

# Stability of Low Crested and Submerged Breakwaters with Single Layer Armouring

Markus Muttray, Erik ten Oever and Bas Reedijk

*Delta Marine Consultants, Gouda 2800 AG, the Netherlands*

**Abstract:** The stability of single layer armour units on low crested and submerged breakwaters has been investigated in 2D hydraulic model tests. Armour unit movements including settlements, rocking and displacements have been determined. The effect of freeboard, packing density and wave steepness on the armour layer stability on crest, front and rear slope has been investigated. 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 towards the rear slope. 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 40% of design wave height.

**Key words:** Rubble mound breakwater, low crested breakwater, armour layer stability, single layer armour units, Xbloc.

## 1. Introduction

Low crested and submerged breakwaters are designed for severe wave overtopping. The armour layer stability of these structures may be higher than for non-overtopped structures; the wave loads on the seaward slope are likely to be reduced when wave energy is passing over the breakwater crest [1]. However, the armour units on the crest and on the rear slope are exposed to larger wave forces [2].

The stability of low crested and submerged breakwaters has been addressed in various studies. Rock armoured breakwaters have been investigated experimentally amongst others in Refs. [1-7]. At low crested structures (with crest level  $R_c/H_s < 1$ ) the armour layer stability is increasing with decreasing crest level [1]. When the breakwater crest level is at the water line ( $R_c/H_s = 0$ ), the armour layer stability is increased by about 20% to 30%. A crest level below the water line (submerged breakwater) will further increase the stability of the rock armour [7]. These results are confirmed amongst others in Refs. [2-5, 8].

Stability on the crest reaches a minimum when the freeboard is zero [8]. The lee side stability is increasing with increasing submergence; the largest lee side damage was observed at low crested structures with positive freeboard [2]. The stability of rock armour on low crested structures is largely independent of rock properties like grading and shape [8].

The lee side stability of rock armoured, low crested structures was investigated numerically in Ref. [9]. The relative freeboard,  $R_c/H_s$ , the relative water depth at the structure,  $d/H_s$  and the breakwater slope gradient,  $\tan(\alpha)$  were identified as governing parameters for the rear slope stability.

Two different stability formulae for the rock armour on low crested and on submerged breakwaters are proposed in Refs. [1, 7]. Design graphs for front slope, crest and rear slope of low crested structures are presented in Ref. [2] and further developed in Ref. [8]. A nominal rock diameter,  $D_{n50}$  of about 33% to 50% of the design wave height,  $H_{s,D}$  is recommended in Refs. [10, 11]. Design formulae and graphs in Refs. [2, 7, 8] are still widely used [11-13].

All above findings refer to rubble mound structures with rock armour. The stability of non-interlocking

---

**Corresponding author:** Markus Muttray, Ph.D., research field: coastal and harbour engineering. E-mail: m.muttray@dmc.nl.

concrete armour units on a submerged breakwater was investigated in a recent study [14]. The stability of these concrete units on a breakwater crest depends largely on the permeability of the armour layer.

Interlocking concrete armour units like Xbloc are widely used for the protection of exposed breakwaters. The stability of these armour units on conventional breakwaters has been extensively studied [15], and the stability on low crested and submerged breakwaters was addressed in a single experimental study (Fig. 1) [16]. Significant rocking of armour units was observed in the crest region of the breakwater. A relative freeboard of about  $0.4 R_c/H_s$  was found to be most critical for the armour layer stability. However, no conclusions are drawn in Ref. [16] on the stability of single layer armour units on low crested breakwaters.

The term “armour units” refers in this paper to interlocking concrete elements that are placed randomly (i.e. on a staggered grid with varying orientation) and in a single layer (e.g. Xbloc<sup>®</sup>, Accropode<sup>™</sup> and Coreloc<sup>®</sup>).

The hydraulic stability of these armour units is—different from rock armour—largely determined by the interlocking, i.e. by the armour unit shape and by the interaction with neighbouring armour units (Fig. 2). The best interlocking is achieved on relatively steep slopes, where the armour units are resting primarily on units of the next lower row (and not on the underlayer) and where the retaining forces exerted by units from the next higher row are relatively large. Interlocking requires thus a slope and support by armour units further upslope.

The interlocking and thus the armour layer stability are likely to be reduced in the crest region of a breakwater, where the stabilising effect of slope and neighbouring units further upslope is lacking [17]. The largest wave forces occur typically near the still water line [18]. The crest region of a low crested or submerged breakwater is thus exposed to larger wave loads as compared to a conventional breakwater, while interlocking and hydraulic stability of the armour layer



Fig. 1 Wave attack on submerged breakwater (with narrow crest, top) and low crested breakwater (emerged, with wide crest, bottom).

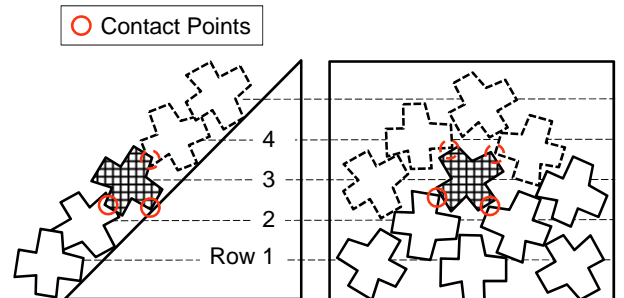


Fig. 2 Placement pattern of interlocking armour units on a breakwater slope: cross section (left) and front view (right).

are reduced. Larger safety factors are therefore recommended for Xbloc armour on low crested structures [19]. These recommendations for design are based primarily on engineering judgement and not on systematic tests.

The experimental results in Ref. [16] have been re-analysed in order to determine the potential reduction in armour layer stability in the crest region of low crested and submerged breakwaters and to provide guidance for design.

## 2. Model Tests

The stability of low crested and submerged breakwaters was investigated experimentally in 2D hydraulic model tests in the DMC (Delta Marine Consultants) wave flume in Utrecht, the Netherlands [16]. The model tests were performed with an Xbloc armoured breakwater; the results are also applicable for other types of single layer armour units with similar interlocking mechanism.

A rubble mound breakwater with 3:4 slopes and with an Xbloc armour layer covering front slope, crest and rear slope was tested (Fig. 3). The seabed slope in front of the structure was 1:30. The water depth at the breakwater toe was 33.9 cm and was constant to ensure consistent wave conditions for all tests.

Five different crest levels were investigated; the relative freeboard  $R_c/H_{s,D}$  was 0,  $\pm 0.4$  and  $\pm 0.8$  (with freeboard,  $R_c = 0, \pm 4.4, \pm 8.9$  cm and design wave height  $H_{s,D}$ ). Two different crest widths were considered: a narrow crest (3 armour units wide, about 10 cm) and wider crest (9 armour units wide, about 25 cm).

The number of armour unit rows on seaward and landward slope was kept constant (14 Xbloc rows) and the toe protection was integrated in the breakwater slope (i.e. no toe berm, as shown in Fig. 3). The armour layer stability is thus not influenced by the length of Xbloc armoured slope or by the toe geometry. The toe

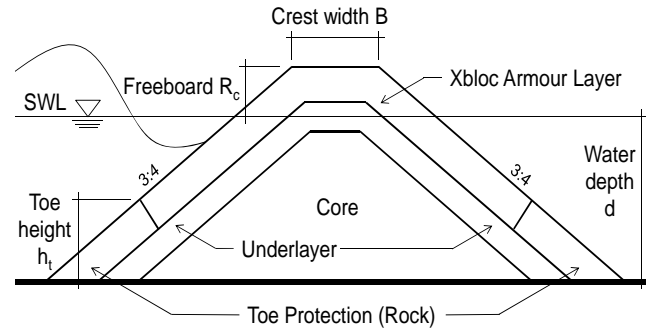


Fig. 3 Cross section of breakwater model.

armour consists of a rock layer protected by wire mesh; the toe height varied with the freeboard. The armour layer (front and rear armour) consisted of Xbloc units of 62 g (unit height 4.3 cm, specific density 2,339  $\text{kg/m}^3$ , design wave height  $H_{s,D} = 11.1$  cm).

The total number of Xbloc armour units was either 326 (147 units on seaward and landward slope and 32 units on the crest) or 389 (95 units on the crest); the latter refers to a wide crested breakwater. The overall packing density was constant in most tests and close to the recommended packing density. A number of test series have been repeated with 3% lower packing density (i.e. the number of armour units was unchanged and the crest width was reduced by 3 cm). The packing densities are specified in Table 1 for each test series.

Stability tests were performed with irregular waves (JONSWAP spectrum,  $\Gamma = 3.3$ ) and 1,000 waves per test. A test series comprised several tests; the wave

Table 1 Test programme [16].

Freeboard $R_c$ (cm)	Crest width $B$ (cm)	Number of tests per test series/ Significant wave height (at breakwater toe) of final test (cm)			
		$s = 0.02^{+)$	$s = 0.02$	$s = 0.04^{+)$	$s = 0.04$
-8.8	10	7/17.1***)	7/17.6*)	7/16.9**)	7/16.8*)
-8.8	36	7/16.5(excl)	7/16.7**)	7/16.6**)	-
-4.4	10	7/16.6**)	6/14.7*)	7/16.6**)	7/16.7*)
$\pm 0.0$	10	6/14.6**)	6/14.7*)	7/16.6**)	7/16.6*)
$\pm 0.0$	10	6/14.5*)	6/14.3*)	7/16.6*)	7/16.6**)
$\pm 0.0$	10	6/14.4**)	-	7/16.8**)	-
$\pm 0.0$	36	6/14.1**)	-	7/16.5**)	-
+4.4	10	5/12.5*)	-	7/17.2*)	-
+4.4	36	6/12.9**)	-	7/16.9**)	-
+8.8	10	7/16.9*)	-	7/16.5*)	7/17.4**)

\*) Recommended packing density; \*\*) Packing density reduced by 3%; \*\*\*) Packing density increased by 3%;

(excl) Toe failure (test excluded from analysis);  $^{+)$  Wave steepness  $s = H_s/L_0$ .

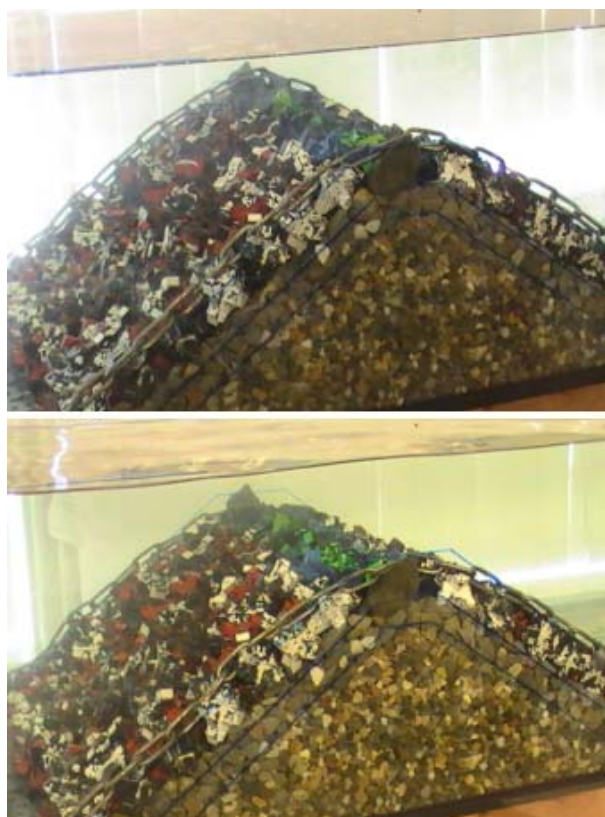
height was increased stepwise until the damage of the armour layer reached about 3% or until the limits of the wave generator were reached. Test series started with a nominal wave height of  $0.6 H_{s,D}$ , followed by tests with 0.8, 1.0 and finally up to  $1.8 H_{s,D}$  (i.e. 180% of the design wave height, Fig. 4). The wave steepness  $H_s/L_{p,0}$  was either 0.02 or 0.04. Thirty test series were performed consisting of 200 individual tests. The test programme is summarised in Table 1; the number of tests per test series and the wave height at the breakwater toe in the final test of a series are specified.

Rocking of individual armour units was detected during the tests by visual observations. Displacements of armour units were determined from overlay photos taken before and after each test. Rocking has been defined as repeated movements (typically rotational movements) of armour units. Displacement of a single armour unit (about 0.3% damage) by more than  $0.5 D$  (with armour unit height  $D$ ) has been considered as start of damage; after displacement of 10 armour units (about 3% damage) testing has been stopped.

### 3. Observations

Observations on hydraulic processes and on response and interaction of armour units can provide some insight into the functioning and stability of an armour layer. Visual observations from hydraulic model tests are therefore briefly summarised in this section. All observations refer to the model tests in Ref. [16] unless otherwise specified.

- Hydraulic processes: Passing or overtopping waves generated a highly turbulent flow in landward direction on the breakwater crest. At low crested and submerged structures, a strong return flow was observed on the crest, when a wave trough approached the structure. The return flow was stronger for longer waves and narrow crested structures. Waves were breaking (surging/collapsing breaker) on the seaward slope (emerged structures) and on the breakwater crest (submerged structures). Overtopping waves impinging on the rear slope were not observed.



**Fig. 4** Breakwater model before and after a test series (narrow crested, submerged breakwater,  $R_c/H_{s,D} = -0.8$ , wave steepness 0.04, test conditions 60% to 180% of design wave height).

- Settlements: Settlements of the armour layer on the seaward slope of emerged structures were observed in the first tests of a test series. The settlements were less in tests with shorter waves and with higher packing densities. Further settlements occurred on front and rear slope of submerged and emerged structures, when the breakwater was exposed to large waves (overload conditions). Settlements led to increased packing densities in the lower part of front and rear slope and to reduced packing densities in the most upper part of the slope. Armour units on the crest followed to some extent the settlements on the slope resulting in reduced packing densities on the crest. The crest armour units of emerged breakwaters moved primarily in landward direction (due to overtopping waves); gaps in the armour layer developed at the transition from the seaward slope to the crest. The crest armour units of submerged breakwaters moved in seaward and



landward direction (oscillating flow pattern); gaps in the armour layer were observed at the transitions from crest to front and rear slope. These gaps were generally smaller than those at emerged structures.

- Rocking: Virtually no rocking was observed on the rear slope while armour units in the upper part of the seaward slope were rocking more frequently. More rocking on the seaward slope was observed at emerged structures (in the top four rows) than at submerged structures (rocking mostly limited to the top row on the slope). The movements of crest armour units on emerged breakwaters were typically limited to a slight shift in landward direction (by overtopping waves); little rocking was observed. At submerged breakwaters crest armour units were rocking more frequently and on the entire crest. At wide crested, submerged structures rocking was mainly observed in the seaward part of the crest. Increased rocking of crest armour units was observed before armour units were displaced.

- Displacements: Armour units on the seaward slope were mostly displaced in the most upper part of the slope (top three rows). There were generally more displacements at emerged structures than at submerged structures. Armour units on the rear slope were hardly displaced; only in two tests with low crested structures units of the two most upper rows were displaced.

Displacement of crest armour units started mostly in the seaward part of the crest. At submerged structures crest elements were mostly displaced in seaward direction; at emerged structures they moved always in landward direction. Damage on the crest was progressing towards the rear side of the crest and in some cases also to the rear slope.

### 4. Test Results and Discussion

#### 4.1 Overview of Results

Rocking of armour units was counted in 24 test series (in the first tests, up to a wave height of 1.0-1.4  $H_{s,D}$ ). The percentage of rocking armour units (number of rocking units divided by total number of armour units) is presented in Fig. 5. In a design storm (stability number  $N_{s,D} = H_s/(\Delta \cdot D_n) = 2.77$  [19]) the number of rocking armour units on a low crested or submerged breakwater may vary significantly (from 0% to 7%).

Damage to the breakwater armour layer (i.e. displacement of armour units) was observed in 21 test series (excluding the test series where toe failure occurred). The accumulated damage (percentage of displaced armour units) as observed in the model tests is presented in Fig. 6. Severe damage (about 3% of displaced armour units) was observed in 14 test series. A stability number of  $N_{s,D} = 2.77$  is commonly applied

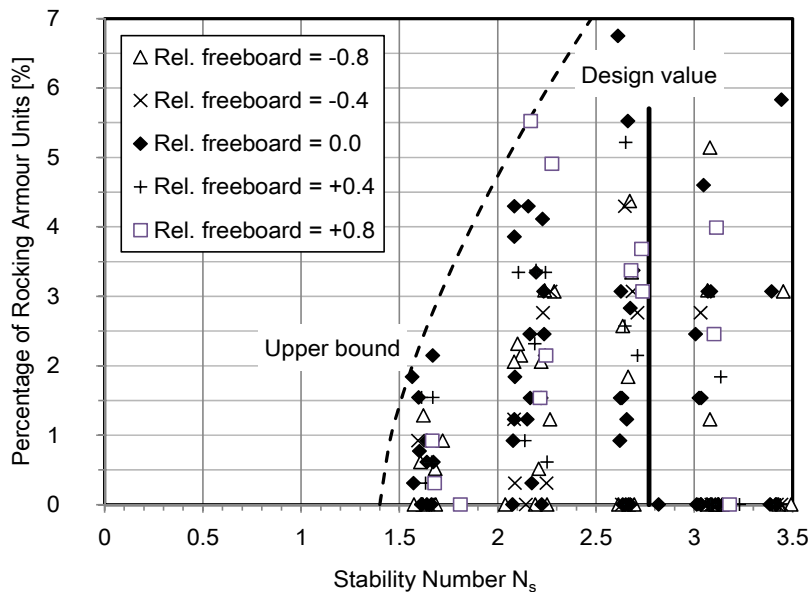
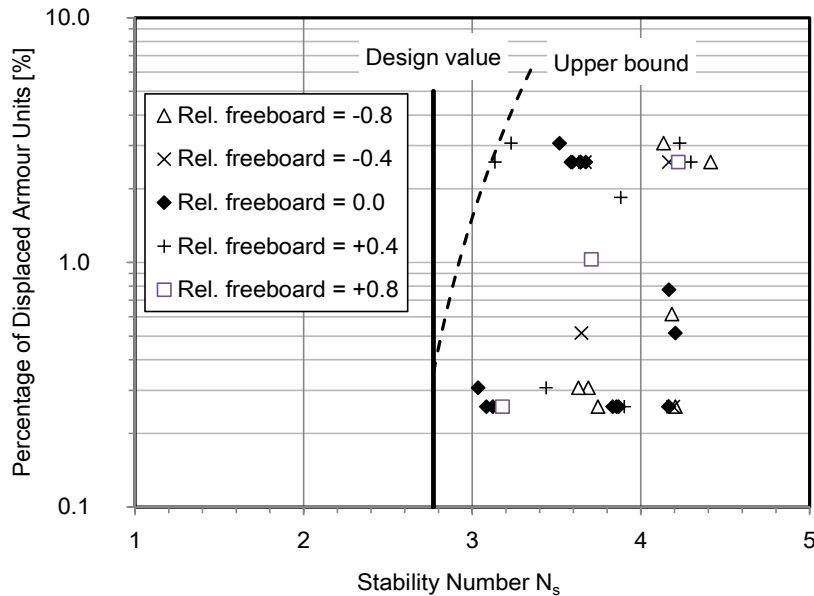


Fig. 5 Overview of rocking armour units (all tests).



**Fig. 6 Overview of displaced armour units (all tests).**

for the concept design of Xbloc armoured breakwaters [19]. Damage is expected when the stability number  $N_s$  exceeds 3.5 (the corresponding stability coefficient of the Hudson formula is 32). At low crested breakwaters the damage starts if  $N_s > 3.0$ . Application of common design rules would thus lead to a smaller safety margin for low crested breakwaters as compared to conventional breakwaters.

#### 4.2 Effect of Packing Density

The effect of packing density on the stability of low crested and submerged breakwaters is presented in Figs. 7 and 8. Packing density refers to the number of armour units per unit area of breakwater slope; the recommended spacing between Xbloc armour units is specified in Ref. [19].

The number of rocking armour units in design conditions (stability number  $N_s = 2.77$ ) is plotted in Fig. 7 against the relative freeboard. The number of rocking units is nearly constant (2% to 3%) at submerged structures and may vary significantly (0% to 7%) at a low crested, emerged breakwater.

An increasing number of rocking units is expected, when the packing density is reduced. This has been observed at a relative freeboard  $R_c/H_{s,D} = \pm 0.0$ . However, in tests with submerged and emerged

breakwaters no correlation can be seen between packing density and the number of rocking units (as shown in Fig. 7).

The worst wave conditions that are associated with little or no armour layer damage are presented in Fig. 8. The stability number (i.e. maximum stability number with at most one displaced armour unit) is plotted against the relative freeboard. The stability of the armour layer varies to some extent with the relative freeboard. A variation of armour layer stability with packing density however cannot be identified. It appears from Figs. 7 and 8 that a variation of packing density by  $\pm 3\%$  has little influence on the armour layer stability of low crested and submerged breakwaters.

#### 4.3 Effect of Wave Steepness

The effect of wave steepness on the armour layer stability is presented in Figs. 9 and 10. The wave steepness  $s = H_s/L_{p,0}$  is defined by the ratio of significant wave height (at the breakwater toe) and deep water wave length (based on peak wave period). The number of rocking armour units in design conditions ( $N_s = 2.77$ ) is plotted in Fig. 9 (the data presented is identical to Fig. 7) and is apparently not affected by the wave steepness.

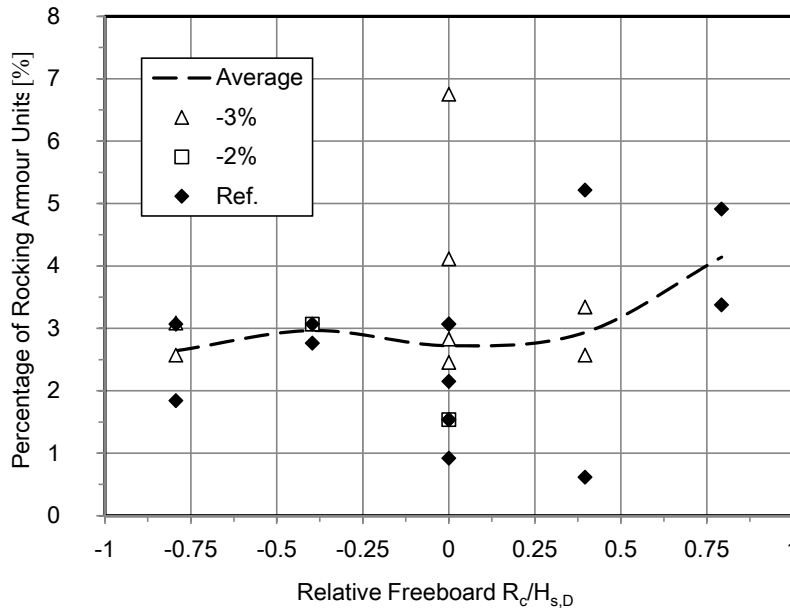


Fig. 7 Effect of freeboard and packing density on the number of rocking armour units (design conditions).

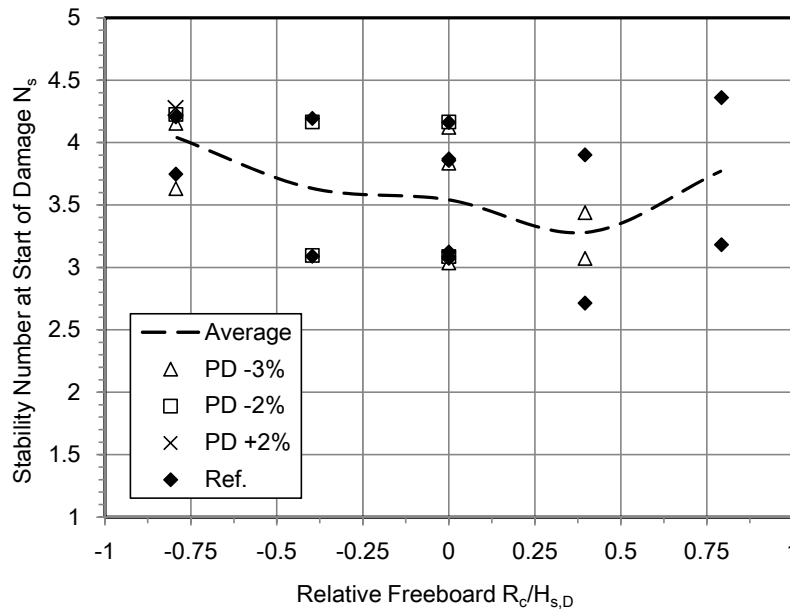


Fig. 8 Effect of freeboard and packing density on the start of damage.

The worst wave conditions that are associated with little or no armour layer damage (i.e. maximum stability number with at most one displaced armour unit) are presented in Fig. 10 (the data is identical to Fig. 8). 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 wave steepness, although it has apparently little influence on the number of rocking armour units, 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.

4.4 Location of Damage

At conventional, high crested breakwaters the armour layer on the seaward slope (at and above the water line) is most exposed. The exposure of the

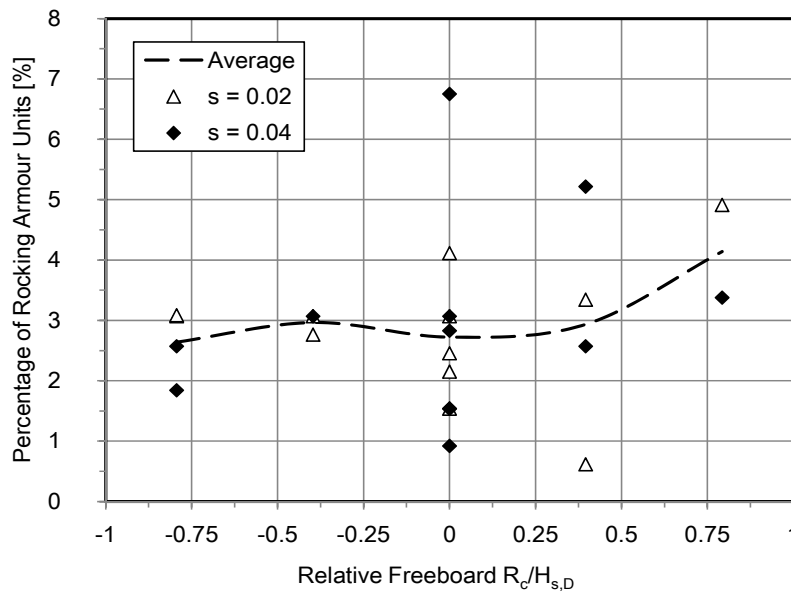


Fig. 9 Effect of freeboard and wave steepness on the number of rocking armour units (design conditions).

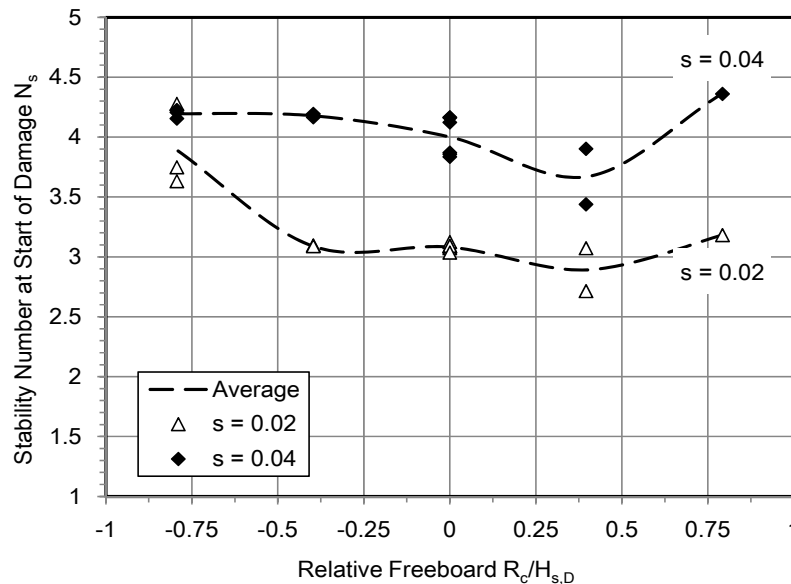


Fig. 10 Effect of freeboard and wave steepness on the start of damage.

breakwater crest is likely to be increased at low crested structures while the wave loading on the seaward slope may be reduced. Movements of armour units on the breakwater crest and on the seaward slope are presented in Figs. 11 and 12.

The number of rocking armour units on the seaward slope and on the breakwater crest (in design conditions, stability number  $N_s = 2.77$ ) is plotted in Fig. 11. The total number of rocking units (as presented in Figs. 7 and 9) has been subdivided in crest-units and

slope-units. The number of rocking units on the crest is about 2% at submerged structures ( $R_c/H_s < 0$ ) and is gradually decreasing when the freeboard is increasing.

The number of rocking units on the seaward slope is less than 1% 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 gradually increasing with increasing freeboard and reaches about 2% to 4%.



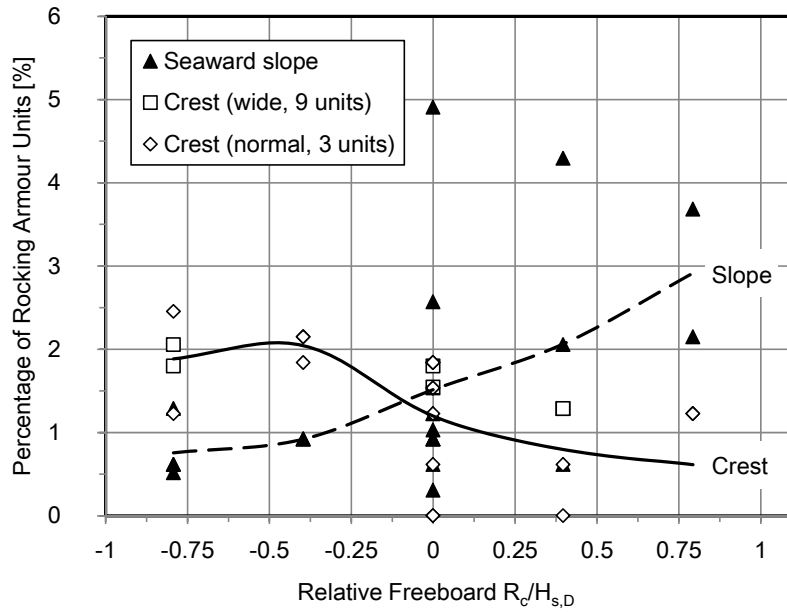


Fig. 11 Occurrence of rocking armour units on crest and seaward slope under design conditions.

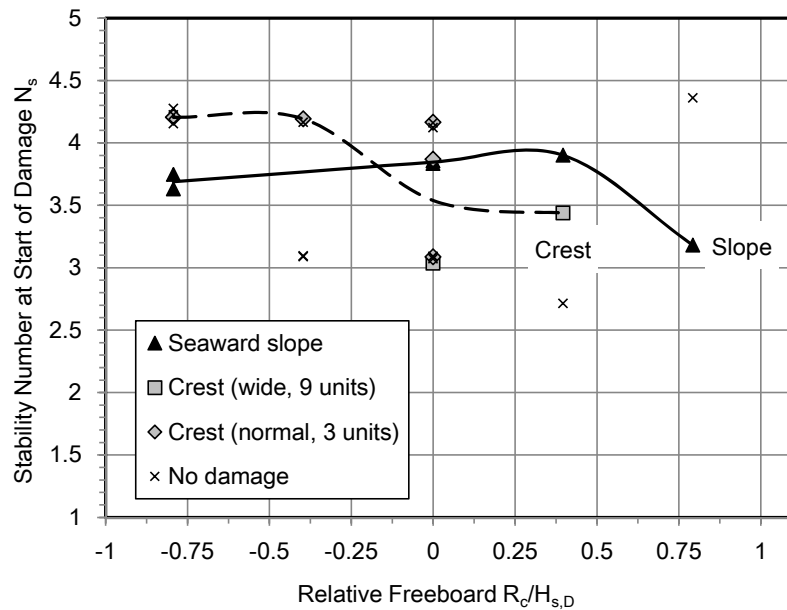


Fig. 12 Test with minor damage on crest and seaward slope.

The maximum damage numbers that are associated with little or no armour layer damage (at most one displaced armour unit) are presented in Fig. 12 (similar to Figs. 8 and 10). It is further indicated whether the first armour unit has been displaced from the crest or from the slope. At submerged structures ( $R_c/H_s < 0$ ) damage on the breakwater crests starts at stability number  $N_s > 4.0$ . At low crested structures ( $R_c/H_s \geq 0$ ) the crest stability is reduced to  $N_s = 3.5$

(average value) and may go down to  $N_s = 3.0$ . The slope stability is typically of order  $N_s = 3.5$  to  $4.0$ . Lower stability numbers at start of damage ( $N_s = 3.2$ ) have only been observed at a relative freeboard of  $R_c/H_s = +0.8$ .

It appears from Figs. 11 and 12 that the stability of the breakwater crest reaches a minimum at relative freeboards  $R_c/H_s$  of  $\pm 0.0$  to  $+0.5$ . The crest stability is not critical at submerged structures and if the relative

freeboard  $R_c/H_s$  exceeds +0.5, the stability of the seaward slope is determining for the overall stability if  $R_c/H_s > 0.5$ .

4.5 Effect of Freeboard

The stability number at start of damage (i.e. the test conditions where the first armour unit has been displaced) are plotted in Fig. 13 against the relative freeboard. Start of damage is presented for the entire structure (regardless of the location of initial damage) as

well as for the breakwater crest, the seaward slope and the rear slope. Stability numbers in Fig. 13 may also refer to test conditions where more than one armour unit has been displaced (i.e. tests with progressive damage), which are excluded from Figs. 8, 10 and 12.

The following can be seen in Fig. 13:

- The overall stability is gradually decreasing with decreasing freeboard, reaches a minimum at zero freeboard ( $N_s = 3.0$ ) and increases to about  $N_s = 3.6$  at submerged structures;

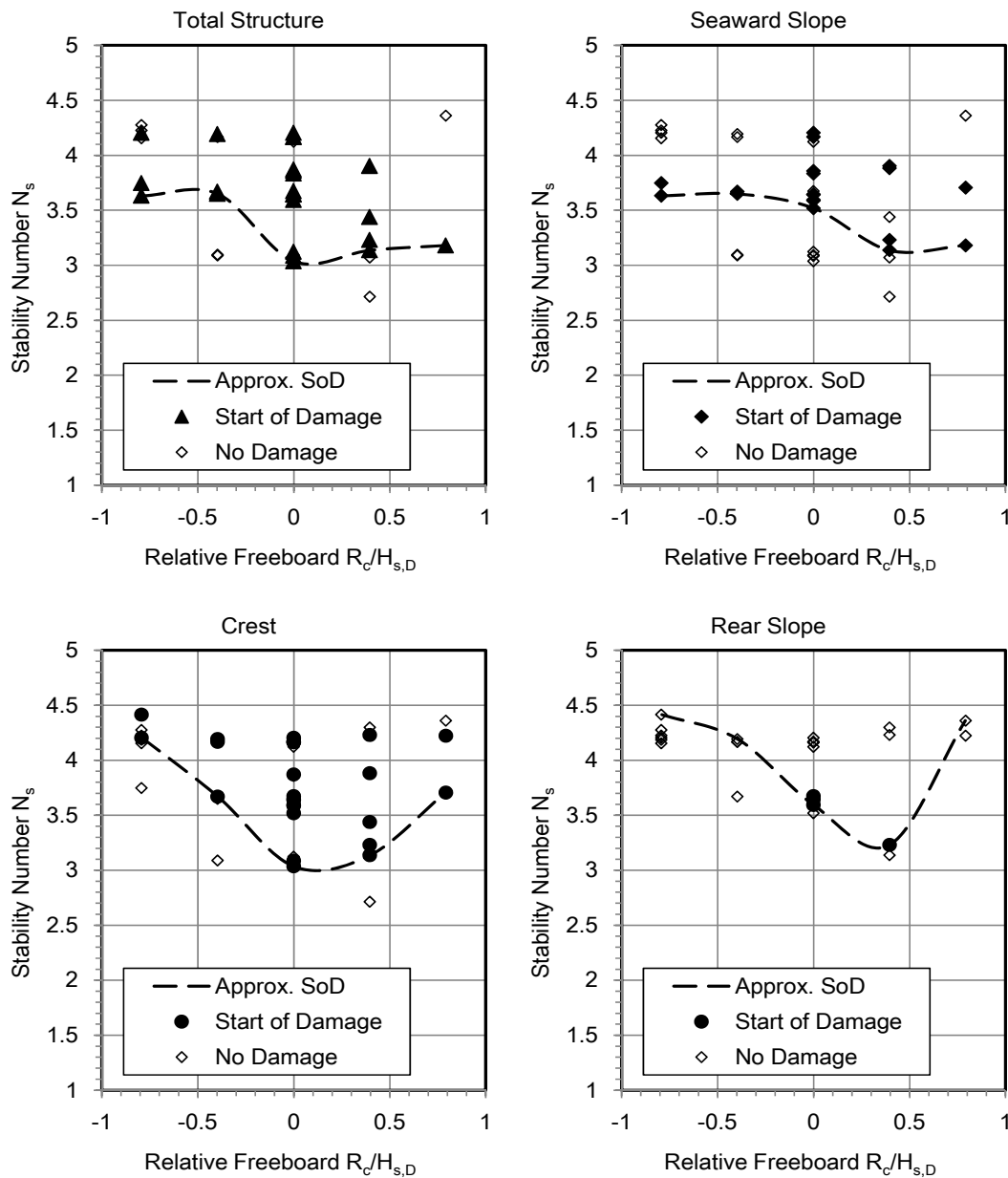


Fig. 13 Stability number  $N_s$  at start of damage: Overall damage (top left), seaward slope (top right), crest (bottom left) and rear slope (bottom right).

- The lowest stability of the seaward slope has been observed at emerged structures ( $R_c/H_s \geq 0.4$ ,  $N_s = 3.1$ ). At submerged structures ( $R_c/H_s \leq \pm 0.0$ ) the stability increased to about  $N_s = 3.5$ ;

- The crest stability reaches a minimum at zero freeboard ( $N_s = 3.0$ ). The crest stability is gradually increasing with increasing freeboard and even more rapidly increasing with increasing submergence;

- Damage at the rear slope has only been observed at low crested structures ( $R_c/H_s = \pm 0.0$  and  $+0.4$ ). The stability of the rear slope appears uncritical for structures with higher freeboard or for submerged structures.

A nominal stability number (typical lower bound of test results) of  $N_s = 3.5$  has been derived for the start of damage at conventional, high crested Xbloc breakwaters [19]. SoD (Start of damage) at lower stability numbers can be expected at low crested and submerged breakwaters under the following conditions:

- Relative freeboard  $R_c/H_s = +0.8$ : Stability of seaward slope was reduced (SoD at  $N_s = 3.2$ );
- Relative freeboard  $R_c/H_s = +0.4$ : Stability of seaward slope, crest and rear slope was reduced (SoD at  $N_s = 3.1$ );
- Zero freeboard,  $R_c/H_s = 0$ : Stability of crest was reduced (SoD at  $N_s = 3.0$ );
- Submerged breakwater,  $R_c/H_s \leq -0.4$ : Stability of seaward slope, crest and rear slope was similar to a conventional, high crested breakwater.

Stability numbers at start of damage (i.e. the trend lines in Fig. 13) are plotted in Fig. 14. The slope stability has been extrapolated for freeboards  $R_c/H_s > +0.8$  (based on Ref. [19]). An increase in Xbloc armour unit weight of 50% (for crest levels  $R_c/H_s < +1.0$ ) and of 100% (for  $R_c/H_s < +0.5$ ) is recommended in Ref. [19]. The corresponding stability numbers are  $N_{s,D} = 2.77$  ( $R_c/H_s > 1$ ),  $2.42$  ( $R_c/H_s < 1$ ) and  $2.20$  ( $R_c/H_s < 0.5$ ). These stability numbers are indicated in Fig. 14 as “design values”. The safety margin between the design value ( $N_{s,D} = 2.77$ ) and the lower bound of the expected start of damage ( $N_s = 3.5$ ) is 26% for conventional,

high crested breakwaters [19]. This safety margin corresponds to a factor 2 on the armour unit weight. The same safety margin has been applied for the reduced design values for low crested breakwaters, resulting in stability numbers  $N_s = 3.05$  ( $R_c/H_s < 1$ ) and  $2.77$  ( $R_c/H_s < 0.5$ ) at start of damage. These values are indicated in Fig. 14 as “nominal start of damage”.

The stability of rock armoured structures [11] is plotted in Fig. 14 for comparison. A design wave height  $H_{s,D} = 1.5 \Delta D_{n50}$  has been applied for rock armour. The stability of a rock armoured front slope is steadily increasing when the freeboard is less than  $R_c/H_{s,D} < +0.6$ . The stability of single layer armour units on the front slope is reduced if  $0 < R_c/H_{s,D} < +1.0$  and nearly constant if  $R_c/H_{s,D} < -0.25$ . The crest stability of both armour types, rock armour and single layer armour units reaches a minimum when the breakwater crest is at the water line ( $R_c/H_{s,D} = \pm 0.0$ ). The stability of a rock armoured rear slope is steadily increasing when the freeboard is less than  $R_c/H_{s,D} < +0.8$ . The stability of single layer armour units on the rear slope starts increasing when  $R_c/H_{s,D} < +0.3$ .

The design approach for low crested breakwaters [19], although not based on systematic model tests, is largely confirmed by the experimental results. The safety margins between the design values and the actual start of damage are similar to conventional breakwaters and correspond to a factor 2 on the armour unit weight.

## 5. Conclusions and Recommendations

Settlements of the armour layer result in reduced packing densities in the upper part of front and rear slope and on the breakwater crest. Gaps in the armour layer may develop at the transition from front slope to crest and at submerged structures also at the transition to the rear slope. The largest gaps were observed at emerged structures. Larger settlements were observed in tests with lower packing density and longer waves. This may explain to some extent the reduced armour layer stability in tests with longer waves.

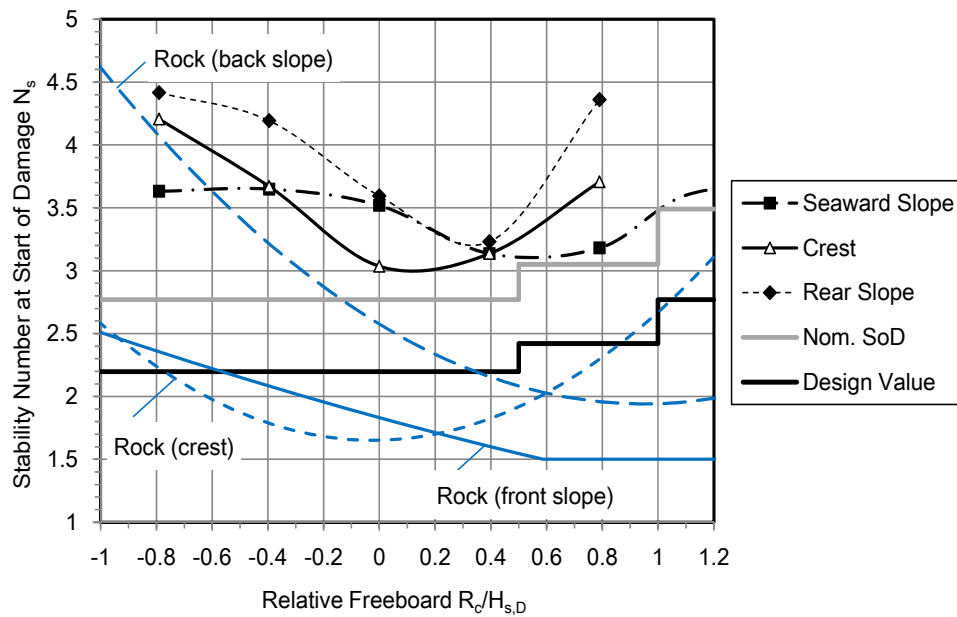


Fig. 14 Stability number  $N_s$  at start of damage.

Rocking is not necessarily a suitable indicator for the hydraulic stability of an armour layer. The total number of rocking armour units (in design wave conditions) was similar for short and long waves while start of damage (displacement of the first armour unit) occurred at about 20% smaller wave heights in tests with long waves. More rocking of crest armour units has been observed on submerged breakwaters as compared to emerged structures. The hydraulic stability of the crest armour however was most critical for low crested, emerged structures.

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 (where gaps in the armour layer developed due to settlements). Damage on the crest was progressing towards the rear side.

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 on front and rear slope.

- Seaward slope: The armour unit stability 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.

- Crest: The stability is reduced by about 14% (50% larger armour unit weight required) at low crested structures. At submerged structures the crest stability is rapidly increasing with decreasing (negative) freeboard.

- Rear slope: The stability is reduced by about 10% (35% larger armour unit weight required) at low crested structures.

Start of damage at low crested and submerged breakwaters can be expected at:

(a) Relative freeboard  $R_c/H_s = +0.8$ : On the seaward slope at  $N_s = 3.2$ ;

(b) Relative freeboard  $R_c/H_s = +0.4$ : On the seaward slope and crest at  $N_s = 3.1$ ;

(c) Zero freeboard,  $R_c/H_s = 0$ : On the crest at  $N_s = 3.0$ ;

(d) Submerged breakwater,  $R_c/H_s \leq -0.4$ : On the seaward slope and crest at  $N_s > 3.5$ .

An increase in Xbloc armour unit weight of 50% for

crest levels  $R_c/H_s < +1.0$  and 100% for  $R_c/H_s < +0.5$  as recommended in Ref. [19] meets the above requirements. The safety margin between the recommended design value and the observed start of damage is more than a factor 2 on the armour unit weight.

No reduction of the armour layer stability has been found for submerged structures with relative freeboard  $R_c/H_s \leq -0.4$ . This aspect has not been addressed in Ref. [19].

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

### Acknowledgments

The support of Peter van der Linde, who provided the experimental data for this study, and the support of Delta Marine Consultants are gratefully acknowledged.

### References

- [1] J.W. van der Meer, K.W. Pilarczyk, Stability of low-crested and reef breakwaters, in: ASCE 22nd Int. Conf. on Coastal Eng., Delft, the Netherlands, 1990.
- [2] C. Vidal, M.A. Losada, E.P.D. Mansard, Stability of low-crested rubble-mound breakwater heads, *Journal of Waterway, Port, Coastal and Ocean Engineering* 121 (2) (1995) 114-122.
- [3] H.F. Burcharth, M. Kramer, A. Lamberti, B. Zanuttigh, Structural stability of detached low crested breakwaters, *Coastal Engineering* 53 (4) (2006) 381-394.
- [4] G. Burger, Stability of low-crested breakwaters. M.Sc. Thesis, Delft University, 1995.
- [5] M. Kramer, H.F. Burcharth, Stability of low-crested breakwaters in shallow water short crested waves, in: Coastal Structures 2003 Conference, Portland, USA, 2003.
- [6] M. Kramer, B. Zanuttigh, J.W. van der Meer, C. Vidal, F.X. Gironella, Laboratory experiments on low-crested breakwaters, *Coastal Engineering* 52 (2005) 867-885.
- [7] J.W. van der Meer, I.F.R. Daemen, Stability and wave transmission at low crested rubble mound structures, *ASCE J. of WPC & OE* 120 (1) (1994) 1-19.
- [8] J.W. van der Meer, W.H. Tutuarima, G. Burger, Influence of rock shape and grading on stability of low-crested structures, in: Proc. of 25th Int. Conf. on Coastal Eng., 1996, pp. 1957-1970.
- [9] M.D. Kudale, N. Kobayashi, Hydraulic stability analysis of leeside slopes of overtopped breakwaters, in: Proc. of 25th Int. Conf. on Coastal Eng., 1996, pp. 1721-1734.
- [10] K.W. Pilarczyk, Design of low-crested (submerged) structures—An overview, in: 6th COPEDEC Conference, Colombo, Sri Lanka, 2003.
- [11] CIRIA, The Rock Manual: The Use of Rock in Hydraulic Engineering, 2nd ed., C683, CIRIA, London, 2007.
- [12] B. Kamali, R. Hashim, Recent advances in stability formulae and damage description of breakwater armour layer, *Australian Journal of Basic and Applied Sciences* (3) (3) (2009) 2717-2827.
- [13] F. Taveira-Pinto, Analysis of Submerged Breakwaters Stability Design, *Coastal Engineering VII—Modelling, Measurements, Engineering and Management of Seas and Coastal Regions*, WIT Press, UK, 2005, pp. 209-223.
- [14] A. Matsumoto, M. Yamamoto, A. Mano, A light concrete block stabilized by distributed holes for submerged breakwaters, *Journal of Coastal Research* SI 64 (2011) 567-571.
- [15] M. Muttray, B. Reedijk, Design of concrete armour layers, *International Maritime Journal* 146 (6) (2009) 111-118.
- [16] P. van der Linde, Stability of single layer armour units on low-crested structures, M.Sc. Thesis, Delft University, 2010, p. 287.
- [17] H.J. Verhagen, K. d'Angremond, F. van Roode, *Breakwaters and Closure Dams*, 2nd ed., VSSD, Delft, the Netherlands, 2009, p. 392.
- [18] T. Hald, H.F. Burcharth, An alternative stability equation for rock armoured rubble mound breakwaters, in: ASCE 27th Int. Conf. on Coastal Eng., Sydney, Australia, 2000.
- [19] Guidelines for Xbloc Concept Design, DMC (Delta Marine Consultants), Gouda, NL, 2011.