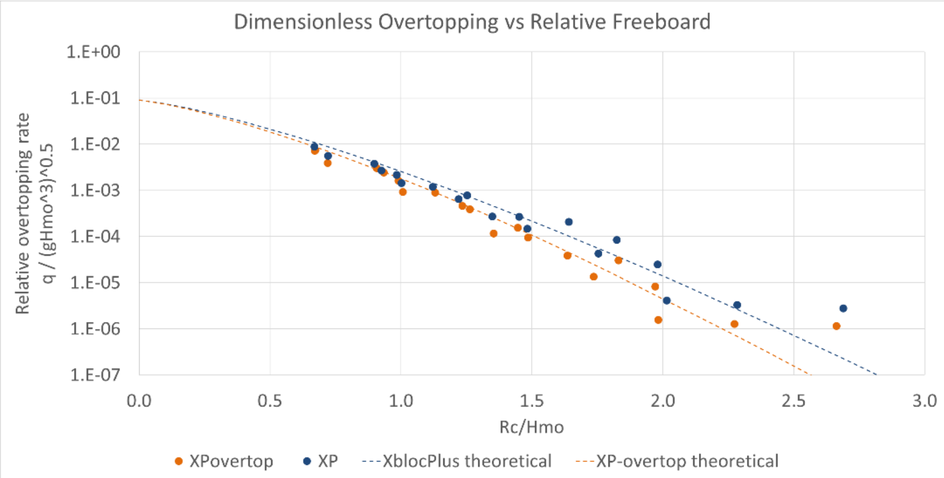

Figure 7. Overtopping measurements and theoretical overtopping predictions based on proposed roughness coefficients

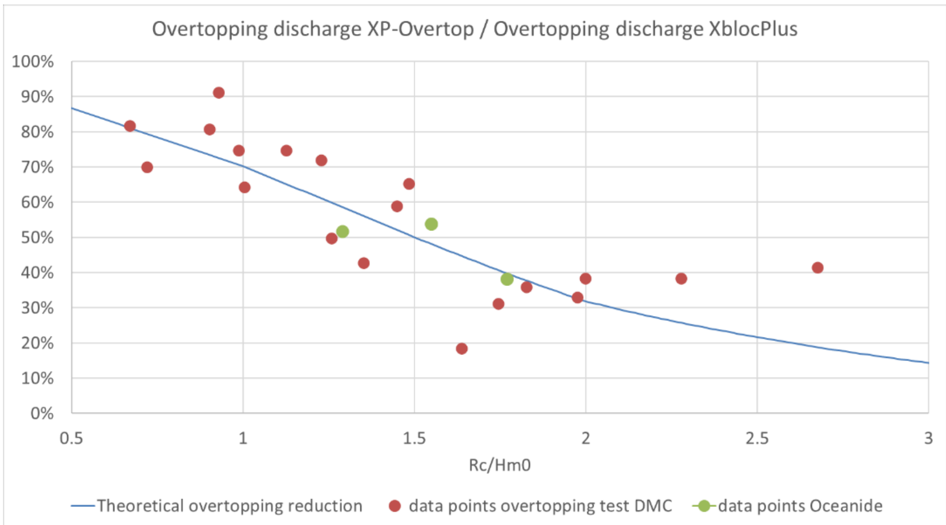

Figure 8. Measured and theoretical ratio overtopping with and without XP-Overtop

COMPARISON BULLNOSE AND XP-OVERTOP

Figure 9 compares the effect of a bullnose on a vertical wall (as shown in Figure 2) and the effect of the XP-Overtop units (as shown in Figure 7). Although details of the caisson structure with bullnose are unknown, the overall trend is similar.

Both for the bullnose and for XP-Overtop it can be seen that the effect becomes larger with increasing relative freeboard. The effect of the bullnose however starts at a relative freeboard of R_c/H_{m0}=0.7 and the effect of the XP-Overtop becomes significant at R_c/H_{m0}=1. This can be explained by the fact that the bullnose is positioned at the crest of the structure whereas the XP-Overtop units (especially the first row) are placed substantially lower where the run-up tongue is significantly thicker. (Figure 10)

The effect of the bullnose seems to be larger than for XP-Overtop. This may be due to different dimensions of the bullnose and the protruding part of the XP-Overtop. Also the fact that the XP-Overtop units are not a continuous structure (like a bullnose) and therefore the wave run-up may pass between and underneath the XP-Overtop units may explain the difference between the overtopping reduction (as shown in Figure 11).

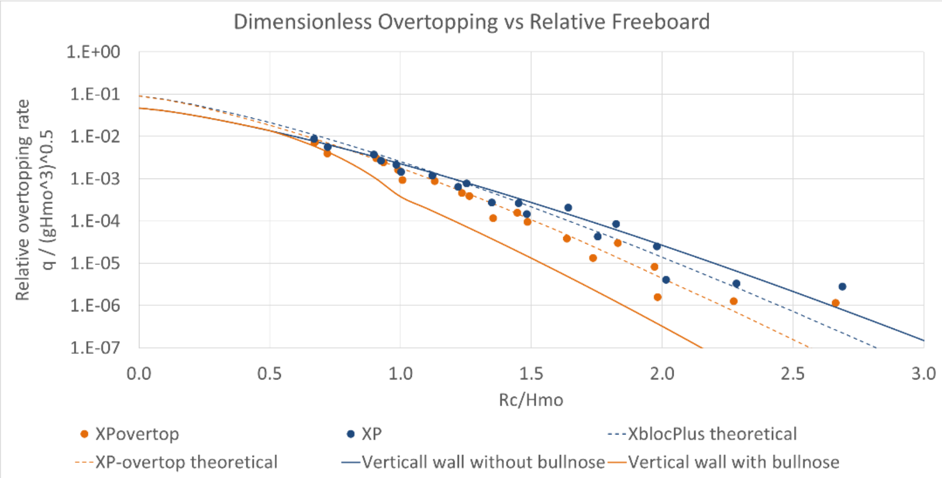

Figure 9. Combined plot of overtopping measurements, theoretical overtopping predictions XblocPlus and XP-Overtop and overtopping effect bullnose from Eurotop 2018

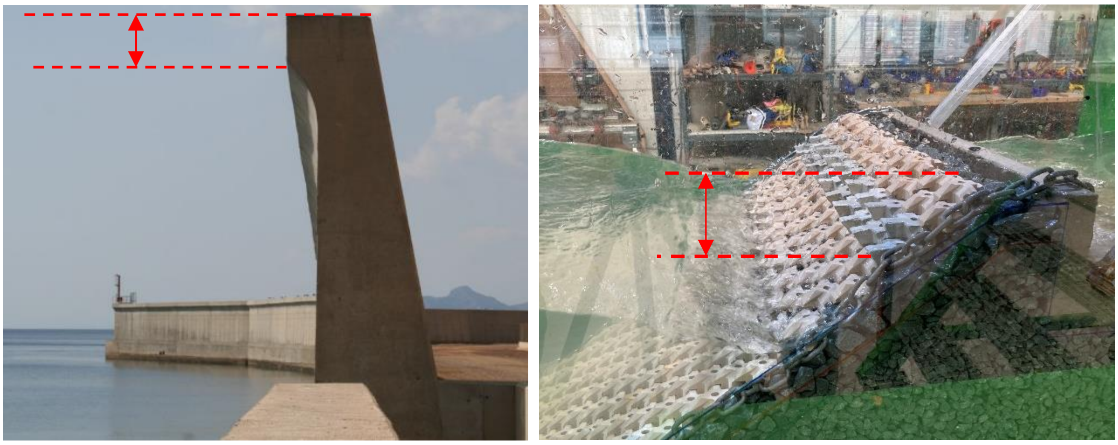

Figure 10. Different level of bullnose (left) and XP-Overtop (right) relative for structure crest level

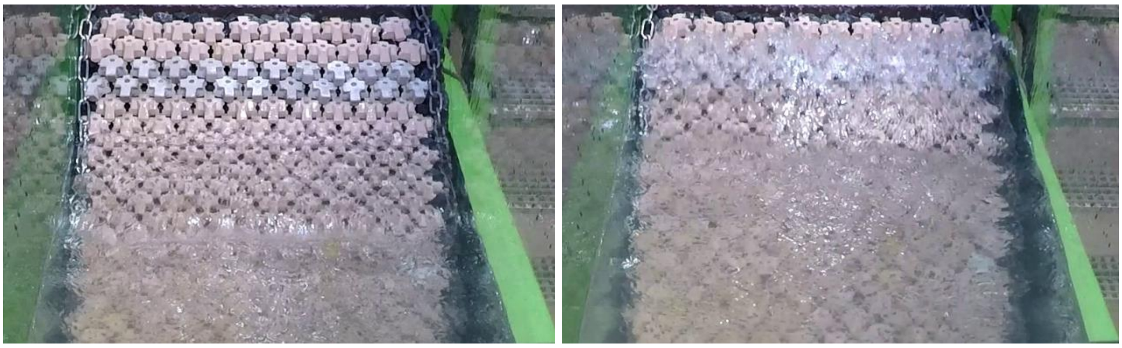

Figure 11. Still from video showing voids between the two rows of XP-Overtop (left) and overtopping wave travelling through (right)

POTENTIAL CREST LEVEL REDUCTION

Figure 12 provides a tool for designers to determine the crest level of a breakwater or shore protection with XP-Overtop that has the same overtopping performance as a structure with only XblocPlus. The horizontal axis shows the relative freeboard R_c/H_{m0} for an XblocPlus structure and the vertical axis shows the reduction in relative crest height ($R_c/H_{m0\_XblocPlus} - R_c/H_{m0\_XP\text{-}Overtop}$) that can be applied when XP-Overtop is applied. It can be seen that the largest reduction can be obtained for structures with a large relative freeboard. Furthermore since the reduction is related to the design wave height, the reduction is especially substantial for structures with a high design wave.

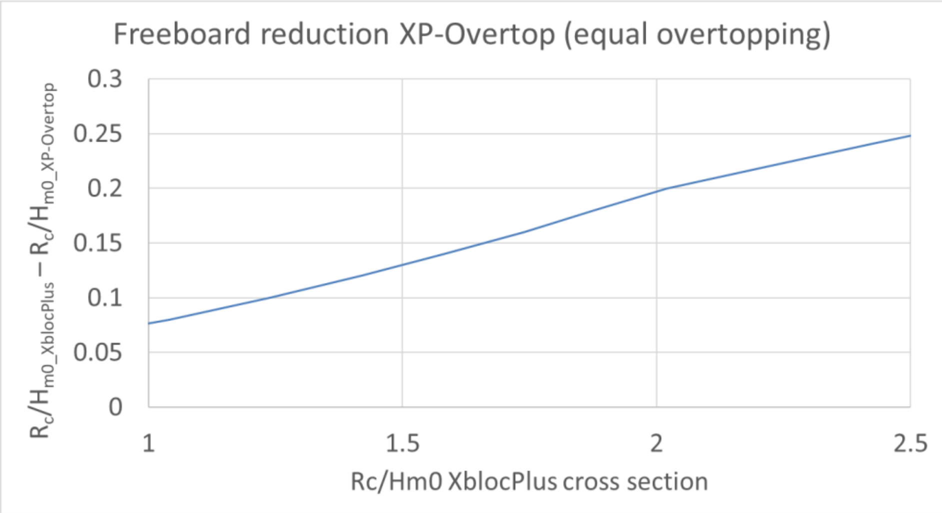

Figure 12. Potential Reduction in Crest Level as function of Relative Freeboard

This reduction is particularly relevant for breakwaters in deep water as the reduced quantity of core material is determined by the width of the breakwater at the seabed. As an example, the breakwater shown in Figure 13 (design wave height H_{m0}=6m and R_c/H_{m0}= 1.5) can be lowered by 0.13 x 6m = 0.78m. For this breakwater which is built in a water depth of 11m, the reduced crest level results in a reduction of 6% in the total rock quantity (which is a saving of 100 tons of rock per linear meter of breakwater) and 3% in the concrete quantity.

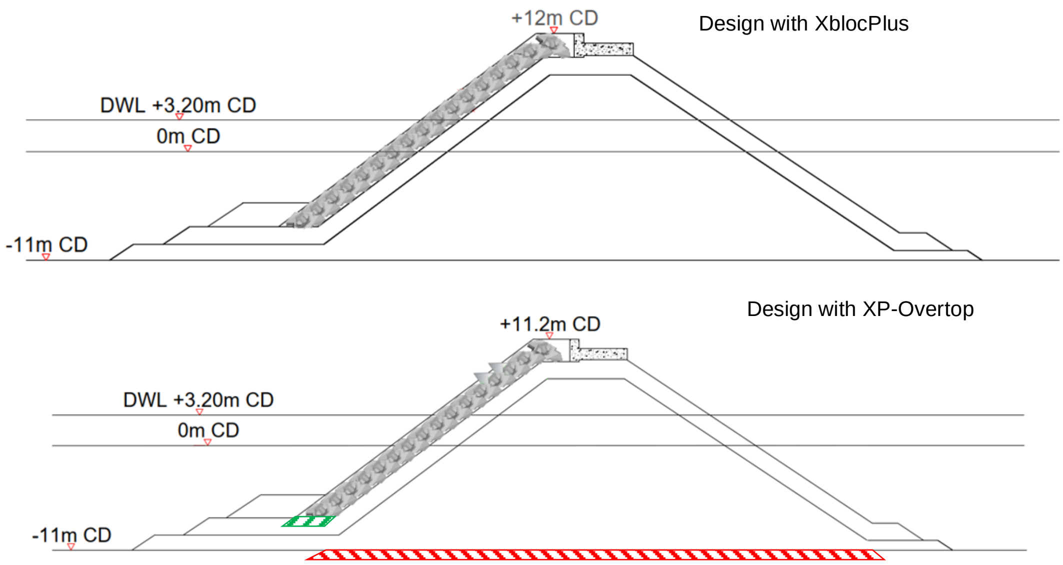

Figure 13. Crest level reduction by 80cm due to use of XP-Overtop: 6% reduction in rock quantity (marked red) and 3% in concrete quantity (marked green)

CONCLUSIONS

Physical model tests have been performed with a new type of armour unit called XP-Overtop which reduces wave overtopping. Combined with XblocPlus, XP-Overtop forms a modular armour system. The XP-Overtop units are placed close to the crest of the structure where wave forces are reduced and the protrusions of the XP-Overtop units are large in relation to the run-up tongue.

Based on the model tests performed, the following conclusions can be drawn:

- XP-Overtop generates relevant overtopping reduction between 30% for $R_c/H_{m0}=1$ and 65% for $R_c/H_{m0}=2$.
- Because of the reduced effectiveness and the reduced stability during the tests with a relative freeboard of 0.75, it is not recommended to apply XP-Overtop for structures with a relative freeboard below $R_c/H_{m0}=1$.
- The roughness factor γf for a structure with XP-Overtop varies from $\gamma f=0.42$ to $\gamma f=0.41$ between $R_c/H_{m0}=1$ and $R_c/H_{m0}=2$ and is $\gamma f=0.41$ above $R_c/H_{m0}=2$ compared to a constant value of $\gamma f=0.45$ for a structure with only XblocPlus.
- The overtopping reduction is similar to the reduction by bullnose elements on caisson structures although the effect of XP-Overtop is smaller and observed at higher relative freeboards.
- XP-Overtop enables a designer to reduce the crest level of a structure. For $R_c/H_{m0}=1$, this reduction is in the order of 0.08 x H_{m0}. For $R_c/H_{m0}=2$ this reduction is in the order of 0.2 x H_{m0}.
- This reduction translates to significant reductions in the construction materials, construction costs and CO2 emissions.

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