DEVELOPMENT OF AN INNOVATIVE BREAKWATER ARMOUR UNIT

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Abstract: A new interlocking breakwater armour unit has been developed by Delta Marine Consultants during the past two years. The development is based on extensive review of existing breakwater armour concepts, consulting of contractors and designers, desk studies and physical model tests. A randomly placed single layer interlocking armour unit turned out to be the best technique for breakwater protection under severe environmental conditions. The new armour unit is called Xbloc® and has a simple, bulky shape. Hydraulic model tests (2-D and 3-D), a numerical structural strength analysis (FE calculations) and prototype drop test have been performed. The test results demonstrated the large hydraulic stability and the easily achieved interlocking (automatic interlocking) of the Xbloc® as well as its very high structural stability. Therefore the Xbloc® is a promising alternative for conventional single layer armour units. Significant cost savings can be achieved due to easy fabrication, fast placement and low concrete demand.

Keywords: Rubble mound breakwater; armour unit, innovation, Xbloc, automatic interlocking, drop test, structural strength, hydraulic stability

INTRODUCTION

A new interlocking breakwater armour unit, which is called Xbloc® has been developed by Delta Marine Consultants [DMC] during the past two years. The Xbloc® development is based on extensive review of existing breakwater armour concepts (Muttray et al., 2003), consulting of contractors and designers, desk studies and physical model tests.

The background and the final outcome of the DMC armour unit development will be presented in this paper. Preliminary results from hydraulic model testing and tests on structural stability are included. A cost comparison between conventional armour layers and Xbloc® armour layers is presented and finally some recommendations for the application of Xbloc® armouring will be given.

REVIEW OF ARMOUR UNIT CONCEPTS

A large variety of breakwater armour units has been developed since World War II. Breakwater armour units can be divided by their placement pattern (random or uniform) in 2 main categories. Randomly placed armour units can be further subdivided into 5 categories by their shape and the governing stability factors (see also Table 1):

I. Randomly placed armour units (stability factors weight and interlocking):
   a) *First generation armour units* (stability factors are weight and to very limited extend interlocking, typical examples are Cube, Modified Cube (1959) and Antifer Cube (1973));
   b) *Second generation armour units of simple shape* (stability factors are weight and to some extend interlocking, examples are Tetrapod (1950), Tribar (1958) Tripod (1962) and Akmon (1962));
   c) *Second generation armour units of complex shape* (governing stability factor is interlocking, examples are Stabit (1961) and Dolos (1963));

   d) *Third generation single layer armour units* (governing stability factor is interlocking, examples are Accropode, Core-loc$^{®}$ and A-Jack$^{®}$);
   e) *First generation single layer armour units* are currently investigated (‘Single-Layer-Cubes’).

II. Uniformly placed armour units (stability factor friction): Parallel-epipedic hollow blocks that are placed uniformly in a single layer (cobblestone-concept), examples are Cob (1969), Shed (1982), Seabee (1978), Haro (1984), Diahitis (1998) and Hollow Cube (1991).

Table 1: Classification of armour units by shape, placement and stability factor

Placement pattern	Number of layers	Shape	Stability factor		
			Own weight	Interlocking	Friction
Random (I)	Double layer	Simple	(**Ia**) Cube, Antifer Cube, Modified Cube		
		Complex	(**Ib**) Tetrapod, Akmon, Tribar, Tripod		
				(**Ic**) Stabit, Dolos	
	Single layer	Simple	(**Ie**) Cube	(**Id**) A-Jack$^{®}$	
		Complex		Accropode, Core-loc$^{®}$	
Uniform (II)	Single layer	Simple			(**II**) Seabee, Hollow Cube, Diahitis
		Complex			Cob, Shed

Uniformly placed hollow block armour (II)

The governing stability factor for uniformly placed hollow blocks (cobblestone-concept) is friction (not interlocking). These armour layers are more homogeneous than layers of interlocking armour and very stable. The friction type armour is a highly efficient armouring concept in its current state of development. However, it is mostly not applicable for exposed breakwaters due to the difficulties that are associated with (a) the toe construction and (b) the underwater placement.

Randomly placed double layer armour (Ia, Ib, Ic)

Random armour placement is mostly performed according to a positioning plan with predefined block orientation. The second layer is necessary to create interlocking between the armour units. This placement concept is typical for most of the randomly placed double layer armour units (Tetrapod, Dolos, Tribar, etc.).

Double layer randomly placed armour is sensible only for compact blocks, which provide large structural stability and which are stable mainly due to their own weight (like Cube, Antifer Cube etc.). However, such a design will be most probably uneconomical with respect to (a) the total volume of concrete and (b) the equipment for the placement of these large blocks. For slender armour units the second layer does not provide additional safety against failure because the top layer tends to rock and thus the structural integrity of the armour units is jeopardized (Sogreah, 1985). Hence, frequent monitoring and regular replacing of broken armour units will be necessary.

Randomly placed single layer armour (Id, Ie)

Accropode

The Accropode has been introduced by Sogreah in 1980. It was the first randomly placed single armour unit and became the leading armour unit worldwide for 20 years. The Accropode has a compact shape that provides a relatively large structural stability. The basic concept of the Accropode was a balance between interlocking and structural stability. The main advantages of single layer armour units are:

- Economically: Reduced number of armour units – thus savings in concrete, fabrication and placement costs;
- Technically: Less rocking than in a double layer armour and therefore a lower risk of impact loads and breakage (Sogreah, 1985).

Sogreah recommended K_D values of 15/12 (for non-breaking/breaking waves) for the design of Accropode armour layers. The Sogreah recommendations appear conservative with respect to experimental results (Van der Meer ,1988). It is interesting to note that even lower K_D values have been applied for the design of most of the existing Accropode breakwaters (see Muttray et al., 2003). Drop tests indicated that prototype Accropodes of 9m^3 that are dropped on a rigid base started breaking at a drop height of about 3 m (Sogreah, 1985).

Accropodes are placed in a single layer on a predefined grid. The orientation of the block has to be varied. Therefore Sogreah recommends various sling techniques for the placement. However, sling techniques and grid placing do not guarantee a perfect interlocking. Therefore, the spatial variation of stability can be significant for an Accropode armour layer (Sogreah, 1985).

The strong points of Accropode armour units are single layer placement and large structural stability. Most critical are the uncertainties related to the interlocking of individual armour units. Therefore relatively conservative K_D values are recommended for design. Unfortunately, Sogreah did not succeed to overcome these difficulties by developing a more reliable placement procedure. Nonetheless the Accropode will be for most applications more favourable than armour units that are placed in double layers.

Core-loc®

The Core-loc® which is a registered trademark of the US Government, has been introduced by the US Army Corps of Engineers in 1994. The shape of the Core-loc® is very similar to the Accropode with respect to the number and orientation of legs. The shape of each leg however is a true copy of the Dolos. Therefore the Core-loc® is more slender than the Accropode and therefore:

- The hydraulic stability of Core-loc® is slightly larger than for Accropodes, nonetheless, a K_D value of 16 is recommended for design (Melby & Turk, 1997) which is in close agreement with the recommendations for Accropodes.
- The structural stability of Core-loc® is significantly better than for Dolos and Tribar due to the more compact central section (Melby & Turk, 1997). However, Core-locs® are significantly more slender and vulnerable than Accropods.
- Core-locs® can be easily combined with Dolos armour units.

Core-loc® armour units are most suitable for some specific cases like the repair of existing Dolos armour layers. However, in most cases the choice between Accropode and Core-loc® will be balanced. The nominal costs for Core-loc® are slightly lower than for Accropodes. However, for most practical applications the armour unit size will be increased in order to minimise the costs of placement and the differences between Accropode and Core-loc® will vanish. On the other hand the costs for maintenance will be probably larger for Core-loc® than for Accropode because rocking of individual blocks cannot be completely averted and the risk of breakage is significantly larger for Core-loc®. The most essential shortcomings of the Core-loc® have been identified with respect to structural stability, residual stability after breaking and finally the ease of casting and placement. Thus, the Core-loc® leaves several options for future improvements.

Single Layer Cubes

At the current stage the Single Layer Cube studies (van Gent, 2000 and d'Angremond et al., 2002) provide very useful input for future armour unit developments with respect to placement methods, maintenance and repair of armour layers. However, Single Layer Cube armour tends to settle and to form a more uniform placement pattern with a very low void ratio (Sogreah, 1985). Thus, the wave run-up will be increased and excess pore pressures can develop, which will affect the stability of the armour layer. It appears very unlikely that Single Layer Cube will be a cost efficient alternative for interlocking single layer armour units like Accropode and Core-loc®.

THE XBLOC® CONCEPT

From the review of existing breakwater armouring techniques the following starting points for the Xbloc® development have been determined:

- The new armour unit shall be applicable for the protection of offshore breakwaters and suitable for a construction in harsh environmental conditions and in large water depth. Therefore the focus was on a random placement procedure.
- Single layer placement has been considered most favourable for economical reasons (minimised concrete volume, placement costs etc.). Furthermore the stability of an armour layer is not necessarily increased by a second layer, which tends to rock and is thus bearing a relatively large risk of armour unit breakage.
- The structural stability of the new armour unit shall be similar to the Accropode. The structural strength of Core-loc® is considered insufficient.
- The new armour unit shall have a simple bulky shape in order to facilitate the fabrication of units and to provide a sufficiently large structural stability.
- The structural and hydraulic stability of the new armour unit shall be balanced. The development shall not be focused only on an optimised hydraulic stability (as for example the development of Dolos armour units in 1963). The target hydraulic stability is of order $K_D = 15$ as for Core-loc® and Accropode.
- The optimised interlocking features of the new armour unit shall include an easy interlocking ('automatic interlocking'). The armour block shall easily find a stable position on the slope, which is widely independent from the block orientation and from the orientation of the neighbouring blocks. This automatic interlocking feature shall facilitate the placement of armour units and thus increase the speed of placement. Furthermore the variation of interlocking will be reduced by automatic interlocking. The armour layer will be more homogeneous and the required safety margins are lower.
- The new armour unit shall have only two different front faces while Core-loc® and Accropode have three different faces. Further a flat front face as the anchor sides of an Accropode shall be avoided. This geometry combined with a bulky shape shall improve the automatic interlocking feature in combination with a high hydraulic stability.

The Xbloc® is the final outcome of the DMC armour unit development. The geometry of the Xbloc® is presented in Figure 1. The width D of the Xbloc® is equal to its height; the volume equals 1/3 of a cube volume [$V = 1/3\ D^3$]. The thickness of the base and the length of the 2 attached cubical blocks is 1/3 of block height [*D*/3]; all 6 legs have a constant width *D*/3. The geometry of the Xbloc is completely defined by the characteristic length *D*.

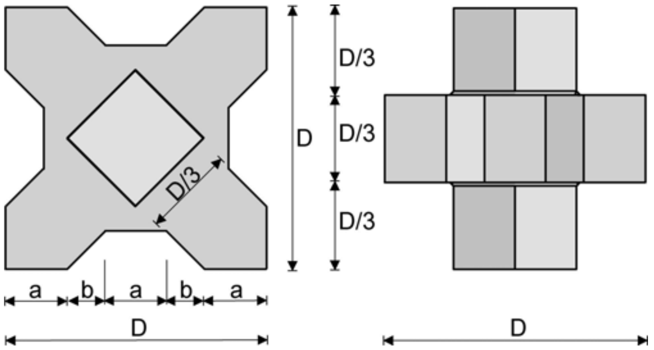

Figure 1: Geometry of the Xbloc®

PRELIMINARY TEST RESULTS

Hydraulic stability

The hydraulic stability of Xbloc® armoured slopes has been determined in hydraulic model tests. Furthermore possible placement procedures, required packing densities and wave overtopping have been investigated experimentally.

The first indicative model tests have been performed at DMC in a small wave flume with regular waves. Subsequently 2-D and 3-D hydraulic model tests have been conducted at WL Delft (Delft Hydraulics). The focus in the 2-D experiments was on hydraulic stability, wave overtopping and on the placement of armour units while the 3-D experiments were focused purely on hydraulic stability.

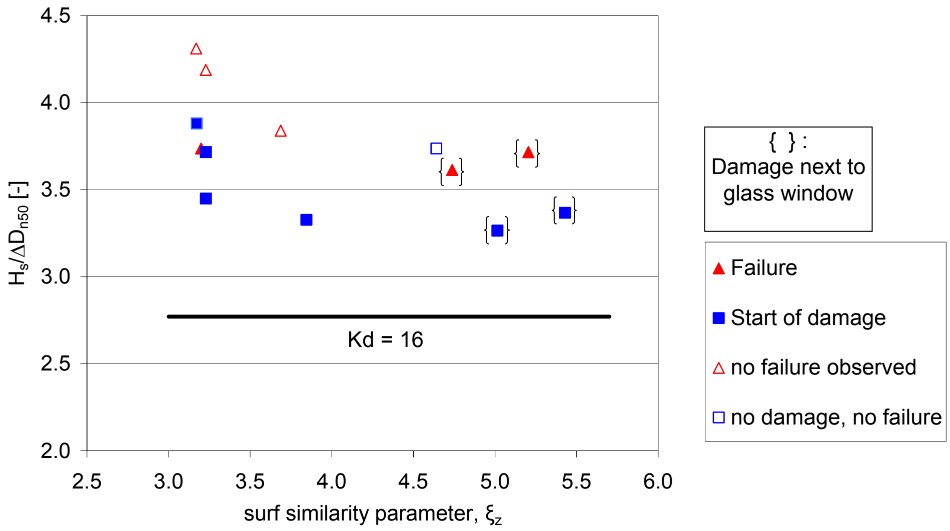

Figure 2: Stability of Xbloc® armouring in 2-D tests at WL Delft

The main results from the hydraulic model tests can be summarised as follows:

- The Xbloc® is highly stable in randomly as well as in regularly placed armour layers. For preliminary design a design stability coefficient K_D of 16 is recommended (for gentle foreshore slopes) in order to have a safety margin of 20 – 40 % on the design wave height for the start of damage (see Figure 2).
- Xbloc® armour layers remain stable after the start of damage. After initial displacement of armour units the damage is only slowly progressing with increasing wave height and the functionality of the armour layer is completely maintained.
- Xbloc® units can easily find a stable position on the slope (automatic interlocking). Therefore the Xbloc® units are easy to place and consequently the placing rates are higher than for other single layer armour units like Accropode and Core-loc®.
- The average packing density is slightly lower for Xbloc® than for other single layer armour units.
- A density specification is sufficient for the placement of Xbloc®, a prescriptive orientation of individual units is unnecessary.

Structural stability

The structural stability of Xbloc® armour units has been studied for realistic load cases with respect to the handling of units, the placement and also to possible settlements and rocking [impacts from neighbouring units] on the breakwater slope:

- Numerical modelling of the structural stability of Xbloc® units as well as Accropodes and Core-locs® has been performed by Finite Element (FE) calculations with ANSYS 6.1. The same properties such as volume ($4m^3$), concrete density, E modulus and Poisson's ratio have been applied to all armour units. Seven load cases have been analysed including the exposure of the units to flexure, torsion, both flexure and torsion and finally the impact due to gravity drops after a full lift.
- Prototype drop tests have been carried out with 4 Xbloc® units of volume 4 m^3 each. The units were dropped more than 50 times on an embedded concrete floor, which was covered by a steel plate. The drop tests comprised the star drops, tip drops, hammer drops and anvil drops. All these tests led to minimal damage to the blocks, even after a large number of repetitions. Therefore, all four blocks were subjected to free fall test from heights of 0.5 to 4 m onto the rigid concrete floor.

From the numerical structural strength analysis it is concluded that tensile stresses in the Xbloc® are significantly lower for standard load cases than in a Core-loc® and of same magnitude as for the robust Accropode. From the drop test results it is concluded:

- Xbloc® units can cope with settlements and repeated rocking in a breakwater slope during extreme conditions.
- The most critical test is the hammer drop test (as found in Core-loc® drop tests), as no energy can be absorbed by the crushing of edges.
- The Xbloc® outperforms the Core-loc® with a large margin with respect to structural strength. Failure of the Core-loc® already occurred for drop heights as low as 0.3 m. The Accropode has only been tested for one drop position, which is regarded not critical for its integrity.

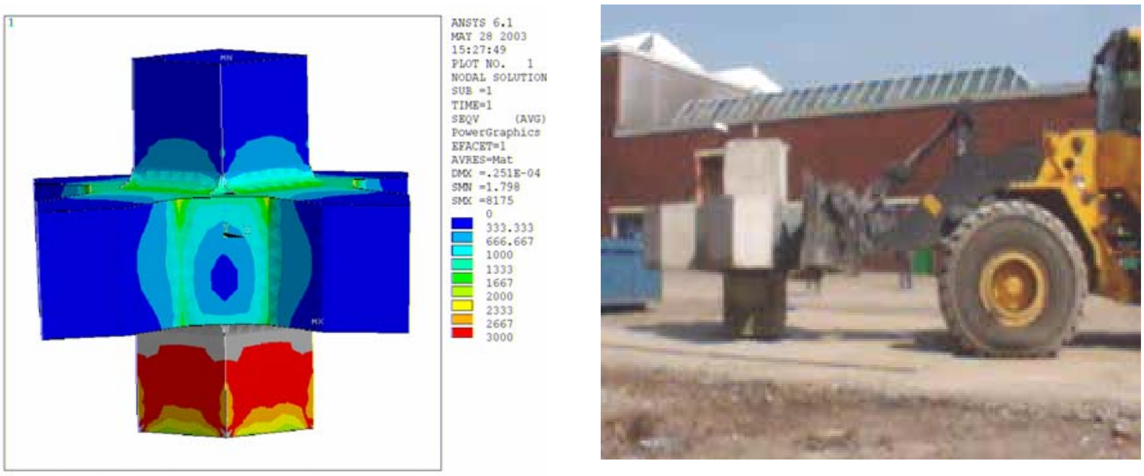

Figure 3: Prototype and numerical model of free fall horizontally orientated Xbloc®

It can be concluded that an Xbloc® can cope with all loads that can be expected for the complete cycle from manufacturing to operation. The structural strength of Xblocs® is comparable to Accropodes and significantly larger than for Core-loc®.

COMPARISON BETWEEN XBLOC AND OTHER ARMOUR UNIT CONCEPTS

An armour layer cost comparison has been made between the Accropode, Core-loc® and the Xbloc®. Based upon the preliminary design values of the Accropode, Core-loc® and the Xbloc® the use of concrete [m^3/m^2] has been determined for significant wave height varying from 2.0 m to 11.0 m (with steps of 0.25 m). The results are shown in Figure 4.

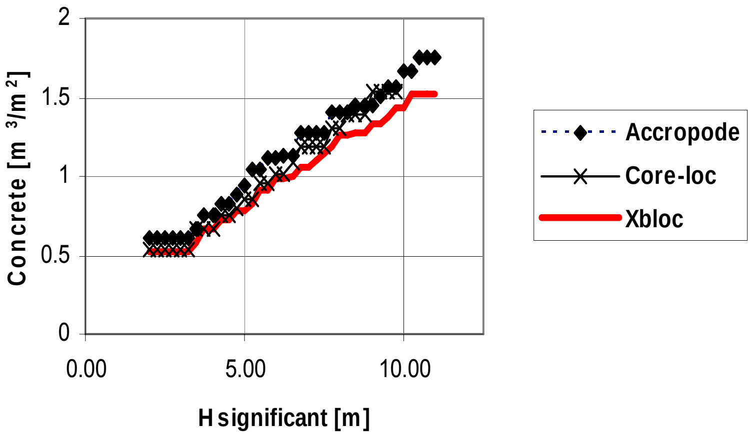

Figure 4: Use of concrete [m^3/m^2] of Accropode, Core-loc® and Xbloc® armour units

The concrete demand for Xbloc® armour is about 10% lower than for Acrropode armour due to higher stability coefficient (K_D = 16 for Xbloc® and K_D = 15 for Accropode) and lower packing density. The cost benefit of an Xbloc® armour layer as compared to Core-loc® armouring varies from 0% – 10% depending on the block size. The differences are mainly due to the different packing densities. The cost benefit of Xbloc® will be further increased for larger armour blocks if the increased concrete quality, which is recommended for Core-loc®, is taken into consideration.

Besides this general comparison of Accropode and Xbloc® a more specific analysis of three practical breakwater cases has been performed. The breakwater projects are listed in Table 2.

Table 2: Initial design for selected breakwater projects

project site	armour units	number of layers	slope	bottom level	breakwater length	design wave height H_s	K_D value (original design)	K_D value for Xbloc® design*
Hazira, India	Accropode	1	1:1.33	CD -11 m (minimum)	2.1 km	5.4 m	10.0	12.6
Coega, South Africa	Dolos	2	1:2	CD – 16.7 m (minimum)	2.4 km	9.3 m	13.7	14.2
Maasvlakte 2, The Netherlands	Cube	2	1:1.5	NAP -15 m (average)	5 km	7.25 m	8.4	15.2

* based on standard block sizes

An alternative Xbloc® design has been determined for the each breakwater listed in Table 2. Slope and crest level have been derived from the applicable boundary conditions and the Xbloc® preliminary design values. The analysis has been performed with a constant density of concrete (2400 kg/m^3) and sea water (1030 kg/m^3). With these densities the stability coefficients (K_D factors) have been derived from the initial design (see Table 2). The K_D values applied for the alternative Xbloc® design are also listed in Table 2.

The following unit rates - based upon average international rates - have been applied for all cases (including material, equipment and labour): geotextile 5 \$/m^2, quarry run 40 \$/m^3, rock for filter layers and toe 50 \$/m^3, concrete (armour units) 250 \$/m^3. The higher placement speed of Xbloc® as compared to Accropode and Core-loc® will provide additional cost benefits for the Xbloc®, which has not been considered in the concrete rate.

The cost benefits that have been assessed for the above breakwater projects are summarised in Table 3. It can be concluded that the application of Xbloc® armouring can be financially very beneficial.

Table 3: Cost benefits for alternative Xbloc® design (as compared to original design)

Hazira	$ 6.9 mln	(8% of the total costs)
Coega	$ 14.6 mln	(6% of the total costs)
Maasvlakte 2	$ 189.1 mln	(42% of the total costs)

CONCLUSIONS

Friction type armour (uniformly placed hollow blocks) is a highly efficient armouring technique. However, it is mostly not applicable for exposed breakwaters due to the difficulties that are associated with (a) the toe construction and (b) the underwater placement.

It can be concluded that a single layer placement of randomly placed interlocking armour units is more cost efficient (with respect to the reduced number of blocks and resulting savings in concrete and costs of fabrication and placement) and safer (with respect to breakage induced by rocking) than double layer placement.

The strong points of the Accropode are large structural and hydraulic stability. The main shortcomings are a large variation in interlocking (and thus in hydraulic stability) within the armour layer and a tedious placement procedure. In order to overcome the uncertainties with respect to interlocking Sogreah recommended a conservative stability coefficient for design and developed very detailed guidelines for the placement.

The strength of the Core-loc® is a large hydraulic stability. However, the placement procedure is as complex as for Accropodes and the structural stability is significantly lower than the stability of Accropodes. Thus, the main shortcoming of the Core-loc® is its fragility. The developers of Core-loc® tried to overcome this problem by recommending a higher concrete quality for larger units.

It is unlikely that Single Layer Cube will be a cost efficient alternative for interlocking single layer armour units like Accropode and Core-loc®.

The Xbloc® has been developed by DMC as a single layer randomly placed armour unit that can be applied for offshore breakwaters, seawalls and revetments. It has been designed with a simple bulky shape in order to provide a large structural stability and to facilitate the fabrication of armour units. The hydraulic stability of the new armour unit has been optimised with respect to the interlocking capacity of individual armour units and to the ease of interlocking. Easily interlocking armour units (also called 'automatically interlocking') can easily find a stable position on the slope and will create a more homogeneous armour layer with less variation in hydraulic stability.

The Xbloc® is a promising alternative for conventional single layer armour units as Accropode and Core-loc® with respect to the processing of armour units (fabrication, handling and storage) and to their function on the breakwater slope (structural integrity and hydraulic stability). Significant cost savings can be achieved due to:

- easier fabrication (Xblocs® have a simple and mostly rectangular shape);
- faster placement (Xblocs® are designed for 'automatic interlocking' and thus can easily find a stable position on the slope);
- lower concrete volume (Xblocs® provide large hydraulic stability and require relatively low packing densities);
- limited requirements for concrete quality (Xblocs® have a large structural stability).

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REFERENCES

d'Angremond, K., Verhagen, H.J., Vliet, K. van der: Positioning of Cubes on a breakwater slope. 28th Int. Conf. on Coastal Eng., Book of Abstracts, Paper No. 134, 2002.

Gent, M.R.A. van: Single layer rubble mound breakwaters. Proc. Int. Conf. Coastal Structures, Santander, Spain, p. 231 – 239, 2000.

Meer, J. van der: Stability of Cubes, Tetrapods and Accropodes. Breakwaters Conference, London, 1988.

Melby, J.A., Turk, G.F.: Core-loc® concrete armour units: Technical guidelines. US Army Corps of Engineers, WES, Technical Report CHL-97-4, 1997.

Muttray, M.; Reedijk, J.; Bakker, P. (2003): Development of Concrete Breakwater Armour Units. CSCE, 1st Speciality Conference on Coastal, Estuary and Offshore Engineering, New Brunswick, Canada.

Sogreah: Rubble mound breakwaters – a new generation of blocks. Brochure, Grenoble, 1985.

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