# Placement and Structural Strength of Xbloc® and other Single Layer Armour Units

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## Abstract

*The Xbloc, a new type of breakwater armour unit has been developed by Delta Marine Consultants. The structural strength of single layer armour units and the ease of placement have been studied extensively in the course of the Xbloc development. Prototype drop tests have been conducted with Xbloc armour units and compared with results from previous studies with Accropode and Coreloc®. The static and dynamic structural response of Xbloc, Accropode and Coreloc® has been investigated with three-dimensional finite element models. It was found that the structural strength of Accropode and Xbloc are of the same order of magnitude while the Coreloc® is more fragile. The placement of Xbloc armour units has been studied systematically including sling placement, the sensitivity to settlements and the variation of interlocking between individual armour units. Three additional design parameters are proposed in order to quantify the quality and the ease of placement and to assess the risks of improper placement.*

## General

Single layer concrete armour units represent the state of the art for the protection of larger breakwaters. These units are characterised by a large interlocking capacity and random placement. The most commonly applied single layer armour units are Accropode™ (more than 120 breakwaters since 1980) and Coreloc® (16 applications since 1996). The Xbloc has been developed by Delta Marine Consultants and has been presented to the public in 2003 (Figure 1). The first Xbloc application was completed early in 2004, the armour unit production for the second project commenced in 2004 and the start of the breakwater construction is expected for 2005. The performance of single layer armour units has been studied extensively in the course of the Xbloc development (2001 – 2003).

The current design practise for breakwater armour layers is mainly focused on hydraulic stability while structural stability and construction aspects play a secondary role. Cases of damage to breakwaters with single layer armouring (Table 1 and Figure 2), indicate a need for a more comprehensive armour design including structural strength and placement of armour units. While the hydraulic stability of breakwater armour units can be determined (in hydraulic model tests) and quantified (by a stability number), no appropriate criteria are available for the structural strength of armour units and for the ease and quality of placement. As a consequence these aspects are frequently neglected by designers.

In this paper the results of a structural strength and placement analysis, which is based on comparative testing with various types of single layer armour units, will be presented and discussed.

Figure 1: Layout of Xbloc

Figure 2: Saba breakwater after hurricane Lenny

Table 1: Damage cases

| Breakwater site | Year of damage | Armour type | Probable cause of damage |
|---|---|---|---|
| Port St Francis, South Africa | 1996/97 | Coreloc® | Breakage of armour units during construction[1)] |
| Fort Bay, Saba | 1999 | Accropode | Exceedence of design wave height, improper maintenance[2)] |
| Argeles, France | 1999 | Accropode | Breakage of armour units, cause uncertain |
| Ventura, California, USA | 2001 | Coreloc® | Toe failure, improper placement[2)] |
| Scarborough, UK | 2004 | Accropode | Breakage of armour units in service[1+2)] |

[1)] strength related; [2)] placement related

## Structural strength analysis

Breakwater armour units are exposed to impact loads during construction (handling and placement) and in service (settlements and rocking). Breakage of armour units is critical for the integrity of the armour layer. The risk of breakage shall be therefore considered in the design process. The structural strength of Xbloc and other armour units has been studied by prototype drop tests and by FE analysis.

### Drop tests

Series of overturning tests and free fall tests have been conducted in order to simulate rocking and major impacts during placement. The results have been compared with drop test results for Accropode (Sogreah, 1984) and Coreloc® (Turk & Melby, 1997).

Four Xbloc units with a volume of 4 $m^3$ (mass of 9.4 t) have been cast for the overturning and free fall tests. A C30/37 concrete quality with an average compressive strength of 33.5 $N/mm^2$ and an average tensile strength of 4.5 $N/mm^2$ has been used. Surface-mounted strain gauges have been applied on the armour units at locations with maximum strains (intersection between X-shaped base and cubical leg). The armour units have been dropped on a reinforced concrete base (dimensions $7.5\times10\times0.5$ $m^3$, mass 90 t) that was embedded in compacted sandy subsoil and covered with steel plates (thickness 30mm). The steel plates have been used to minimise the absorption of fall energy by the foundation (and as a result the loads on the armour unit will be maximised). This test set-up, which is considerable conservative as compared to prototype conditions, has been selected in order to generate reliable and reproducible results.

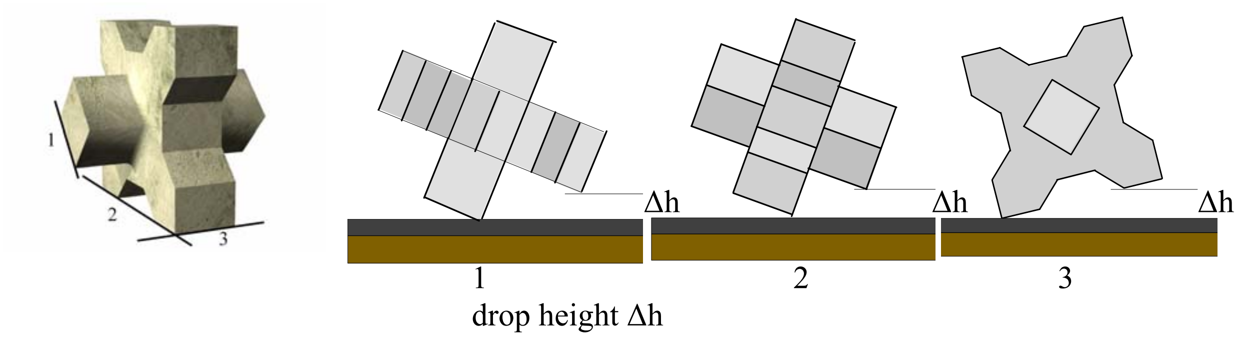


Figure 3: Definition sketch for Xbloc drop tests

Three types of overturning tests have been performed with Xbloc armour units where the units are rotated around the 3 main axes (line 1, 2 and 3 in Figure 3). The fall height was incrementally increased with steps of typically a few centimetres up to the maximum geometrical fall height (the point where the armour block tends to move back into an upright position). If the maximum geometrical fall height was reached without significant damage, the overturning tests have been repeated about 50 times with maximum fall heights (see Table 2).

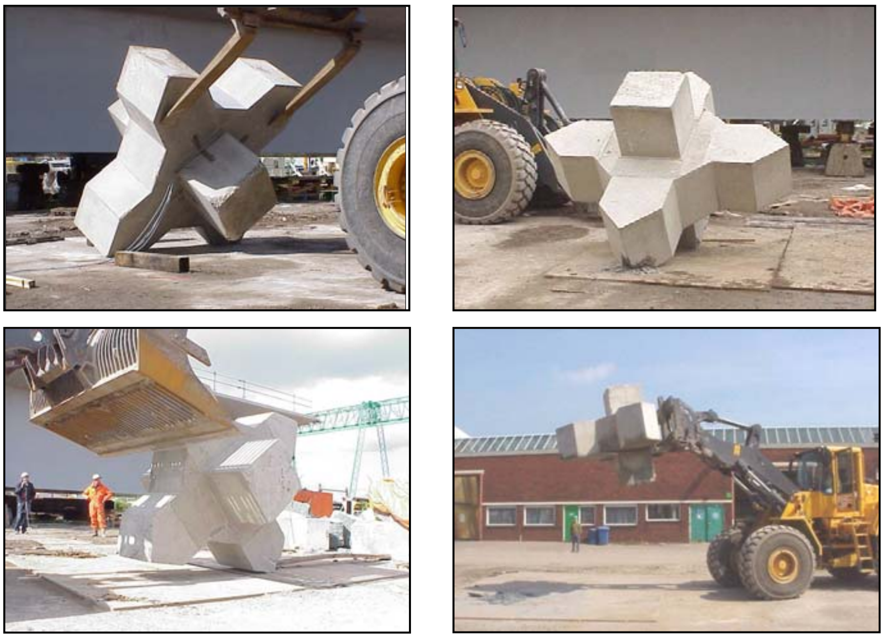


Figure 4: Xbloc prototype drop tests (overturning tests type 1, 2, 3 and free fall tests)

During the free fall tests the armour units have been dropped on the concrete base (covered with steel plates, Figure 4). The fall height varied between 0.4 m and 2.6 m and has been increased stepwise (steps of about 0.5 m) until breakage of the armour units. Various Xbloc orientations have been tested. The free fall tests have been conducted with a large loader (Volvo L150). The units have been lifted with a fork and dropped by either rapidly lowering the fork or by tilting the fork. Details of the free fall tests can be found in Hakenberg et al. (2004).

Sogreah (1984) reported free fall tests with Accropodes (6.3 $m^3$, 15t). The test units were dropped onto consolidated breakwater core material (quarry run) and on a concrete cube (2.25 × 2.25 × 1.4 $m^3$, 16.5 t). No damage occurred when Accropodes were dropped onto the breakwater core (drop heights 1.5 – 5.1 m) as the kinetic energy was absorbed by deformation of the core material; the fall heights were 1.5m, 2.8m, 4.2m and 5.1m. The drops onto a concrete cube resulted in 35% weight loss due to breakage for drop height 3.7 m (for the first Accropode) and 16% weight loss at drop height 7.3 m (for the second Accropode).

Overturning and free fall tests have been conducted with Coreloc® (4 $m^3$, 9.2 t) (Turk, 1997). The Coreloc® overturning tests are comparable to Xbloc overturning tests type 2 (tip drop) and type 3 (hammer drop). Only one armour unit orientation has been considered in the free fall tests (Coreloc® has been dropped on the anvil). The test units have been dropped onto a rigid concrete base. The damage to the armour units has not been quantified (weight loss is not specified). A vertical member (anvil) of the Coreloc® broke off after 46 drops (type 2) with a maximum drop height of 30 cm. The tip of a vertical member broke off after 18 drops (type 3) with a maximum drop height of 10 cm. During the free fall tests (4 series of 9 drops with constant fall) the maximum fall height was 23 cm when the tip of a vertical member broke off.

The results of Xbloc, Accropode and Coreloc® drop tests are summarised in Table 2. Details of the Xbloc drop test including strain measurements and damage pattern can be found in Hakenberg et al. (2004).

The prototype drop test results for Xbloc, Accropode and Coreloc® differ significantly. These differences are partly due to the different test procedures and test conditions. Nonetheless the test results give some indication about the relative strength of the different armour units:

- Free fall tests: The critical fall heights for Coreloc® (0.23 m) are significantly lower than for Accropode and Xbloc (more than 1.0 m);
- Overturning tests 2: Breakage of Coreloc® (33% weight loss) while the Xbloc damage is insignificant (0.2% weight loss);
- Overturning test 3: The critical fall heights for Xbloc (0.31 m) are about 3 times higher than for Coreloc® (0.1 m).

It can be concluded that the structural strength of Accropode and Xbloc are of the same order of magnitude while the Coreloc® is more fragile.

The Xbloc drop test procedure is recommended for future drop tests in order to produce comparable results. A stiff concrete base shall be used. The mass of the base shall be significantly larger than the mass of the armour unit; damage or displacements of the concrete base shall be monitored. It should be noted that overturning tests are reproducible (the movement of the armour unit is well defined and location of impact will be constant for each consecutive drop) while free fall test are less reproducible (the armour unit might be rotated during the fall and the impact location might vary). Nonetheless series of free fall tests (with varying armour unit orientation) are considered useful as the fall height is almost unrestricted (and can be thus increased until breakage).

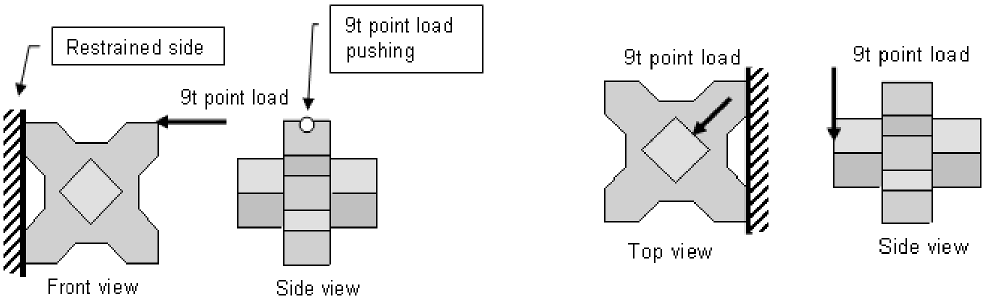
Table 2: Drop test results for various types of single layer armour units

| | Xbloc | Accropode | Coreloc® |
|---|---|---|---|
| | (Hakenberg et al., 2004) | (Sogreah, 1984) | (Turk, 1997) |
| Unit size | 4 m$^3$ | 6.3 m$^3$ | 4 m$^3$ |
| Base | 10 × 7.5 × 0.5 m$^3$ concrete base (covered with 3 cm steel plate) | 2.25 × 2.25 × 1.4 m$^3$ concrete cube | Approx. 4 × 3 × 1 m$^3$ concrete base |
| Concrete compressive strength | 34 N/mm$^2$ | not specified | 43 N/mm$^2$ |
| Overturning test 1 | | | |
| Number of drops | 60 (50 at max height) | n.a. | n.a. |
| Max fall height [m] | 0.37 (max possible) | | |
| Weight loss | 0.05% | | |
| Overturning test 2 | | | |
| Number of drops | 69 (51 at max height) | n.a. | >40 |
| Max fall height [m] | 0.33 (max possible) | | 0.30 |
| Weight loss | 0.2% | | Approx. 33% |
| Overturning test 3 | | | |
| Number of drops | 9 | n.a. | 18 |
| Max fall height [m] | 0.31 | | 0.10 |
| Weight loss | 14% | | Approx. 10% |
| Free fall test | | | |
| Drop method | Tilting or lowering forks of wheel loader | Releasing drums of crawler crane | not specified |
| Number of drops | 2 / 5 / 9 | 15 / 9 | 4 × 9 |
| Max fall height [m] | 1.4 / 2.6 / 2.1 | 3.7 / 7.3 | 0.23 |
| Weight loss | 40% / 40% / 20% | 35% / 16% | Approx. 10% |

## Finite element analysis

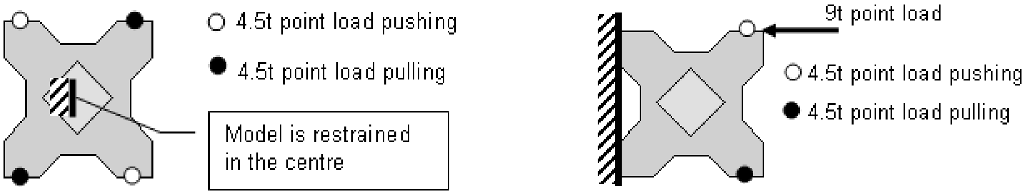
The static and dynamic structural response of Xbloc, Accropode and Coreloc® has been investigated with three-dimensional finite element models (FE) developed in ANSYS 6.1. The models of all three armour units have the same properties (volume 4 m$^3$, density 2350 kg/m$^3$, Young's Modulus 30 kN/mm$^2$, Poisson's ratio 0.20, number of elements 2,000). The armour units have been exposed to flexure, torsion and combined flexure and torsion. The properties of the FE models and the load cases are similar to previous studies (Sogreah, 1980 and Melby, 1997). However, this study includes one flexure load case and two quasi-dynamic free fall cases that have not been considered in previous studies.

The static load cases are outlined in Figure 5. A gravitational acceleration of 20g has been applied for the quasi-dynamic load cases, two different armour unit orientations (with cubical legs sideward or up-/downward) have been considered. The dynamic load cases comprised overturning tests (type 3) and free fall tests. Details of the dynamic load tests can be found in Hakenberg et al. (2004).



**Flexure 1**

**Flexure 2**



**Torsion**

**Flexure and Torsion**

Figure 5: Static load cases for FE analysis

The results of the static and quasi-dynamic load analysis are plotted in Figure 5. The FE results confirm the findings from the prototype drop tests. The tensile stresses for Xbloc are for most of the load cases similar to the Accropode stresses and lower than the Coreloc® stresses. The tensile stresses for Coreloc® are mostly higher than for the other two armour units. A direct comparison of the results from this study and previous studies can be seen in Table 3. It is interesting to note that the results of the Sogreah study (load case torsion) are confirmed by this study while the results of Melby for Accropode (1.5 MPa) and Coreloc® (1.1 MPa) are in contradiction with this study (Accropode 1.2 MPa and Coreloc® 1.4 MPa).

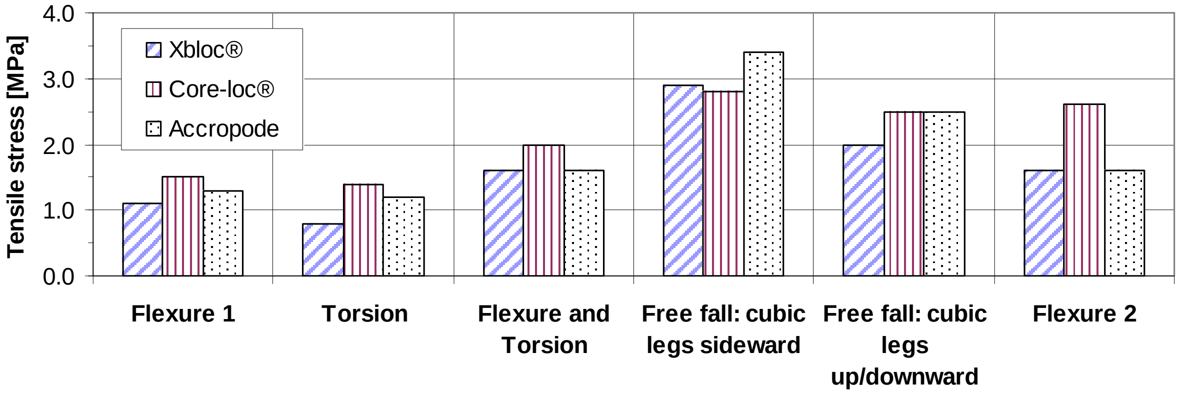


Figure 6: Results of FE analysis

The FE analysis is a useful supplement to prototype drop tests for the structural strength analysis. Static load analysis provides well defined load cases and boundary conditions. The results for various block shapes can be therefore directly compared and easily reproduced. The dynamic load analysis has been mainly used in this study to provide insight in the structural strength of units and to indicate areas of maximum stress (critical sections). The peak values of impact loads depend very much on the characteristics of the model (especially the resolution in time domain). Therefore, quantitative results of dynamic load analysis require careful interpretation while qualitative results are of practical use (for example for the preparation of prototype drop tests).

Table 3: Comparison of static load test results

| Armour type | Study | Flexure [MPa] | Torsion [MPa] | Flexure & Torsion [MPa] |
|---|---|---|---|---|
| Xbloc | this study | 1.1 | 0.8 | 1.6 |
| Coreloc® | this study | 1.5 | 1.4 | 2.0 |
|  | Melby (1997) | 1.1 | 1.1 | 1.9 |
| Accropode | this study | 1.3 | 1.2 | 1.6 |
|  | Melby (1997) | 1.5 | 1.5 | – |
|  | Sogreah (1980) | – | 1.1 | – |

## Placement analysis

The placement of single layer armour units is essential as it affects the hydraulic stability of the armour layer as well as the structural integrity of individual blocks. The armour placement is mostly the limiting factor for the construction progress and thus also a significant cost factor for the entire project. Placement schemes have been optimised with respect to interlocking; little attention has been paid to facilitate the placement procedure.

### Placement of single layer armour units

Single layer armour units are placed with random orientation on a predefined staggered grid. The guidelines for the placement of Accropode and Coreloc® armour units include requirements for the positioning and criteria for the orientation of individual units (see Sogreah, 1988 and Melby & Turk, 1997). The most important criteria are:

- *Positioning:* The acceptable deviations from the placement grid are typically limited to less than 10% of the unit size.
- *Orientation:* (i) Adjacent armour units shall have different attitude; (ii) armour units must not be in contact with units of the same row; (iii) each armour units must be keyed into two armour units of the row below; (iv) less than one third of the units shall have the plane face parallel to the slope; (v) armour units with this orientation (plane side parallel to the slope) must be distributed throughout the slope and must not be found in groups and (vi) armour units shall rest on three points (two neighbouring units and the slope).

Strict placement regulations will affect the placement speed, especially if a specific unit has to be placed several times in order to meet these regulations. The placement rates for single layer armour units are typically 3 – 6 units/hour and may vary significantly for placement above and under water depending on equipment, experience and environmental conditions (waves, currents and visibility). In harsh conditions it will be more difficult to comply with the placement regulations.

The placement of Xbloc armour units at trunk sections and roundheads has been studied in order to improve the ease of placement and the placement speed. It was found that Xbloc will form a reasonable stable and homogeneous armour layer if the placement complies with the following two criteria:

- *Positioning:* Placement on a predefined staggered grid in order to guarantee the requested packing density;
- *Orientation:* Random orientation implying interlocking with the neighbouring armour units.

The criteria that are related to the armour unit orientation and to the relative orientation of neighbouring armour units (criteria (i) to (iii) of the above listing), which are essential for a proper placement of other armour units, have been omitted for the Xbloc. A typical Xbloc placement pattern is presented in Figure 7. The underlying Xbloc placement studies are described in the following section.

## Xbloc placement tests

The Xbloc placement studies comprise (i) the sling placement of armour units, (ii) the effect of placement on hydraulic stability and settlements and (iii) the variation of interlocking between individual armour units.

The packing density that can be achieved when armour units are placed with a sling has been determined in model scale. Units of 61 g have been placed on a plain 3:4 slope with a horizontal spacing of about 1.3 D. Two different placement methods have been studied; the sling has been attached either to a leg of the X-shaped base (method I) or to a cubical leg (method II). The results of the sling placement tests are summarised in Table 4.

Table 4: Results of Xbloc placement test

| Method of Placement | | Number of Tests | Packing density (as compared to recommended packing density*) | | |
|---|---|---|---|---|---|
| | | | min | max | mean |
| I | Sling attached to leg of X-shaped base | 13 | 95% | 104% | 101% |
| II | Sling attached to cubical leg | 3 | 89% | 92% | 90% |

*Recommended packing density = $1.20/D^2$ with characteristic Xbloc length D

It was found that an upslope spacing of less than 0.64 D has been achieved in most of the placement tests (12 out of 16 tests). A packing density of $(0.64\ D \times 1.3\ D)^{-1} = 1.20/D^2$ shall be therefore used as guidance for Xbloc placement. The recommended packing density can be easily achieved by placement method I (12 out of 13 tests) while it is difficult to achieve by method II. Method I is therefore recommended for Xbloc placement.

The effect of improper Xbloc placement on the hydraulic stability has been determined in 2D hydraulic model tests at Delft Hydraulics. The horizontal spacing varied between 1.11 D and 1.39 D and the upslope spacing between 0.63 D and 0.73 D. In Figure 8 the stability number ($H_s/\Delta D_n$) at start of damage is plotted against the packing density. A displacement of one armour unit, which correspond to 0.25% damage, has been considered as start of damage. It has been found that the stability of the armour layer is slightly increasing with increasing packing density (see Figure 8). The tests indicated also that the packing density affects the sensitivity to settlements.

Settlements have been measured during 2D model tests at Delft Hydraulics on a relatively long breakwater slope with 28 rows of armour units. The results are summarised in Table 5. Significant settlements have been observed for packing densities of less than $1.15/D^2$. The armour unit above the water line have been displaced by about 0.5 D during the first test; no further settlements have been observed in the following tests. No settlements have been observed for packing densities of more than 1.20/D$^2$.

Settlements can be expected for as built packing densities $P_b$ that are lower than the stable packing density $P_s$ (about 1.18/D$^2$ – 1.20/D$^2$ for Xbloc). The resulting settlements Δs (on a slope of length l) can be assessed by:

$$\frac{\Delta s}{D} = \left(1 - \frac{P_b}{P_s}\right)\frac{l}{D} \qquad (1)$$

A packing density of 1.20/D$^2$ has been concluded from the results of sling placement and hydraulic model tests as guidance for the Xbloc placement. This value provides a relatively large safety margin (high hydraulic stability and no settlements) and a relatively low concrete demand. The as built packing density shall be within a range of 97% to 105% of the target value.

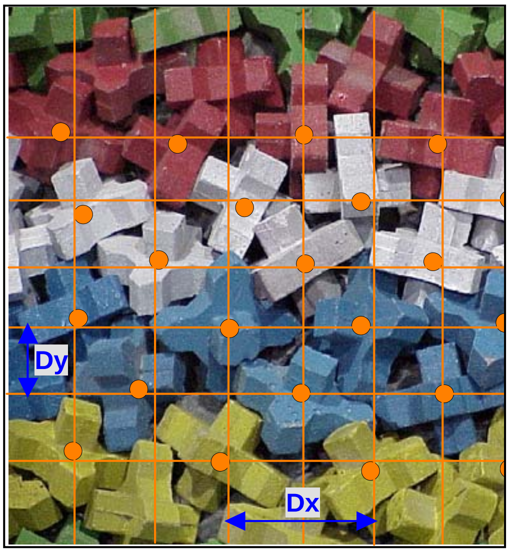


Figure 7: Placement of Xbloc armour units in a staggered grid with random orientation

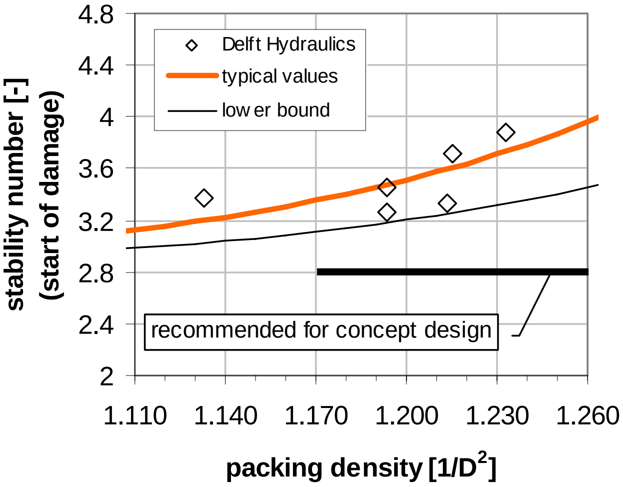


Figure 8: Effect of packing density on hydraulic stability

Table 5: Settlements of Xbloc armoured slopes

| Packing density | Number of tests | Results |
|---|---|---|
| 1.13 / D$^2$ [94%] | 1 | Significant settlements (displacements of 0.5 D) |
| 1.19 / D$^2$ [99%] | 2 | Minor or no settlements |
| > 1.20 / D$^2$ [> 100%] | 3 | No settlements |

The interlocking of individual Xbloc armour units has been determined by pullout tests. The pullout force has been determined experimentally. Armour units have been placed on a plain 1:1.5 slope with standard placement pattern and packing density. A total of 8 rows of armour units have been placed, individual units from row 3 to 7 have been pulled out perpendicular to the slope; the maximum force has been recorded. 53 pullout tests have been conducted. The results are summarised in Table 6 and Figure 9.

The probability of occurrence and exceedence of the relative pullout force F/G (with pullout force F and armour unit weight G) is plotted in Figure 9. The results of pullout experiments with rock (Hald and Burcharth, 2000) are presented for comparison. It is interesting to note that the pullout force for Xbloc was in average about 7 times larger than the weight of the armour unit and varied between 5G and 10G. The average pullout force for rock is about 1.8G.

A lognormal distribution has been applied for the description of the maximum pullout force. The parameters of the lognormal distribution (average value $\mu$ and the standard deviation $\sigma$) are listed in Table 6. Typical pullout forces (with 10%, 50% and 90% exceedence) that have been derived from the measured data are listed for comparison.

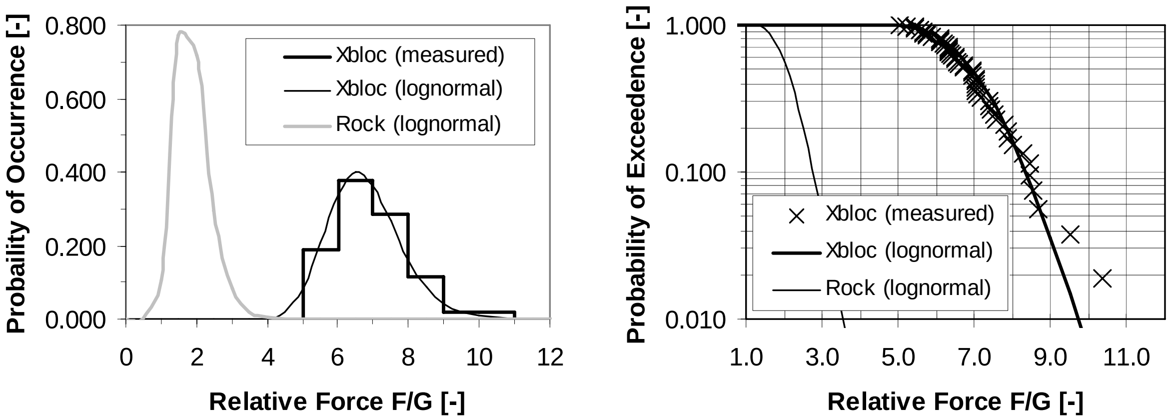


Figure 9: Results of Xbloc pullout test

Table 6: Pullout tests force distribution for Xbloc and rock armour

| Type of armour | Estimated lognormal parameters | | | Relative pullout force | | | |
|---|---|---|---|---|---|---|---|
| | $\mu$ | $\sigma$ | $R^2$ | $F_{10\%}/G$ | $F_{50\%}/G$ | $F_{90\%}/G$ | $F_{mean}/G$ |
| Rock | 0.6 | 0.26 | 0.97 | 2.6 | 1.8 | 1.3 | 1.8 |
| Xbloc | 1.9 | 0.15 | 0.99 | 8.4 | 6.7 | 5.7 | 6.9 |

The main results of the placement study are summarised in Table 7. It should be noted that pullout tests have been conducted only for Xbloc armour units. No information about the variation of interlocking is available for other types of single layer armour units. The interdependency of packing density and settlements has been studied systematically only for Xbloc armouring. The conclusions that have been drawn for other armour units are based on qualitative observations from model tests (Pearson et al., 2004) and in prototype (breakwaters at Port St Francis, South Africa and Ventura Harbour, California). Pearson et al. observed in comparative overtopping tests with various types of armour units settlements of about 5% for Accropode and Xbloc and of about 120% for Coreloc® (see Eq. 1).

Three design parameters have been derived from the Xbloc placement analysis: Target packing density $P_a$ (sling placement tests), stable packing density $P_s$ (settlement observations during hydraulic model tests) and pullout force F (pullout tests). These parameters provide useful input for the choice of armour units and for assessing the risks of improper placement. Armour units that are not sensitive to settlements shall be selected for longer slopes. Armour units with little variation of interlocking are most suitable for the placement in harsh environment conditions. If the actual packing density is significantly lower than the stable packing density the armour layer will settle and as a result the hydraulic stability in the most critical section (at and above the water line) will be reduced. Settlements and the resulting stability of the armour layer can be assessed from the results of the placement analysis (see Figure 8 and (1). Future placement studies shall include various types of single layer armour units and the placement on the roundhead.

Table 7: Main results of the placement analysis

| Armour type | Unit size<br>$D/D_n$<br>[-] | Advised packing density<br>$P_a\,D^2$<br>[-] | Variation of interlocking (relative pullout force)<br>F/G<br>[-] | Settlements of the armour layer |
|---|---|---|---|---|
| Xbloc | 1.44 | 1.20 | mean: F/G = 7 (range 5 – 10)<br>lognormal distributed<br>(with $\mu = 1.9$ and $\sigma = 0.15$) | $P_s = 1.18 – 1.20$<br>Settlements for<br>$P_b < P_s$ (see Eq. 1) |
| Accropode | 1.43 | 1.34 | No information available | $P_s \approx P_a$<br>Settlements are similar as for Xbloc |
| Coreloc® | 1.65 | 1.62 | No information available | $P_s > P_a$<br>Larger settlements than for Accropode and Xbloc |

with: $D_n$ = nominal diameter (= $V^{1/3}$, with unit volume V)
D = characteristic unit length
$P_a$, $P_b$, $P_s$ = advised, as built and stable packing density

## Conclusions

The risk of rocking and impact loads during a major storm is inherent to randomly placed armour units. Armour units with a negligible risk of breakage shall be preferably applied. A strict monitoring and maintenance scheme appears to be the only promising way to handle the risk of breakage for slender armour units. Structural analysis based on prototype drop tests and FE simulations indicated that the structural strength of the Xbloc is similar the Accropode strength while Coreloc® is more susceptible to breakage. The critical drop heights for Coreloc® are lower (see Table 2) and internal stresses are higher (see Figure 6) than for Xbloc and Accropode. The structural strength of armour units is of vital importance for the integrity of the armour layer (i) in case of depth limited wave conditions (breakwater is frequently exposed to near-design wave conditions), (ii) for exposed breakwaters (subjected to extreme wave loads) and (iii) in case of uncertain maintenance.

The stability of the armour layer depends on the interlocking capacity of the armour units and on the quality of placement. The ease of armour unit placement becomes increasingly important in difficult environmental condition. The guidelines for Xbloc placement have been simplified as compared to other single layer armour units. The requirements for the unit orientation have been reduced from six to one. This has been done in order to facilitate the placement and to ensure that the quality of placement will be similar in model tests and in prototype.

Sling placement, sensitivity to settlements and the variation of interlocking have been studied for Xbloc armouring. Three design parameters have been proposed in order to quantify the ease and quality of placement. These parameters can be used to assess the risks of improper placement. Future research shall provide placement parameters for various types of single layer armour units in order to provide a rational basis for a project-specific choice of armour units.

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**Note**

More research papers on the development and design of Xbloc breakwaters can be found at:
http://www.xbloc.com/htm/downloads.php