STABILITY OF INTERLOCKING ARMOUR UNITS ON A BREAKWATER CREST

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The hydraulic stability of single layer, interlocking armour units on low crested and submerged breakwaters was investigated in 2D hydraulic model tests. Displacements of armour units and rocking were monitored and have been applied as indicators for the armour layer stability on the crest, front and rear slope. The effect of freeboard, packing density and wave steepness on the armour layer stability have been investigated. The stability of interlocking concrete armour units on low crested and submerged structures is qualitatively different from rock armour. About 40% to 50% larger armour units are required on the seaward slope and crest of low crested structures (as compared to conventional high crested breakwaters). About 35% larger armour units are required on the rear slope. Larger armour units are not required on submerged breakwaters if the water depth on the crest exceeds 50% of design wave height.

Keywords: Single layer armour, interlocking armour, low crested breakwater, crest armour, armour stability

INTRODUCTION

The armour layer stability of a low crested breakwater may be determined to some extent by the crest level. This effect has been investigated in various studies, amongst others by van der Meer and Daemen (1994). They found that the hydraulic stability of low crested and submerged breakwaters with rock armour is increasing with decreasing crest level. A crest level at the water line leads to 20% to 30% increase in armour layer stability; a crest level below the water line (submerged breakwater) will further increase the stability of the rock armour. These results are confirmed amongst others by Vidal et al. (1995), Burger (1995) and Kramer and Burcharth (2004).

Interlocking concrete armour units like Xbloc®, Accropode™ and Coreloc® are widely used for the protection of exposed breakwaters. The stability of these armour units on conventional breakwaters is addressed in various studies (see for example Muttray & Reedijk, 2009) and is – different from rock armour – largely determined by the interlocking, i.e. by the unit shape and the interaction with neighbouring armour units. The best interlocking is achieved on relatively steep slopes, where the armour units are strongly supported by neighbouring armour units further upslope. The interlocking and thus the armour layer stability are likely to be reduced on a breakwater crest, where the stabilising effect of the slope is lacking. For low crested and submerged structures, this is especially important as the crest is largely exposed.

The stability of interlocking armour units in the crest region of low crested and submerged breakwaters was investigated experimentally by van der Linde (2010) in a comprehensive model study. To the authors' knowledge, there are no other studies on this subject. The model testing results of van der Linde have been re-analysed in order to confirm and quantify the potential reduction in armour layer stability in the crest region of low crested and submerged breakwaters and to provide guidance for design.

MODEL TESTS

Stability tests on low crested and submerged breakwaters were performed by van der Linde in the DMC wave flume in Utrecht, The Netherlands. The tests are described in detail by Muttray et al. (2012). Images of a wave impinging on a low crested breakwater are presented in Fig. 1; photos from each test series and tabular test results can be found in van der Linde (2010). A rubble mound breakwater with 3:4 slopes and Xbloc armour layer was tested (see Fig. 2). Although the tests were performed with Xbloc armour units (of 62 g, unit height 4.3 cm, specific density 2339 kg/m3), it is believed that the results would also be applicable for other types of interlocking armour units.

The water depth at the breakwater toe was constant (33.9 cm); the seabed slope in front of the structure was 1:30. Five different breakwater crest level and two different crest widths were tested. The relative freeboard $R_c/H_{s,D}$ was 0, ±0.4 and ±0.8 (with freeboard, R_c = 0, ±4.4, ±8.9 cm and design wave height, $H_{s,D}$ = 11.1 cm). The crest was either 3 or 9 armour units wide (about 10 cm or 25 cm, respectively). The lower part of the slope was protected by a rock layer; the transition from “rock toe” to Xbloc armour varied with the crest height. The number of armour units on the seaward and landward slope was kept constant (14 Xbloc rows, i.e. 147 units were placed on front/rear slope and 32 or 95 units on the crest). The armour layer stability was thus not influenced by the length of Xbloc armoured slope or by the toe geometry.

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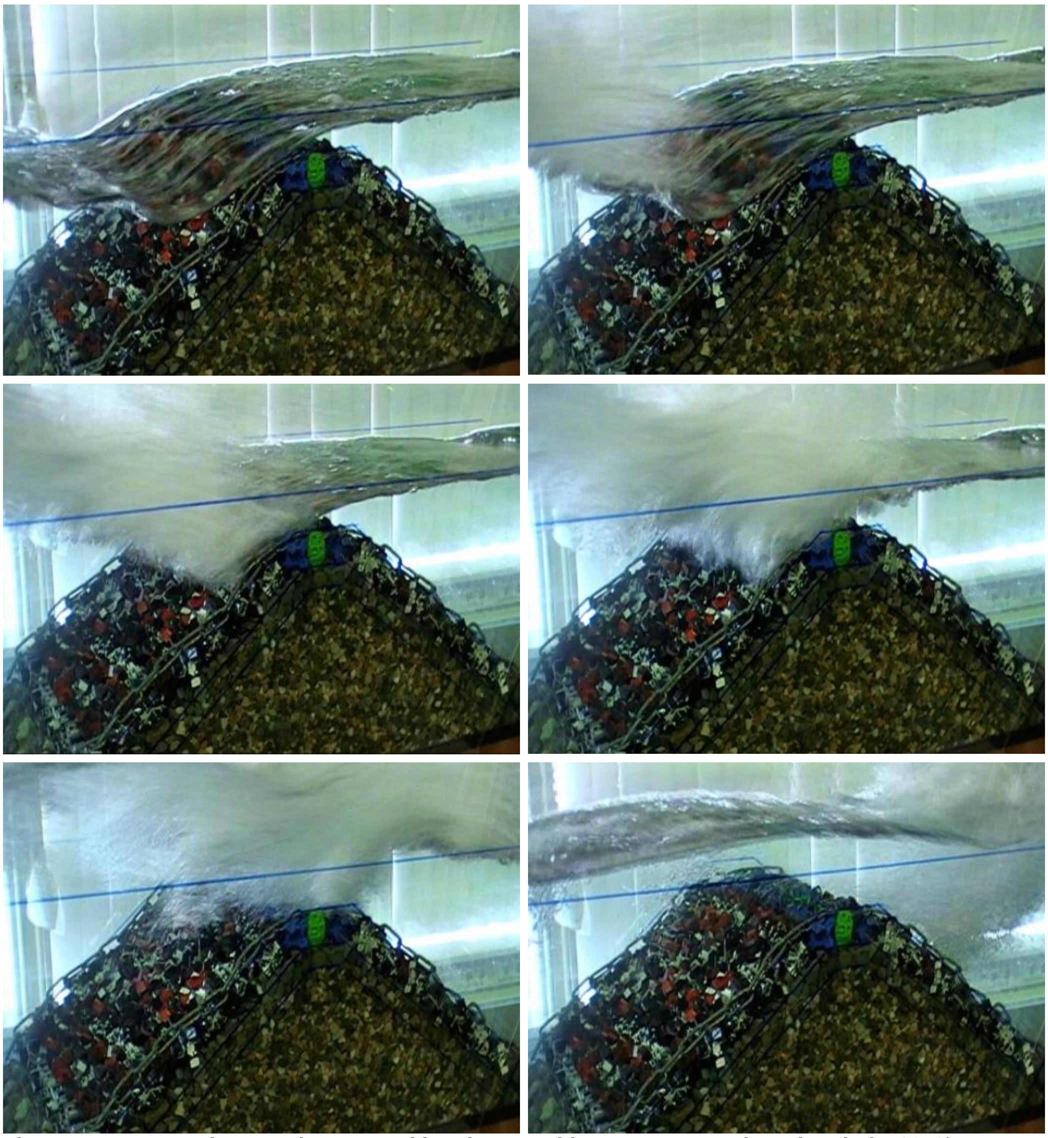

Figure 1: Wave passing over low crested breakwater with a narrow crest (van der Linde, 2010)

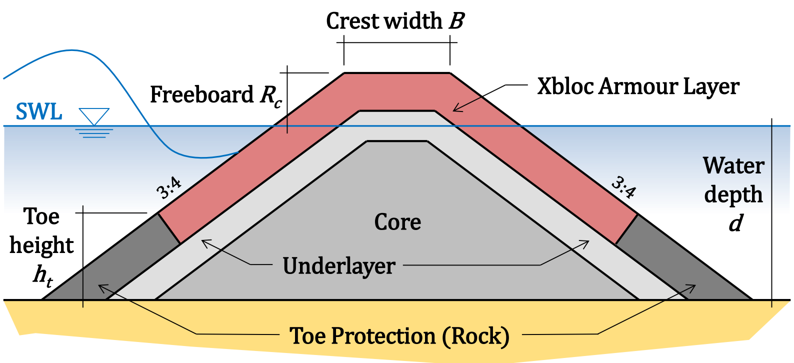

Figure 2: Cross section of breakwater model

The armour layer stability was tested in a series of tests with increasing wave height and constant wave steepness (of either 0.02 or 0.04). Tests were performed with irregular waves (1,000 waves per test). The wave height was stepwise increased by increments of 0.2 $H_{s,D}$ starting with 0.6 $H_{s,D}$ until a wave height of 1.8 $H_{s,D}$ (i.e. 180% of the design wave height) was reached or until 3% of the armour units were displaced. Van der Linde performed 30 test series with 200 individual tests. The number of test series per breakwater geometry, the number of tests per test series and the wave height at the breakwater toe in the final test of a series are specified in Table 1.

Table 1. Test programme of van der Linde (2010)

Free-board R_c	Crest width B	Wave steepness $s = H_s/L_0$ [-] s = 0.02			Wave steepness $s = H_s/L_0$ [-] s = 0.04		
		No. of test series	No. of Tests per test series	Significant wave height of final test	No. of test series	No. of Tests per test series	Significant wave height of final test
[cm]	[cm]	[-]	[-]	[cm]	[-]	[-]	[cm]
		2	7	17.1 – 17.6	2	7	16.8 – 16.9
	36	2	7	16.5 – 16.7	1	7	16.6
-4.4	10	2	6 – 7	14.7 – 16.6	2	7	16.6 – 16.7
±0.0	10	5	6	14.3 – 14.7	5	7	16.6 – 16.8
	36	1	6	14.1	1	7	16.5
+4.4	10	1	5	12.5	1	7	17.2
	36	1	6	12.9	1	7	16.9
+8.8	10	1	7	16.9	2	7	16.5 – 17.4

The armour layer stability was assessed by counting rocking and displaced armour units. Repeated movements of armour units, typically rotational movements are called "rocking". Rocking units have been counted in 24 test series by visual observations, mostly in the first tests up to a wave height of 1.0 – 1.4 $H_{s,D}$. Lasting changes of the armour unit position are called "displacement". They were determined from overlay photos taken before and after each test. The extraction of an armour unit on the breakwater crest is shown in Fig. 3. Displacement of a single armour unit by more than 0.5 D (with armour unit height D) has been considered as start of damage (about 0.3% damage); displacement of 10 armour units (about 3% damage) has been considered as severe damage. Severe damage was observed in 14 test series; displacements were observed in 21 test series.

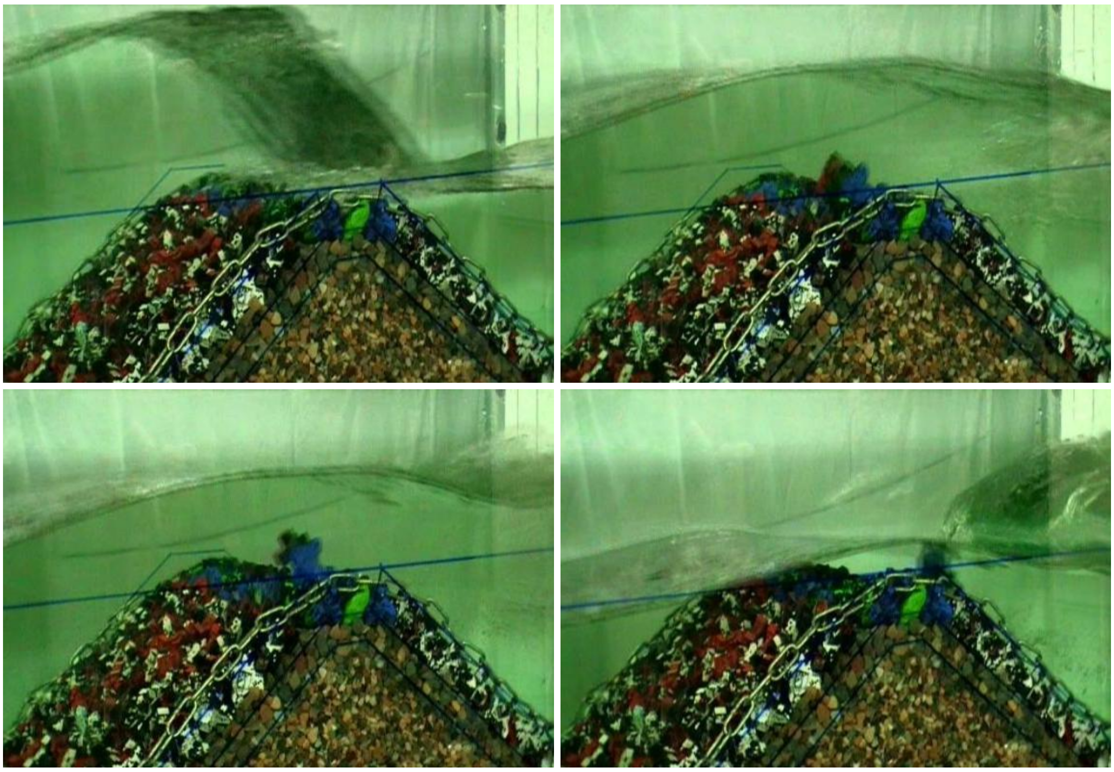

Figure 3: Displacement of an armour unit at the landward side of the breakwater crest (van der Linde, 2010)

The percentage of rocking armour units and the accumulated damage (percentage of displaced armour units) are presented in Fig. 4. A stability number, $N_{s,D}$ (=$H_s/\Delta \cdot D_n$) of 2.77 is commonly applied for the concept design of Xbloc armoured breakwaters (DMC, 2011). Damage is expected when the stability number, N_s exceeds 3.5. At low crested breakwaters the damage starts if $N_s > 3.0$. The number of rocking armour units on a low crested or submerged breakwater may vary in a design storm from 0% to 7%. Application of common design rules would thus lead to a smaller safety margin for low crested breakwaters as compared to conventional breakwaters.

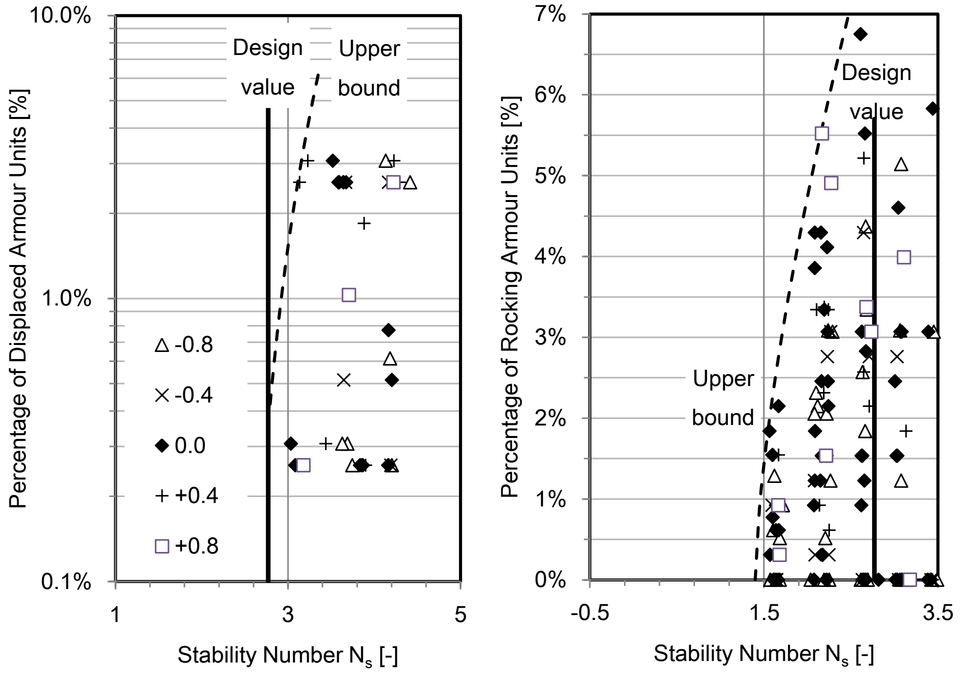

Figure 4: Overview of displaced armour units (left) and rocking armour units (right)

Muttray et al. (2012) proposed two different definitions of initial damage, which have been applied also in this paper. These are "Start of Damage" (SoD) referring to the test conditions where the first armour unit is displaced and "Almost no Damage" (AnD) referring to the worst test conditions with at most one displaced armour unit (i.e. the final test in a test series with no damage or the test before extraction of a second unit in a test series with damage).

During the model tests it has been observed that the seaward slope of emerged structures and the crest of submerged structures were primarily exposed to breaking waves. Armour units on the crest of emerged structures were pushed in landward direction by overtopping waves. Armour units on the crest of low crested and submerged structures moved in land- and seaward direction. Rocking occurred mainly on the seaward slope of emerged structures and on the crest and at the transition from crest to slope of submerged structures. Increased rocking of crest armour units was observed before armour units were displaced. Displacement of armour units was mostly observed in the most upper part of the seaward slope of emerged structures. Displacements of crest armour units started mostly at the seaward side of the crest and progressed from there towards the rear side. Armour units on the rear slope were hardly displaced.

The performance of emerged breakwaters is qualitatively different from submerged breakwaters. The crest armour units on emerged breakwaters move primarily in landward direction (due to overtopping waves). Gaps in the armour layer are likely to develop at the transition from the seaward slope to the crest. On submerged breakwaters the crest armour units move in seaward and landward direction. Gaps in the armour layer are likely to develop at the transitions from crest to front and rear slope. The gaps are generally smaller at submerged breakwaters.

TEST RESULTS

Stability of Seaward Slope and Crest

Rocking and displacement of armour units on low crested and submerged structures as observed in the hydraulic model tests is presented in this section. The wave loading on the breakwater crest is likely to be increased at low crested structures as compared to conventional high crested breakwaters while the wave loading on the seaward slope may be reduced.

The number of armour units on the seaward slope and on the breakwater crest that were rocking in design conditions (stability numbers of about 2.77) is plotted in Fig. 5 (left). Tests with almost no damage (AnD) are presented in Fig. 5 (right).

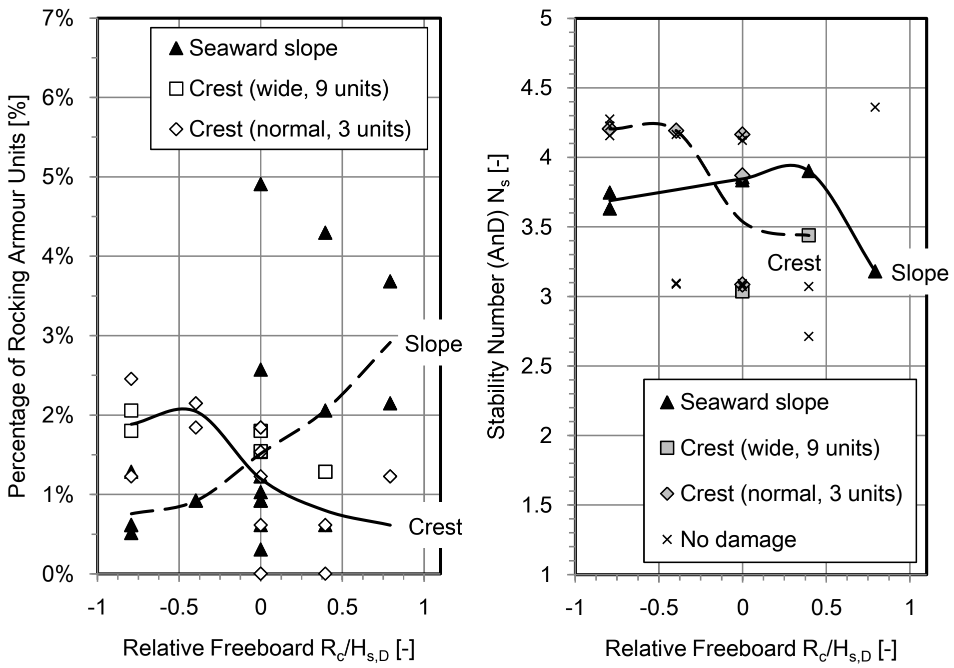

Figure 5. Occurrence of rocking armour units under design conditions (left) and stability numbers in tests with almost no damage (AnD, right)

The number of rocking units on the crest is about 2% at submerged structures and is gradually decreasing when the crest is at or above the waterline. The number of rocking units on the seaward slope is significantly larger at submerged structures than at low crested, emerged structures. About 1% of the armour units were rocking on the slope in design conditions at submerged structures. In tests with zero freeboard the number of rocking units on the slope varied from 0% to 5% (1.5% on average). The average number of rocking units on the slope is apparently increasing with increasing freeboard and reaches about 2% to 4% if $R_c = H_s$.

The worst test conditions with no or at most one displaced armour unit (called AnD) are presented in Fig. 5 (right). In case that one armour unit had been displaced it is indicated whether it was extracted from the slope or from the crest. Displacement of armour units on the slope starts around stability number of 3.5 to 4.0. This is similar to a conventional, high crested structures, where the first damage can be expected when the stability number exceeds 3.5. A lower armour unit stability has been observed at emerged structures with a relative freeboard, R_c/H_s of 0.8, where damage starts at a stability numbers of about 3.2. Displacement of armour units on the crest of submerged structures starts at stability numbers of about 4.0. At structures with zero freeboard the stability number of the crest armour is reduced to 3.5 (average value) and goes even down to 3.0 in several tests. No damage was observed on the crest of emerged structures with a relative freeboard, R_c/H_s of 0.8.

The armour unit stability on a breakwater crest reaches apparently a minimum if the crest is close to the water line. The crest stability is increasing at submerged structures and if the freeboard exceeds about 0.5 H_s. The number of rocking armour units on the seaward slope indicates a gradually decreasing armour layer stability with increasing positive freeboard (Fig. 5, left). This trend is in line with the damage development on the slope as depicted in (Fig. 5, right). The percentage of rocking units on the crest indicates that an emerged crest would be more stable than a submerged crest (Fig. 5, left). The damage development on the crest shows a somewhat different trend (see Fig. 5, right); the crest of low crested emerged structures appears least stable. Thus, the percentage of rocking armour units may not necessarily be a suitable indicator for the armour layer stability, especially on the crest.

Effect of Packing Density and Wave Steepness

Packing density, i.e. the number of armour units per unit area of breakwater slope, is commonly applied in construction projects as a criterion for the approval of single layer, interlocking armouring. Nonetheless, the packing density is not explicitly addressed in design formulae and it is uncertain if a slight variation of packing density will have any influence on the armour layer stability.

The stability number in tests with almost no damage (AnD) is plotted in Fig. 6 against the relative freeboard; the variation of packing density from the design value (referred to as 100% packing density) is indicated. The stability of the armour layer varies to some extent with the relative freeboard. A distinct relationship between armour layer stability and packing density however cannot be seen. It appears from Fig. 6 that a variation of packing density by ±3% has little influence on the armour layer stability of low crested and submerged breakwaters.

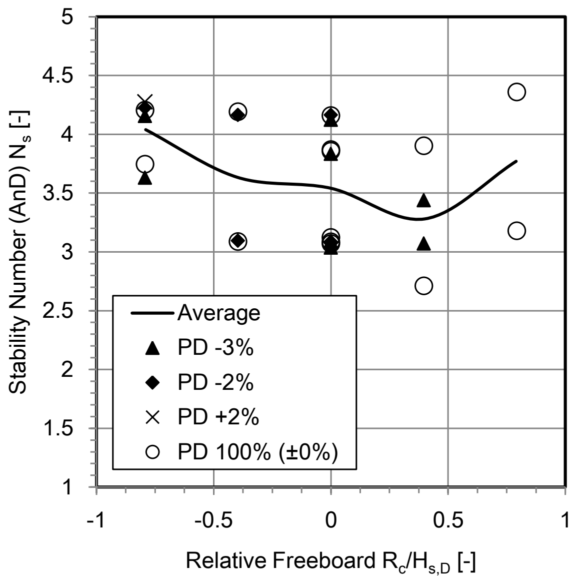

Figure 6: Variation of armour layer stability with freeboard and packing density

Stability tests are commonly performed in test series with constant wave steepness assuming that the wave steepness would have some influence on the armour layer stability. Nonetheless, the wave steepness, commonly defined by the ratio of significant wave height (at the breakwater toe) and deep water wave length (based on peak wave period), is not is not explicitly addressed in design formulae for single layer armouring.

The effect of wave steepness on the armour layer stability is presented in Fig. 7. The stability number in tests with almost no damage (AnD) is plotted in Fig. 7 (right) against the relative freeboard for wave steepness s = 0.02 and 0.04. The stability of the armour layer is significantly lower (on average 21%) for long waves (wave steepness 0.02) as compared to shorter waves of steepness 0.04. The number of rocking armour units in a design storm is presented in Fig. 7 (left). No marked difference can be seen between wave steepness 0.02 and 0.04.

The wave steepness has apparently little influence on the number of rocking armour units, but has some influence on the overall stability of the armour layer of low crested and submerged breakwaters. The armour layer stability is reduced by about 20% when the wave steepness goes down from 0.04 to 0.02.

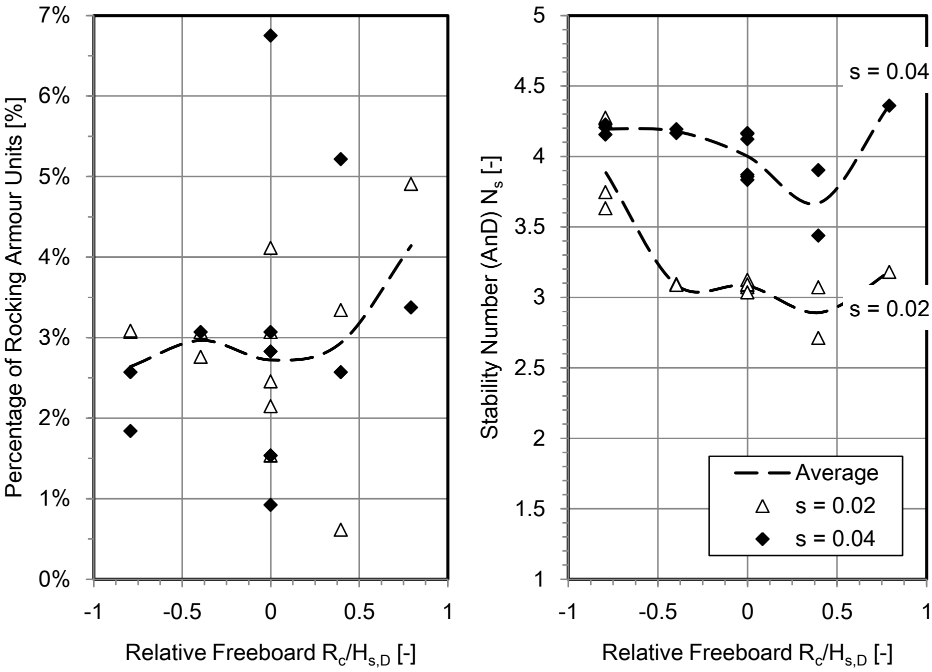

Figure 7: Effect of wave steepness on the number of rocking armour units under design conditions (left) and on the stability number in tests with almost no damage (AnD, right)

Effect of Freeboard

Different performance of emerged and submerged breakwaters has been observed during the model tests. The effect on the armour layer stability is addressed in this section.

Stability numbers at start of damage (i.e. the test conditions where the first armour unit has been displaced) are plotted in Fig. 8 against the relative freeboard. It should be noted that stability numbers in Fig. 8 may refer to test conditions where more than one armour unit has been displaced (i.e. tests with progressive damage), which are excluded from Fig. 5, Fig. 6 and Fig. 7.

The overall stability (i.e. armour layer stability on crest, front and rear slope) as presented in Fig. 8a reaches a minimum at zero freeboard (N_s = 3.0). Somewhat larger stability numbers are determined for submerged structures (N_s = 3.6) and for emerged structures (N_s = 3.2). The stability of the seaward slope in Fig. 8b is similar to the overall stability. However, the least stability (N_s = 3.1) was observed at low crested emerged structures with a relative freeboard of 0.4. The crest stability in Fig. 8c reaches a minimum at zero freeboard (N_s = 3.0) and is rapidly increasing with if the crest is submerged or emerged. Damage at the rear slope has only been observed at low crested, emerged structures with a relative freeboard of ±0.0 and +0.4 (Fig. 8d). The stability of the rear slope appears uncritical for structures with higher freeboard or for submerged structures.

Damage at conventional, high crested Xbloc breakwaters starts when the stability number exceeds 3.5 (DMC, 2011). The experimental results indicate a reduced armour layer stability at low crested and submerged breakwaters. The area that is primarily affected and the stability numbers at start of damage (SoD) are summarized in Table 2.

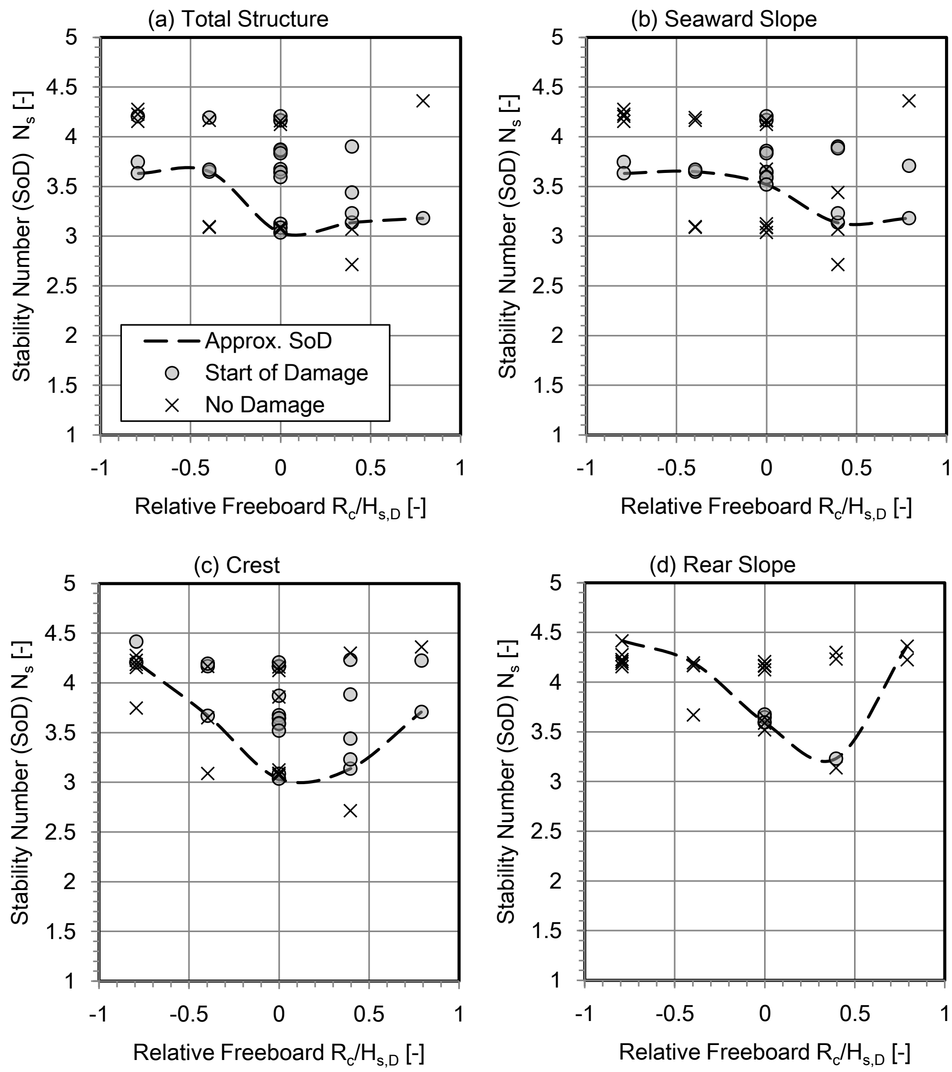

Figure 8: Stability number N_s at SoD: Overall damage (a), seaward slope (b), crest (c) and rear slope (d)

Table 2. Reduced armour layer stability at low crested and submerged breakwaters

Structure	Relative freeboard $R_c/H_{s,D}$ [-]	Reduced armour stability	Stability number N_s at SoD [-]
Emerged	+0.8	Seaward slope	3.2
	+0.4	Seaward slope, crest, rear slope	3.1
Zero freeboard	±0.0	Crest	3.0
Submerged	-0.4 -0.8	No reduction	3.5

The stability numbers at start of damage (i.e. the trend lines in Fig. 8) of front slope, crest and rear slope are shown in Fig. 9 (red and orange lines). The slope stability of low crested structures matches with the stability of conventional, high crested breakwaters according to DMC (2011). Fig. 9 includes further the design value for Xbloc armouring on low crested breakwaters according to DMC (2011). The blue lines refer to the stability of rock armour on low crested breakwaters according to CIRIA (2007). A design wave height $H_{s,D} = 1.5\ \Delta\ D_{n50}$ has been applied for rock armour on conventional breakwaters.

The design value for rock armour (i.e. the minimum of crest and slope stability) is steadily increasing when the relative freeboard drops below 0.6. In case of single layer, interlocking armour units the most likely start of damage (i.e. the minimum of crest, front and rear slope stability) corresponds to the upper bound of the orange area in Fig. 9. The stability of single layer armouring on low crested structures is qualitatively different from rock armour. The stability is decreasing at low crested, emerged structures. The least armour layer stability has been observed when the relative freeboard is of order 0 to 0.5. The armour layer stability is increasing again when the structure is submerged.

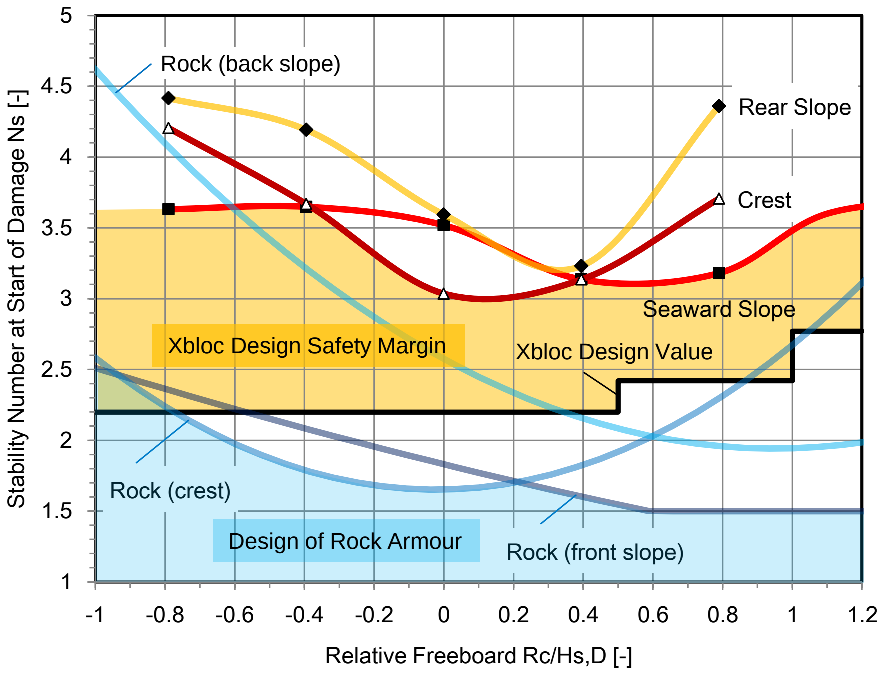

Figure 9. Stability of rock and Xbloc armour on low crested and submerged breakwaters

The design safety margin, i.e. the difference between the recommended design value and start of damage is marked orange in Fig. 9. The design value (N_s = 2.77 for conventional breakwater) is reduced to 2.42 (i.e. 50% increased armour unit weight) if the relative freeboard is less than 1 and is further reduced to 2.20 (i.e. 100% increased armour unit weight) if the relative freeboard drops below 0.5. The safety margin is relatively constant (about 25% of the design value, which corresponds to a factor 2 on the armour unit weight) at low crested emerged structures. At submerged structures the safety margin is gradually increasing with increasing submergence. The design value for submerged breakwaters with relative freeboard below -0.5 could and should be similar to the design value for conventional, high crested breakwaters.

CONCLUSIONS AND RECOMMENDATIONS

The stability of interlocking concrete armour units on low crested and submerged structures is qualitatively different from rock armour. Concrete armour units on front slope, crest and rear slope may be less stable, while an increased stability has been observed in other studies for rock armour.

The transition from the seaward slope to the crest is most vulnerable part of the armour layer. Armour units were mostly displaced in the most upper part of the seaward slope and at the seaward side of the crest. Damage on the crest was progressing from front side towards the rear side. Rocking is not necessarily a suitable indicator for the hydraulic stability of the armour layer on low crested structures. Short and long waves showed similar rocking while long waves caused significantly more damage. Crest armour on submerged structures showed more rocking while the crest armour stability was most critical for low crested, emerged structures.

The armour layer stability on the seaward slope is reduced by about 12% (40% larger armour unit weight required) at low crested structures. At structures with zero freeboard and at submerged structures the stability of the slope is comparable to conventional, emerged breakwaters. Armour units on the rear slope of low crested structures should be about 35% larger than on a conventional, high crested breakwater.

The armour layer stability on the crest is reduced by about 14% (50% larger armour unit weight required) if the relative freeboard is close to zero. At submerged structures the crest stability is rapidly increasing with decreasing (negative) freeboard.

The functioning and interlocking mechanism of Xbloc armour units is similar to other types of interlocking single layer armour units (Coreloc®, Accropode™ etc.). Therefore, the results of this study should also be applied for other types of single layer armouring unless other guidelines recommend otherwise.

ACKNOWLEDGMENTS

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