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Introduction of the Xbloc® Breakwater Armour Unit

Abstract

Over the past two years Delta Marine Consultants has developed a new breakwater armour unit called Xbloc®. The new armour unit has proven to be reliable and easy to use leading to significant cost savings. The new armour development included extensive 2-D and 3-D physical model tests, finite element stress calculations, prototype drop tests, a production and handling analysis, and placement studies.

Whereas originally concrete armour units were simple heavy shapes, the development in the 1960s and 70s focussed more and more on slender shapes.
The advantage of slender shapes is the high hydraulic stability caused by improved interlocking. As these shapes turned out to be vulnerable to breakage, a more robust shape was developed in the 1980s. Although this unit combined a relatively high hydraulic stability with a robust shape, a new slender unit was developed in the 1990s with a slightly higher hydraulic stability but a larger vulnerability to breakage. Therefore, the main focus of the DMC armour unit development was to create a unit with a hydraulic stability that is comparable to the present state of the art units, but with a robust shape.

The reliability of the Xbloc® was proven during the physical model tests. The structure proved difficult to damage, even at a significant exceedance of the design wave height. Furthermore the unit provides a large safety margin between the start of damage and failure of the armour layer. The structural stability of the armour unit was proven by the finite element stress calculations and the prototype drop tests.

The Xbloc® (Figure 1) is easy to use because of the simple mould, the simple handling and storage methods and especially because of its easy placement on the breakwater slope. The placement of the present interlocking armour units is subject to very stringent specifications about the orientation of each armour unit. Obviously this decreases the speed of construction. No such specifications apply for the placement of the new unit as it easily finds its position on the slope.

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Martijn Klabbers

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Bas Reedijk

Figure 1. The 4 m^3 Xbloc® with one of the engineers.

Introduction

Concrete armour units are generally applied in breakwaters and shore protections (Figure 2). The function of the armour layer in these structures is twofold. Firstly it must protect the finer material below the armour layer against severe wave action. Secondly the armour layer must dissipate the wave energy in order to reduce the wave run-up, overtopping and reflection. These two functions require a heavy, but porous armour.

A typical cross section of a breakwater armour layer is shown in Figure 3. The cross section of a shore protection is similar, but instead of a core, the soil material is protected. In both structures, the armour layer is placed on top of a filter layer which covers the fine material in the core of the breakwater (or the soil material of the shore). This filter layer must prevent that the fine material washes away through the pores in the armour layer. Near the seabed the armour layer is generally supported by a rock toe.

As the armour layer is an expensive part of the whole structure, it is worthwhile to put effort in the optimisation of the armour layer design. Depending on the local situation it can be economical to apply a rock armour layer, if sufficiently large rock is available near the site. If this is not the case, concrete armour units are the best solution. However as there are various concrete armour units available and the choice has great financial consequences, the choice of the armour units should be made carefully.

In this article, the development is described of a new concrete armour unit called Xbloc®. This armour unit, which is reliable and easy to use leads to significant costs savings as the concrete volume applied in the armour layer is low. Although concrete armour units can be applied both in breakwaters and shore protections, the focus in the remainder of this article will be on breakwater applications.

History of Breakwater Development

The development of breakwater construction is closely related to the development of ports around the world over the centuries. In the ancient times harbours were constructed in sheltered locations such as river mouths, bays and areas sheltered by islands where the wave climate is calm.

In time nautical trade developed and more harbours were built. Near more densely populated areas, ports were constructed in less sheltered locations where the port operations were hindered by the wave climate. In order to reduce the waves entering the harbour constructions were made of wood, stone or even concrete. The constructions made in these days include wooden pile rows, masonry quay walls and rubble mound structures. Over the years these structures have evolved into breakwaters as they are presently known (Figure 4).

As ships became bigger, the required water depth in the ports increased to cope with the increased draught. The location of the harbours therefore shifted seaward which resulted in increased wave exposure. Longer and wider breakwaters were required and as they extended further seaward they were subjected to higher waves.

In order to withstand these high waves breakwaters were built that consisted of an outer layer — armour layer — of large heavy rocks. However, the application of rock is limited as the maximum rock size is limited and in some parts of the world no large size rock or good rock quality was available. Therefore, for locations where a rock armour layer was impossible, concrete armour units were developed. Nowadays most of the major ports in the world are protected using breakwaters with concrete armour units.

Development of concrete armour units after 1950

Before World War II the only concrete armour units that were used were cubes. In a cube armour layer – just like a rock armour layer – the stability against the wave action is derived from the weight of the armour units. Each block on the slope must be sufficiently heavy to withstand the wave forces. Therefore the cubes in a breakwater armour layer are always heavy elements.

As opposed to stability owing to the armour unit's weight, another stabilising mechanism was developed after 1950 when armour units were developed which are interlocking. Because of the more slender shapes, these armour units not only use the weight of each


Figure 2. Concrete armour units are generally applied in breakwaters (left, Scheveningen, The Netherlands) and shore protections (right, Scarborough, U.K.).

individual element, but also of the surrounding elements. This leads to a higher hydraulic stability of the units. The first interlocking unit on the market was the Tetrapode (1950). Apart from the interlocking feature, another advantage compared to the cube was the increased porosity of the armour layer which is required for wave energy absorption and reduction of wave run-up.

In the period between 1950 and 1980 a number of different armour units were developed based on the principle of stability through the combination of unit weight and interlocking (Figure 5). In fact during this period the armour units became more and more interlocking as a result of the increasingly slender shapes. The best example of hydraulic stability is the Dolos (1963). Owing to the efficient interlocking properties of this block, the required unit weights reduced significantly compared to the simple cube elements.

Looking back at the development of the Dolos, it can be concluded that one aspect was to a certain degree overlooked. As the units became more and more slender, the *structural stability* decreased as they became vulnerable to breakage. Too much focus was put on hydraulic stability (interlocking) whereas structural stability was undervalued. This became clear in 1978 when the Sines breakwater in Portugal collapsed due to broken armour units. The Dolos units applied were so slender (for optimal interlocking) that they broke into pieces because of wave action. Once the elements were broken, the interlocking mechanism vanished and the entire armour layer failed.

In 1980 the Accropode was introduced. As this unit was the first single layer armour unit, significant cost savings were made compared to the double layer units. This is illustrated in Figure 6.

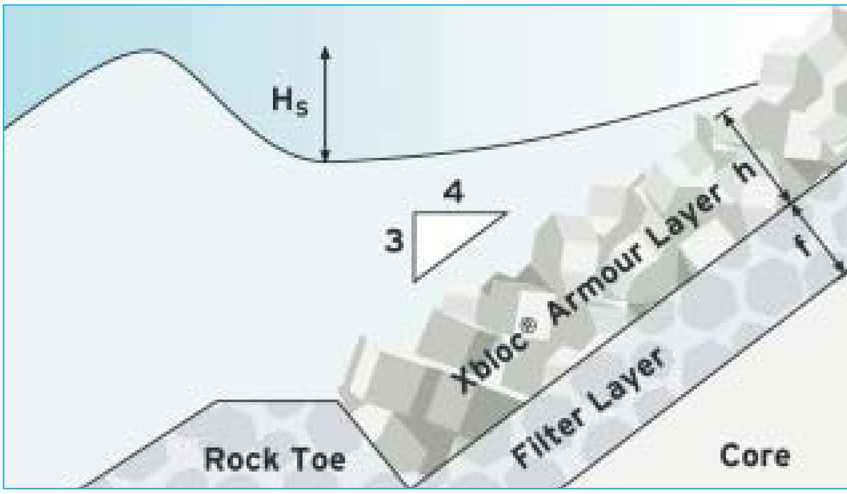


Figure 3. Typical cross section of a breakwater armour layer.

Figure 4. The ancient Port Claudius near Ostia, Italy including primitive breakwaters (±50 AD) ref. ABC-klubben.

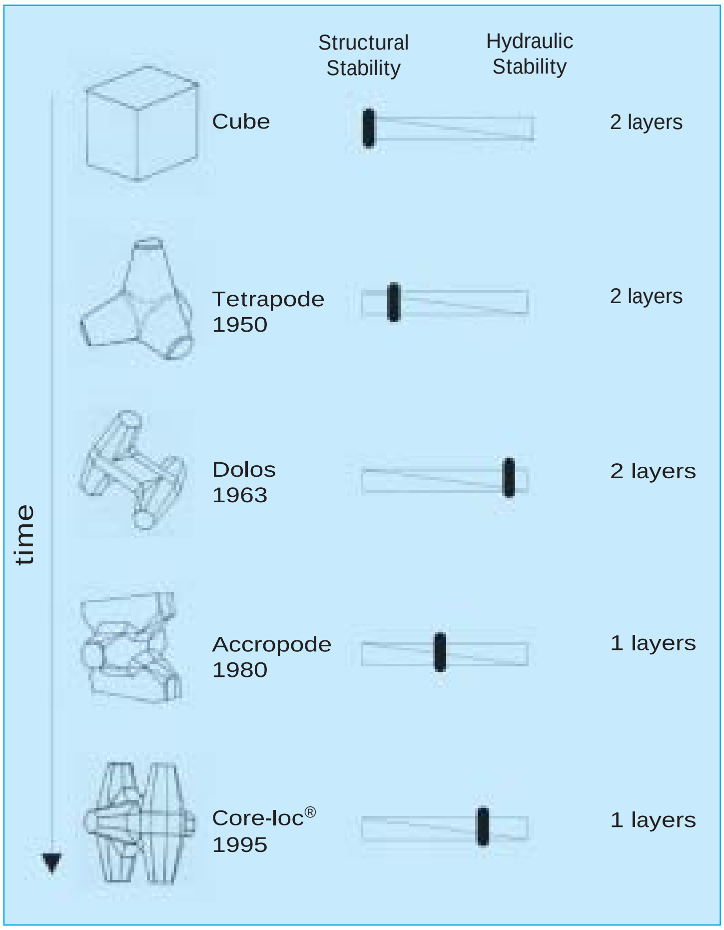


Figure 5. Overview of development of some widely applied armour units.

Compared to the Dolos, the Accropode is a robust and bulky unit which is far less vulnerable to breakage. As the interlocking capacities were still relatively high, there was a good balance between hydraulic and structural stability. Owing to this balance and the costs savings, the Accropode has been a successful unit since its launch.

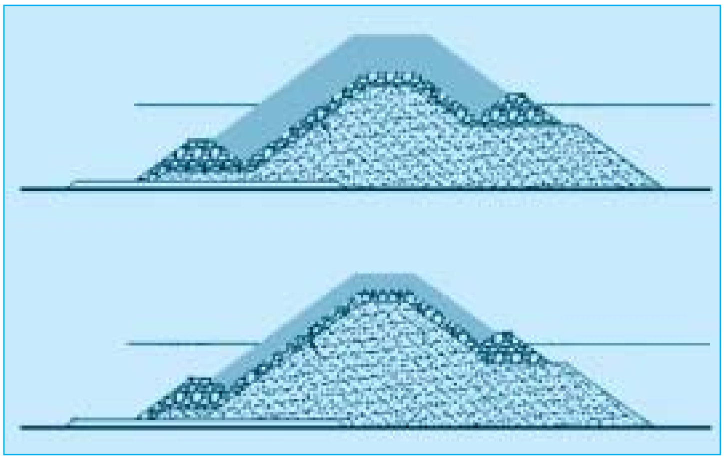


Figure 6. Thickness of armour layer for double (top) and single layer (bottom) armour units designed for equal conditions.

One of the latest developments has been the Core-loc®, which is a registered trademark of the US Government. Developed to repair damaged Dolos breakwaters the Core-loc® is a mix of the Dolos and the Accropode shape. The configuration of the legs is similar to that of the Accropode while the shape of the legs has strong similarities with the Dolos. The hydraulic stability is slightly higher compared to the Accropode, but the slender shape of the unit makes it more vulnerable to breakage. It therefore seems that the balance between structural and hydraulic stability has been shifted again towards hydraulic stability.

Uniformly placed armour units

The elements described above are all randomly placed units. A whole different type of armour units is formed by the uniformly placed elements. Examples of such elements are the Cob, the Shed, the Diahitis and the Seabee. These revetment-like elements gain their stability not from their weight or from interlocking but from friction between the surrounding elements.
As placement of these elements is very difficult under water, they are normally only applied where construction can be done above low water. Therefore no further attention is paid in this article to uniformly placed units.

Development of the Xbloc®

Motive for development of the Xbloc® armour unit

During a breakwater rehabilitation project on Fregate Island, the Seychelles, DMC made the detailed design and provided site assistance during execution of the works. The armour layer applied consisted of Accropode units. Experiences on this project brought up the idea to develop an improved armouring system based on single layer application. The new unit should decrease the weak points of the existing units while maintaining the strong points.
The new unit should therefore have a right balance between hydraulic and structural stability. A strong focus on a high hydraulic stability would result in a slender unit vulnerable to breakage. Therefore the unit should have a hydraulic stability in the same order of the latest single layer armour units combined with a higher structural stability.

Another starting point was to have a unit that is easy to apply for a contractor. The placement on the breakwater slope should be easy, as this is considered one of the main shortcomings of the existing single layer armour units.

Summarised, the main objectives for the Xbloc® development were to create an armour unit that:
– is applied in a single layer;
– has a high hydraulic stability;
– has a high structural stability;
– is easy to produce and to handle;
– is easy to place on the slope.

Table I. Overview of different development phases.

Tests performed	Date	Conclusions
phase 1: Investigation of Hydraulic Stability		
2D physical model tests at DMC flume	December 2001	High hydraulic stability
2D physical model tests at Delft Hydraulics	October 2002	Limited wave overtopping due to porous armour layer
3D physical model tests at Delft Hydraulics	June 2003	Self repairing capacity instead of progressive failure
2D physical model tests at Delft University of Technology	June 2003	High porosity of armour layer
phase 2: Investigation of Structural Stability		
Finite Element Calculations	June 2002	High structural stability
Prototype Drop tests	May 2003	
phase 3: Investigation of Production and Handling		
Production of prototype moulds	February 2003	simple moulds
Production of 4m^3 prototype units	March 2003	easy handling by simple sling technique or by fork
Analysis of casting options	May 2003	compact storage possible on site
Analysis of handling and storage options	May 2003	
phase 4: Investigation of Placement on Breakwater Slope		
Placement analysis	June 2003	no requirements to orientation of units on the slope; easy placement by simple sling technique
phase 5: Comparison concrete use and costs		
Concrete volume comparison single layer units	June 2003	concrete savings up to 10% compared to other single layer units
Cost comparison based on case studies	June 2003	Savings add up to millions of euros

Overview of development steps

The Xbloc® development started in 2001 with a brainstorm session about shapes that would fulfil the objectives described above. This creative process resulted in various shapes and concepts. The most promising shape of these looked in fact very similar to the final shape of the Xbloc®. Only minor changes have been applied since, based on the development steps that were taken.

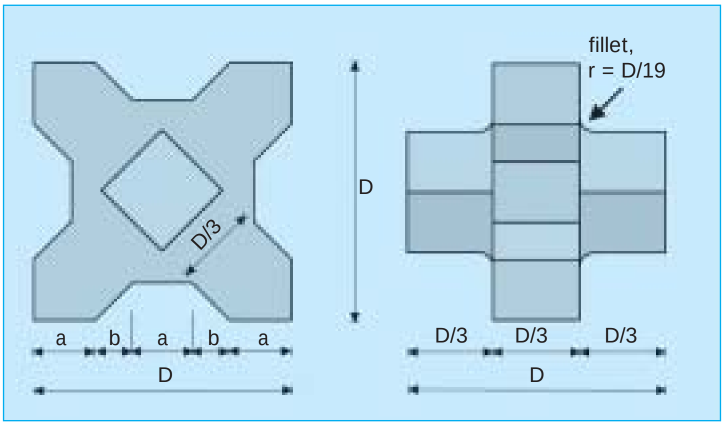
After the brainstorm session, the most promising shape was tested in a small flume facility of DMC in order to confirm that investments in the development of this shape were justified. As the results of these preliminary tests were very promising, the development was continued. The different development phases and the key results are shown in the Table I. A more detailed description of the different tests and their results is given in the following sections. These development steps have lead to the Xbloc® as shown in Figure 7.

The Xbloc® can be applied in the range:
- Unit height [D]: 1.3 to 3.9 m
- Unit volume [V]: 0.75 to 20 m^3
- Design wave height [Hs]: 3 to 10 m

Hydraulic Stability Tests

Physical model tests have been performed at Delft Hydraulics in the new 2-D Scheldt flume and the 3-D Jo Vinje wave basin. During these tests, the stability of the armour units and the wave overtopping were tested. Furthermore during the 3-D tests, the influence of oblique wave attack was investigated. In total 104 tests were performed in 11 series, 4 of which during

Figure 7. Xbloc® dimensions.



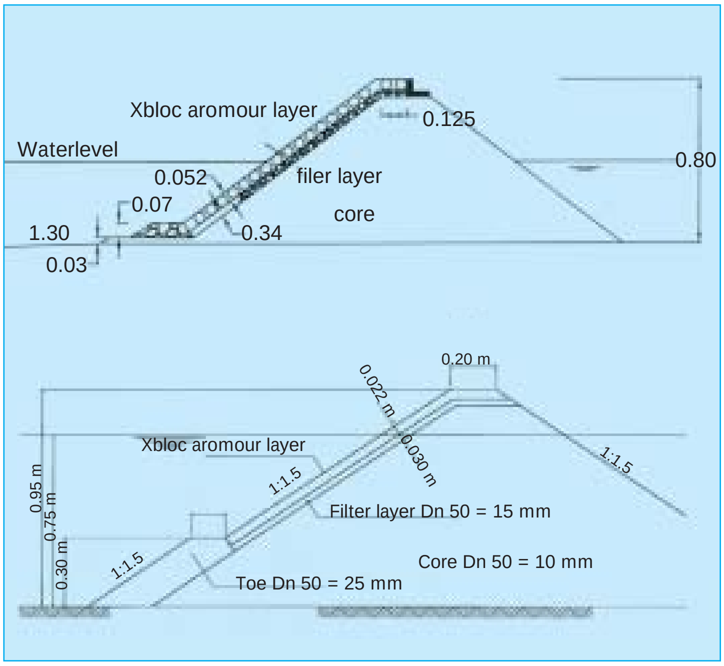


Figure 8. Cross section of 2-D model setup (top) and 3-D model setup (bottom).

the 3-D tests. The cross sections of the two settings are shown in Figure 8.

During the many series, the following parameters have been varied:
– water depth;
– wave height;
– wave length;
– wave steepness;
– packing density of the units;
– wave direction.

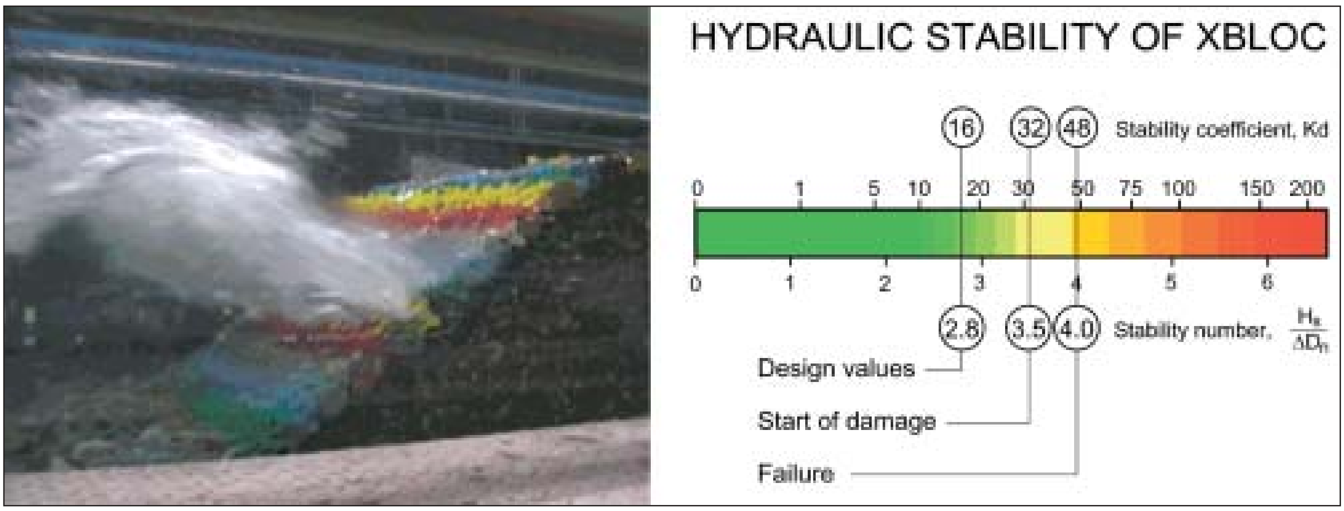
It must be noted that no demands were made about the placement of the units on the slope. The elements were quickly and easily placed on the slope after which the packing density was determined. This is in contrast to other single layer armour units, where the orientation of each unit on the slope has certain requirements.

During the tests it was observed that only at a severe exceedance (>20%) of the design wave height the start of damage occurred. Furthermore, for a number of tests it was observed that the hole left by a unit taken out of the armour layer was filled by the units positioned above this hole. Subsequently the armour layer sustained the increased wave loading to the limit of the wave flume. It can therefore be concluded that an Xbloc® armour layer is to a certain degree self repairing. The margins between the design wave height (which was based on a stability coefficient of Kd=16) and the start of damage and the failure of the armour layer are shown in Figure 9.

Another important finding from the physical model tests is the fact that the required packing density on the slope is low. This is very favourable for the porosity of the armour layer and the wave runup and overtopping therefore are low. Furthermore the low packing density leads to large concrete savings.

Conclusions from the physical model tests:
- The Xbloc® has a high hydraulic stability equal to the present state of the art single layer armour units.
- There is a large safety margin between the design wave height and the start of damage and between the start of damage and failure of the armour layer.
- The Xbloc® armour layer is to a certain degree self repairing.
- The wave runup and overtopping are limited due to the porosity of the armour layer.
- Owing to the low packing density, the number of units required is low; this leads to faster construction and lower concrete volumes used.

Figure 9. Wave impact on Xbloc® slope and key results on hydraulic stability



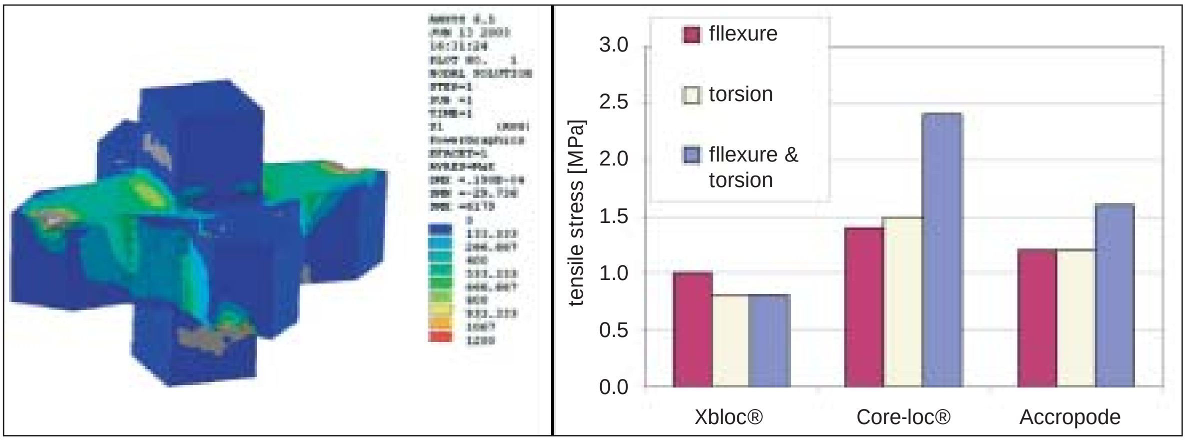


Figure 10. Example of structural tests by Finite Element Calculations and the key results.

Structural Stability

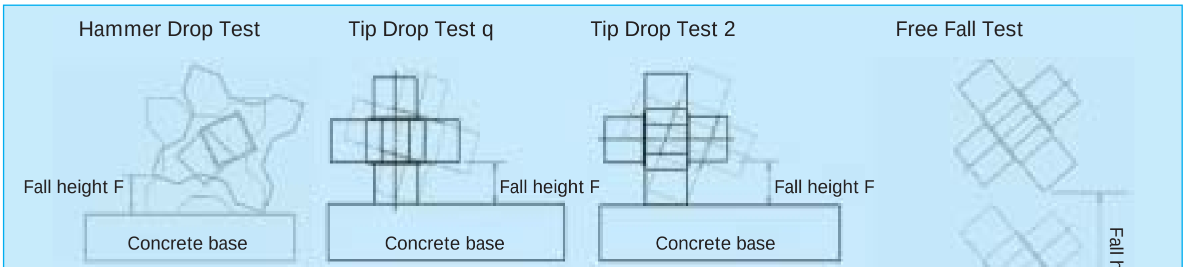
The first tests performed to the structural stability of the Xbloc® were Finite Element calculations to compare the stresses in the Xbloc® under 7 standard load cases with the stresses in the present state of the art armour units. The load cases applied consisted of flexure, torsion and a combination of these two.
The main results of these calculations are shown in Figure 10. From these calculations it can be concluded that the tensile stresses in the Xbloc® are low.

As a reality check of the calculations described above, prototype drop tests have been performed using 4 Xbloc® units of 4 m^3. Concrete with a 28-day compressible strength of 35 MPa was used to cast the units. The test consisted of 2 different series. Firstly three repetitive drop tests were performed in order to simulate the loads due to the rocking movement of the armour units on the breakwater during severe wave attack. Secondly destructive free fall tests were performed with increasing fall heights. The results of both these tests confirmed that the structural stability of the Xbloc® is outstanding (Figures 11 and 12).

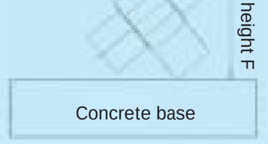
The conclusions of the Structural Stability tests were that the Xbloc® has an outstanding structural stability.

Figure 11. Tip Drop Test in reality.

Figure 12. Results of the various drop tests performed.



Type of test	Repetitions	Drop Height	Result
Hammer drop		10 40 cm	Damage at 0.4 m
Ti[drop 1	50	50 cm	Nodamage
Tip drop 2	50	50 cm	No damage
Free Fall test		increasing	Breakage at 2.5 m



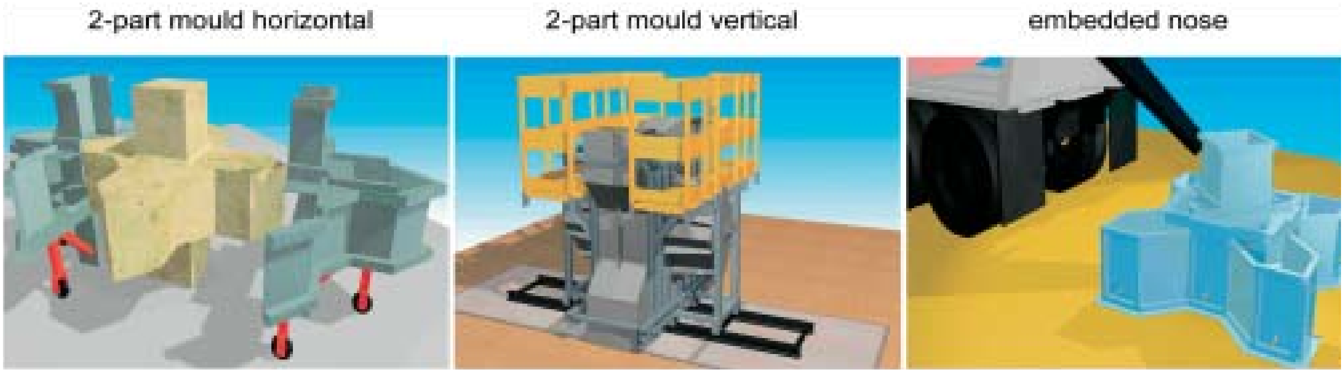
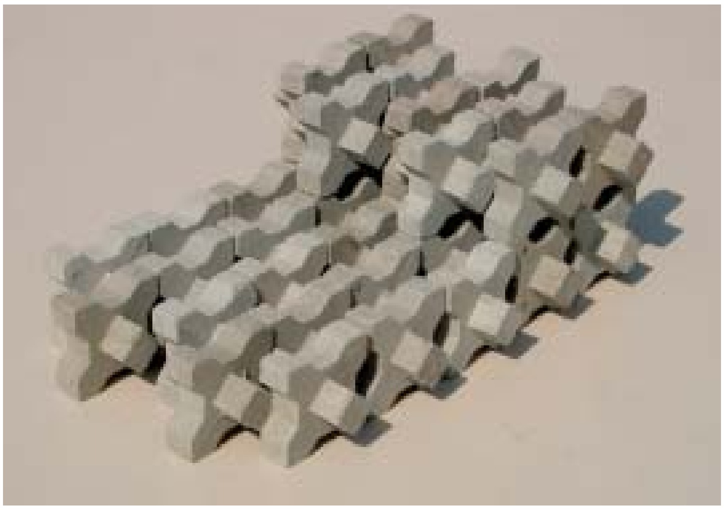


Figure 13. Various mould options for casting.

Figure 14. A forklift was the most suitable equipment for handling the Xbloc.

Figure 15. Stacking the Xbloc® for storage, after production and before placement.



Production and Handling

The prototype Xbloc® units were cast in a simple wooden mould and it was concluded that the unit is very easy to cast owing to the large openings in the mould. For large breakwater projects, steel formwork will be used for repetitive casting. Although only one steel prototype mould was made, there are various casting options and per project the most suitable casting method can be chosen. In the Figure 13, three practical casting options are shown.

The storage method of the Xbloc®s between production and placement on the breakwater slope will depend completely on the local conditions (Figure 15). If space is scarce, very compact stacking is required whereas in case of sufficient area, very quick stacking will be preferred. If required, the Xbloc®s can be stacked very compactly and if the soil conditions are suitable, the units can be stacked in multiple layers. The area required for stacking 100 4 m^3 units in a double layer for example is approximately 13 m x 14 m.

The conclusions drawn from the Production and Handling analysis are:
- The Xbloc® is easy to produce, handle and store;
- The methods used for production, handling and storage depend on local conditions and the preferences of the contractor.

Handling of the Xbloc® can be done using various techniques with a sling, a forklift or a clamp. With the 4 prototype 4 m^3 units, experience was gained with various practical sling techniques around the whole block, around the legs of the "X" and around the nose of the unit. It was found that the sling around the nose of the block was simple and stable. However a forklift seems to be the most suitable equipment for handling of the units. Using a forklift, the units can be rolled on their sides, transported and stacked in the storage area (Figure 14).

Placement on Breakwater Slope

The placement of single layer armour units on a breakwater (or shore protection) slope is of key importance as the placement of the presently available units determines to a large degree their hydraulic stability. If the orientation of these units is not correct, the effectiveness of the interlocking mechanism is significantly reduced and the armour layer might not be stable under the design conditions. Therefore strict specifications are applied for the placement of these units. This makes placement a tedious and expensive procedure, as blocks have to be picked up repeatedly in order to place them in the specified orientation.

As opposed to these placement specifications, the requirements for an Xbloc® slope are:
1) the packing density on the slope, and
2) the restriction that it may not be possible to remove any unit from the slope without touching the surrounding blocks.

Because of the new shape of the Xbloc®, each of the 6 sides of the unit is efficiently interlocking. Therefore the blocks easily find a position that fully activates the interlocking mechanism. This was observed during the hydraulic model tests where technicians of Delft Hydraulics placed the armour units. As a result of the fact that the Xbloc® interlocks so easily, the second requirement is easily met (Figure 16).

An extensive placement analysis was performed using scale models and slings. The objective of this analysis was to confirm that the required packing densities could be achieved with a sling. It was found that the required packing densities could easily be met. It was furthermore found that the sling technique around the leg of the "X" of the element was most suitable (Figure 17). Based on this analysis, it can be concluded that the first requirement can easily be met.

Comparison of the Concrete Use

A general comparison has been made of the concrete use of the Xbloc® compared to other concrete armour units. For varying wave heights, the concrete use was determined based on the required unit size and the packing density of the armour units. It was concluded that the Xbloc® can lead to concrete savings of more than 10% compared to other single layer armour units and even more compared to double layer armour units.

Apart from this theoretical analysis, a detailed cost comparison has been made based on various case studies. Although the relative cost savings depend on the local boundary conditions and prices for each project, the use of Xbloc® armour units did lead to significant savings in each of the case studies.

Figure 16. Because of their 6-sided shape, units placed on a slope easily interlock.

Figure 17. Handling the Xbloc® with a sling around the nose was the most suitable technique for placement.

Owing to the fact that breakwater construction is very costly and that the armour layer is an expensive part of it, these savings easily add up to millions of euros.

Conclusions

The Xbloc® is a new armour unit that fulfils all the requirements Delta Marine Consultants had determined to be necessary before the start of the development.

The Xbloc® is a single layer armour unit with a high hydraulic stability and a high structural stability. It is easy to produce, to handle and to store. Because of its interlocking mechanism, it is easy to place on the slope.

Furthermore it was shown that application of the Xbloc® armour unit leads to significant cost savings. Based on case studies, these cost savings primarily resulted from the lower concrete volumes required. This makes the Xbloc® an economically attractive alternative to other state of the art armour units.