1reConférence spécialisée sur le génie côtier, des estuaires et de l'*offshore*
de la Société canadienne de génie civil

1st Coastal, Estuary and Offshore Engineering Specialty Conference
of the Canadian Society for Civil Engineering

Moncton, Nouveau-Brunswick, Canada
4-7 juin 2003 / *June 4-7, 2003*

DEVELOPMENT OF CONCRETE BREAKWATER ARMOUR UNITS

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ABSTRACT: A large variety of concrete breakwater armour units has been developed in the past. Today design engineers have the choice between a number of completely different breakwater armour concepts.

The most commonly applied types of armour units are presented and classified. The strong and weak points of the various concepts as well as possible applications are discussed. Demands for future improvements are specified with respect to hydraulic and structural stability, placement and casting.

Finally a concept for an improved armour unit with a simple bulky shape and two different front faces is outlined, which is easy to cast and easy to place. This block shall be capable to find easily a stable position on the slope. The structural stability shall be similar to Accropodes in order to minimise the risk of breakage and subsequent progressive failure. The optimum interlocking capability has to be balanced between hydraulic stability and the ease of fabrication, placement and strength of the units.

1. INTRODUCTION

A large variety of concrete breakwater armour units has been developed in the past 50 years. Today design engineers have the choice between a number of completely different breakwater armour concepts. However, in many cases standard type solutions are applied and possible alternative concepts are not seriously considered.

This paper is intended to give an overview of the different types of breakwater armour units that have been developed in the past decades. The strong and weak points of the various concepts will be highlighted and possible applications will be discussed. Finally the latest trends in breakwater armour unit developments will be analysed and demands for future improvements will be specified.

2. Historical overview

Until World War II breakwater armouring was typically either made of rock or of parallel-epipedic concrete units (cubes). The placement was either random or uniform. Breakwaters were mostly designed with gentle slopes and relatively large armour units that were mainly stabilised by their own weight.

The Laboratoire Dauphinois d'Hydraulique (predecessor of Sogreah) introduced in 1950 the Tetrapod, the first interlocking armour unit. The main advantages of the Tetrapod were a slightly improved interlocking as compared to a Cube and a larger porosity of the armour layer, which causes wave energy dissipation and reduces the wave run-up.

A large variety of concrete armour units has been developed in the period 1950 – 1970 (see also SPM, 1984). However, most of the blocks from those days have been applied only for a very limited number of projects. Some of the more commonly used armour unit developments from this period are listed in Table 1. These armour units are typically either randomly or uniform placed in double layers. The governing stability factors are the units' own weight and their interlocking.

The failure of the Sines breakwater (Portugal, 1978) and the introduction of the Accropode by Sogreah in 1980 set an end to the rapid development of randomly placed concrete armour units. The breakwater at Sines was initially designed with 42 t Dolos and later rebuilt with Antifer Cubes. The failure indicated that (a) slender armour units, which are designed for maximum interlocking, provide insufficient structural stability and (b) breakage of armour units may cause progressive failure.

Single layer randomly placed armour units have been applied since 1980. The Accropode was the first block of this new generation of armour units and became the leading armour unit worldwide for the next 20 years. CoreLoc and A-Jack are further examples of this type of armour unit that have been developed subsequently. The typical features of these armour units are high interlocking and single layer random placement. Hence, these blocks are more economical than traditional double armour layers.

The parallel development of a completely different type of armour concept started in the late 60th. The armour layer consists of hollow blocks that are placed uniformly in a single layer (cobblestone-concept). Each block is tied to its position by the neighbouring blocks. This armour concept is not based on weight or interlocking but on friction, which provides an extremely high hydraulic stability. Typical examples of these armour blocks are Cob, Shed and Seabee (see Table 1).

Table 1: Historical development of selected breakwater armour units

Armour unit	Country	Year	Armour unit	Country	Year
Cube	–	–	Seabee	Australia	1978
Tetrapod	France	1950	Shed	UK	1982
Tribar	USA	1958	Accropode	France	1980
Modified Cube	USA	1959	Haro	Belgium	1984
Stabit	UK	1961	Hollow Cube	Germany	1991
Akmon	NL	1962	Core-Loc	USA	1996
Tripod	NL	1962	A-Jack	USA	1998
Cob	UK	1969	Diahitis	Ireland	1998
Dolos	RSA	1963	Samoa Block	USA	2002
Antifer Cube	France	1973			

3. CLASSIFICATION OF ARMOUR UNITS

Breakwater armour units can be either classified by their shape (see Table 2) or by the placement pattern (random or uniform placement). Furthermore blocks can be classified by the risk of progressive failure as:

- Compact blocks: The stability is mainly due to the own weight. The average hydraulic stability is low. However, the structural stability is high and the variation in hydraulic stability is relatively low. Thus, the armour layer can be considered as a parallel system with a low risk of progressive failure.
- Slender Blocks: The stability is mainly due to interlocking and the average hydraulic stability is large. However, the variation in hydraulic resistance is also relatively large and the structural stability is low. Therefore slender blocks shall be considered as a series system with a large risk of progressive failure.

Table 2: Classification of breakwater armour units by shape

Shape	Armour Blocks
Cubical	Cube, Antifer Cube, Modified Cube, Grobbelar, Cob, Shed
Double anchor	Dolos, Akmon, Toskane
Thetraeder	Tetrapod, Tetrahedron (solid, perforated, hollow), Tripod,
Combined bars	2-D: Accropode, Gassho, Core-Loc 3-D: Hexapod, Hexaleg, A-Jack
L-shaped blocks	Bipod
Slab type (various shapes)	Tribar, Trilong, N-Shaped Block, Hollow Square
Others	Stabit, Seabee

A more general classification of armour units that comprises shape, stability and placement pattern divides the most commonly used armour units in 6 categories (see Table 3):

Table 3: Classification of armour units by shape, placement and stability factor

<table>
<tr><th rowspan="2">Placement pattern</th><th rowspan="2">Number of layers</th><th rowspan="2">Shape</th><th colspan="3">Stability factor</th></tr>
<tr><th>Own eight</th><th>Interlocking</th><th>Friction</th></tr>
<tr><td rowspan="5">Random</td><td rowspan="3">Double layer</td><td>Simple</td><td>(**1**) Cube, Antifer Cube, Modified Cube</td><td></td><td></td></tr>
<tr><td rowspan="2">Complex</td><td colspan="2">(**2**) Tetrapod, Akmon, Tribar, Tripod</td><td rowspan="2"></td></tr>
<tr><td></td><td>(**3**) Stabit, Dolos</td></tr>
<tr><td rowspan="2">Single layer</td><td>Simple</td><td>(**5**) Cube</td><td rowspan="2">(**4**) A-Jack Accropode, Core-Loc</td><td></td></tr>
<tr><td>Complex</td><td></td><td></td></tr>
<tr><td rowspan="2">Uniform</td><td rowspan="2">Single layer</td><td>Simple</td><td></td><td></td><td>(**6**) Seabee, Hollow Cube, Diahitis</td></tr>
<tr><td>Complex</td><td></td><td></td><td>Cob, Shed</td></tr>
</table>

1) Randomly placed armour units – stability factors weight and interlocking
   a) *First generation armour units*
      i) The units have a simple shape; the stability factors are weight and to very limited extend interlocking. The placement is random in 2 layers. Typical examples are Cube, Antifer Cube, Modified Cube etc.
      ii) First generation armour units that are placed randomly in a single layer are currently investigated ('Single-Layer-Cubes').
   b) Second generation armour units
      i) Simple shape: Stability factors are weight and to some extend interlocking. The placement pattern is mostly random and in 2 layers. Typical examples are Tetrapod, Akmon, Tribar, Tripod, etc.
      ii) Complex shape: The governing stability factor is interlocking; the placement is random in 2 layers. Typical units of this type are Stabit and Dolos.

   - c) *Third generation armour units*
     The units are placed randomly in a single layer. The shape varies from relatively simple (A-Jack) to complex (Accropode and Core-Loc). The governing stability factor is interlocking.
2) Uniformly placed armour units – stability factor friction
   - a) Parallel-epipedic hollow blocks with either simple (Seabee, Hollow Cube and Diahitis) or complex shape (Cob and Shed). The placement is uniform in a single layer (cobblestone-concept). The governing stability factor is interlocking.

4. COMMON ARMOURING TECHNIQUES

Different armour unit concepts are briefly described in this section. The strong and weak points are discussed with respect to (i) structural and hydraulic stability, (ii) risk of progressive damage, (iii) fabrication, storage, handling and placement of armour units and (iv) maintenance and repair of armour layers.

Hollow block armour

At La Colette Harbour, Jersey (1973/74) uniformly placed hollow block units have been applied for the first time. Cobs have been placed on a 1:1.33 slope, the design wave height was about 3.8 m (significant wave height). The toe of the structure was at low water level. A block weight of 2 t has been selected with respect to the most economical placement.

The first Shed application has been at St. Helier Sea Wall, Jersey in 1983. Fibre reinforced concrete units have been placed on a 1:1.5 slope, the design wave height was about 3.5 m. Shed armour layers have a constant porosity of about 60%. The roughness of the surface can be increased by double units (Shephard Hill, 1989).

Hollow Cubes have been applied for the first on a breakwater at Baltrum, Germany in 1992. The Diahitis has been introduced by University Cork and Ascon Ltd. in 1998. It has been applied for a causeway at Galway Bay, Ireland in 1999 (Cullinane, 1998).

The stability of Seabee units is mostly dependent on the layer thickness and not on the unit weight. Stability coefficients up to $K_D = 800$ have been determined in model tests. Therefore, the Seabee has been considered as a cost efficient alternative for Dolos and Tribar revetments if the toe can be constructed in the dry (Brown, 1983).

The hollow block units can be manufactured either on site or in a factory. Fibre reinforcement is recommended for Shed and Cob to improve the handling stress resistance.

Construction above the waterline can be very effective. Cob units have been also placed in pairs (Soil Structures International, 1985). In some cases hollow blocks have been applied for the protection of breakwaters. For example at Bangor North Breakwater, Northern Ireland (1983) Sheds have been placed above tidal low water while the lower part of the slope was protected by rock armour. Sheds have been placed for the first time under water with a prefabricated concrete toe at Pyrgos Marina, Limassel, Cyprus (1984) in a water depth of 6 m.

However, the underwater placement of hollow blocks requires final placing by divers, which is very critical with limited visibility or continuous wave or current action. Furthermore, a pre-fabricated concrete toe has to be installed. Hence, hollow blocks are significantly more efficient if they can be placed above the water level. Furthermore, spacers are required for the placement of Cobs and Sheds at breakwater heads (HR Wallingford, 1983).

The design scheme for these hollow cube armour units is completely different from a conventional armour layer design. Thus, new design procedures had to be developed for these units (see for example Seabee Developments, 1994).

The stability of uniform placed hollow blocks is based on friction between neighbouring blocks. The friction in between uniformly placed bocks varies significantly less than the interlocking between randomly placed blocks. Therefore a friction type armour layer is more homogeneous than interlocking armour and very stable. Furthermore, the required safety margins for design are lower than for interlocking armour. Other advantages of hollow blocks are single layer placement, relatively small armour blocks, placement of multiple blocks and a relatively high porosity of the armour layer (advantageous with respect to concrete savings and hydraulic performance).

However, a uniform placement of hollow cubes on slopes with complex geometry (berms, intersecting slopes, breakwater heads etc.) can be tedious. Underwater placement in a harsh environment can be almost impossible. Therefore it has to be checked from case to case if friction type armour units can be applied. If so it might be a cost efficient alternative for conventional concrete armour units or for rock armour. However, this will be the case mostly for revetments. For typical exposed breakwaters the friction type armour is currently not applicable.

Randomly placed double layer armour

The first Tetrapod breakwater has been constructed in Casablanca, Morocco (1951). A Tetrapod armour layer has a void ratio of about 50%. Tetrapods have been applied for breakwaters, seawalls, beach erosion control as well as scour and bank protection (SOTRAMER, 1978).

The Akmon has been been developed for new breakwaters at IJmuiden , Netherlands in 1962. An Akmon armour layer has a porosity of almost 60% and a stability coefficient (K_D factor) that is slightly higher than for Tetrapods. Thus it has been considered as a cost efficient alternative for Tetrapods (Paape & Walther, 1962).

Stabits have been applied for the first time at Benghazi Harbour, Libya in 1961. The recommended stability coefficient for Stabits is K_D = 12/10 for breaking/non-breaking waves. The porosity of a Stabit armour layer typically varies between 50% and 55%.

The Dolos was invented by A. Kruger, East London Harbour Engineer's Office in 1966 (Denison, 1999) for the protection of the breakwater guarding the entrance to the East London harbour. K_D factors of 31/15 (for non-breaking/breaking waves) are recommended by the SPM (1984) that shall be reduced by 50% for no rocking. The British Standard (1991) recommends K_D coefficients of 12/10 (for non-breaking/breaking waves).

The first layer of Cube armour tends to settle and to form an almost solid layer. Therefore, a second layer is necessary as separators for the blocks of the first layer. The placement of Cubes is relatively difficult. The use of slings is impossible, therefore the efficiency is limited. If a fixed pin is applied to the blocks, all blocks will have the same orientation at placing, which is unfavourable. Cubes are commonly gripped with tongs. However, this technique also provides a constant orientation of the blocks and thus a risk of a uniform placement pattern (Sogreah, 1985). A random placement is essential for Cubes in order to guaranty the porosity of the armour layer. Otherwise the excess pore pressure that develops inside the breakwater may lift the blocks.

Tetrapods are placed according to a positioning plan with predefined block orientation. The second layer is necessary to create interlocking. This placement concept is typical for most of the randomly placed double layer armour units (Dolos, Tribar, etc.). However, the second layer tends to rock and to create breaking (Sogreah, 1985). Thus, double layer armouring does not necessarily mean additional safety.

The structural stability of the most commonly used armour units of this group has been extensively studied after the failure of the Sines Breakwater. Several drop tests have been performed with prototype armour units. Tetrapods for example that have been dropped on an underlayer were breaking at a drop height of about 1.0 m. 8 m^3 When Tetrapods have been dropped on a concrete foundation (Port of Sete, France, 1983) breakage has been observed after 3 to 4 drops from a height of some decimetres (Sogreah, 1985).

The damage at breakwaters maintained by US Army Corps of Engineers, which are mostly protected by Dolos, Tribar, Tetrapod, modified Cube, Tetrapod or Quadripod has been reviewed by Melby & Turk (1996). Possible reasons for breakage according to this study are static failure, construction related breaks and insufficient concrete cover on reinforcement. However, most of the breakages are induced by movements. These findings are confirmed by CUR (1990).

Armour units with slender shape (Dolos, Tribar etc.), a relatively slender central section and long legs will face high stresses in central part of the armour block. These blocks have a high risk of breaking in the central part. Broken armour units have little residual stability (Sogreah, 1985). Adequate reinforcement of these armour units is uneconomical (CUR, 1990 and Melby & Turk, 1996).

A reduction of impact forces due to rocking by a modified armour unit surface (rubber, hardwood, asphalt etc.) has been proposed by CUR (1990). This approach has been considered more cost efficient than reinforcement.

The main shortcomings of randomly placed double-layer armour units have been summarised by Melby & Turk (1996) as follows:

- Armour units with slender central section (like Dolos and Tribar) tend to break;
- Randomly placed blocks tend to move and rock (especially the second layer is sensitive to rocking according to Sogreah, 1985)
- Double layer armour that is placed on flat slopes is uneconomical

Thus, is can be concluded that double layer randomly placed armour is sensible only for compact blocks, which provide large structural stability and are which are stable mainly due to their own weight (like Cube, Antifer Cube etc.). An example might be the design of the new breakwater at La Coruna, Spain (Burcharth et al., 2002). 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.

An improved design with more slender, interlocking armour units will probably reduce the construction cost and increase the costs for maintenance. One should be aware that slender blocks like Dolos, Tetrapod and Tribar that are placed in 2 layers tend to rock and to break. Hence, frequent monitoring and regular replacing of broken armour units will be necessary.

Randomly placed single layer armour

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 the next 20 years. The Accropode has been compact shape that provides a relatively large structural stability. The basic concept of the Accropode was a balance between interlocking and structural stability.

The hydraulic stability of Accropode has been studied extensively in 2-D and 3-D model tests. Van der Meer (1988) determined the start of damage at stability number 3.7 (corresponds to $K_D = 38$) the armour layer failed at stability number 4.1 ($K_D = 52$). These results have been obtained in 2-D experiments with a 1:1.33 slope. Melby and Turk (1993) stated that the best interlocking can be achieved on steep slopes and that the hydraulic stability is very sensitive to placement. Sogreah recommended K_D values of 15/12 (for non-breaking/breaking waves) for the design of Accropode armour layers. The Sogreah recommendations appear very conservative. 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 Figure 1).

Drop tests have been performed in order to assess the structural stability of Accropode. 9 m^3 blocks have been dropped on a rigid base at Bizerte, Tunesia (1984). The blocks started breaking at a drop height of about 3 m and lost about 5% of their initial weight. A blocks of 6.3 m^3 has been dropped by incident on other block from height of 3 m (at Monastir, Tunesia). Only minor damage has been observed to both blocks (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 guaranty a perfect interlocking. Therefore, the spatial variation of stability can be significant for an Accropode armour layer (Sogreah, 1985).

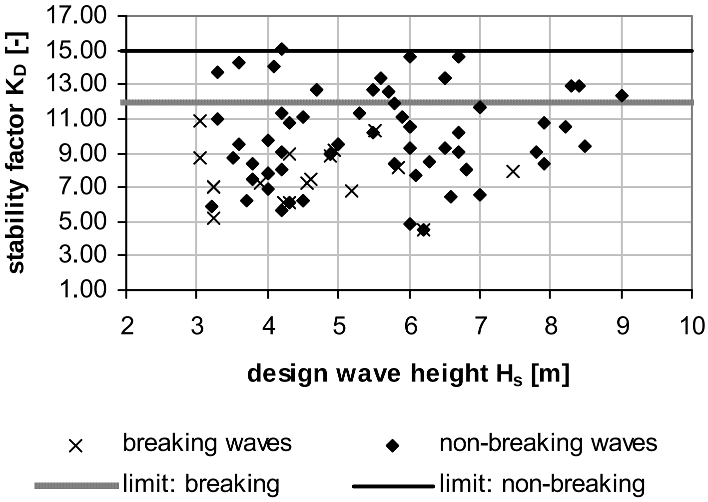

Figure 1: Design K_D values for Accropode (Based on Sogreah, 2000)

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).

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 all armour units that are placed in double layers.

Core-Loc

The Core-Loc has been introduced by the US Army Corps of Engineers in 1994. The following features of an optimum armour unit had been defined as a starting point for the Core-Loc development (Melby & Turk, 1996): (a) Single layer placement (minimum concrete volume), (b) High hydraulic stability and a reserve stability if the design wave height is exceeded , (c) no tendency to rock and a large residual stability after breaking , (d) high porosity and roughness of the armour layer (maximum dissipation of wave energy), possible placement between other types of armour units (especially Dolos), (e) large structural stability (low internal stresses), (f) easy to cast, (g) easy construction of armour layer (especially in low visibility water), (h) minimum casting yard and barge space and (i) conventional construction materials and techniques.

In 2-D hydraulic model tests Core-Loc armour was found to be stable up to stability numbers of 6 (correspondes to a K_D factor of about 160). Thus, the hydraulic stability of Core-Loc appears to be even better than for Accropodes. Nonetheless, K_D values of 16 are recommended for design (Melby & Turk, 1997), which are in close agreement with the recommendations for Accropodes.

Drop tests have been performed in order to determine the structural stability of Core-Locs (Turk & Melby, 1997). The armour untis have been equipped with surface mounted strain gauges in order to determine the internal stresses. Different types of drops have been considered: (i) the 'hammer drop' (typical drop test for Dolos), the 'anvil drop' (typical for Tetrapods) and the 'tip drop' (considered most critical for Core-Locs). Core-Locs of 9.2 t were dropped in incremental heights. They started cracking at a height of about 30 cm. A typical failure for hammer and anvil drop was breaking of one vertical or horizontal member tip while the major mass of the unit was left intact. However a complete vertical member sheared off after a sequence of tip drops and the Core-Loc broke into two pices.

The Core-Loc drop tests have been compared to Dolos drop test results and it was found that the structural stability of Core-Loc is significantly better than for Dolos units (the number of drops before breaking more than 4 times larger, Turk & Melby, 1997). The central section of a Core-Loc is more compact than the central section of Dolos and Tribar but Core-Locs are significantly more slender and vulnerable than Accropods.

The costs for different type of breakwater armour have been compared by Sogreah (2000) for the Macao Airport Project. A constant rate for manufacturing and placement of 146 $/m^3 of concrete has been applied. The main parameters for the design and the resulting costs are listed in Table 4. It is interesting to note that the costs for Accropode and Core-Loc differ by only 10% while the K_D values differ by about 30%.

Table 4: Costs for different types of armour (Macao Airport Project, Sogreah, 2000)

Type of armour	Stability coefficient K_D	Slope	Total costs*
Tetrapod	9	1:1.5	91%
Antifer Cube	7.5	1:1.5	100%
Accropode	12	1:1.33	57%
Core-Loc	16	1:1.33	51%

*as compared to Antifer Cube design

The placement procedures for Accropode and Core-Loc are very similar. Various sling techniques are applied for both types of armour units. The placement of Core-Locs might be even slightly more complex. If the placement procedure is considered as the weakest point in the Accropode concept the Core-Loc will be definitely not a major improvement.

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 as expected:

- The hydraulic stability is slightly larger than for Accropodes;
- The structural stability is significantly lower than for Accropodes;
- 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 or if the required Accropode size is just beyond the crane limits. However, in most cases the weighting 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.

All in all the Core-Loc development appears as a repetition of the armour unit development in the 1960th when armour units became more and more slender in order to improve the interlocking capability and to minimise the total costs for the armour layer. This development led to a number breakwater failures in the 1970th and early 80th. One could argue that Accropodes are over designed with respect to structural stability that a Core-Loc is much closer to an optimum design. However, the large risk of progressive failure that is related to the breakage of armour units justifies in the authors opinion the safety margins of the Accropode concept.

The Core-Loc does not comply with all demands that have been defined by its developers. The most essential shortcomings have been identified with respect to structural stability, residual stability after breaking as well as ease of casting and placement. Thus, the Core-Loc leaves several options for future improvements.

Single Layer Cubes

Single layer Cubes armour has been investigated by van Gent (2000) and by d'Angremond et al. (2002). Both considered Cubes that are placed in a single layer as a cost efficient alternative for conventional double layer armour. Especially innovative placement procedures like dropping armour blocks from the water surface, which have been studied by d'Angremond et al. are a promising potential for future armour unit developments.

However, it should be noted that irregular placement of Cubes is essential to obtain a rough and porous armour layer. Inevitable settlements may create a more uniform placement pattern and thus reduce the void ratio of the armour layer (Sogreah, 1985). The consequences are an increased wave run-up and an increased pore pressure gradients perpendicular to the slope that may lift the blocks.

At the current stage the Single Layer Cube concept appears a bit like re-inventing the single layer breakwater armour while almost 25 years of Accropode experience are neglected. The Single Layer Cube studies provide very useful input for future armour unit developments with respect to placement methods, maintenance and repair of armour layers etc. But it is hard to believe that Single Layer Cube will be the ultimate armouring technique.

Others

Innovative single layer armour units that have not been discussed yet are for example A-Jack and Samoa Block.

The Samoa Block concept (Turk & Melby, 2002) shall be considered as a modification of the hollow block concept because the blocks are uniformly placed and most suitable for revetments that can be constructed in the dry. Samoa Blocks are solid; therefore the void ratio of the armour layer is significantly lower than for typical hollow block armour. The shape of the blocks is cylindrical and voids are located in between the blocks. Thus, the friction forces in between the armour blocks are reduced and interlocking is required to keep the blocks in position. Samoa Blocks can easily follow the shape of the slope and they might be therefore more favourable then other hollow block armour units for slopes with a complex geometry. However, on a plane slope a conventional hollow block with a fairly simple shape (Seabee, Hollow Cube, Diahitis etc.) will be more cost efficient with respect to concrete volume and casting of the blocks.

The A-Jacks is a slender, highly interlocking armour unit that has been introduced by Armortec (1997). A-Jacks are placed in a single layer either randomly or uniform. The void porosity is about 40% for a uniform placement pattern. A-Jacks have been applied up to know only for revetments and not for breakwater armouring. However the protection of breakwaters has been studied in hydraulic model tests. K_D values of 75 – 100 are recommended for the design of breakwater armour.

A-Jacks are very slender and therefore the structural stability might be critical if the blocks exceed a size of 1 – 2 m^3. However, the very large K_D value will limit the block size and therefore A-Jacks might be a cost efficient alternative for (i) temporary structures and (ii) moderate wave conditions.

6. REQUESTS FOR FUTURE ARMOUR UNIT DEVELOPMENTS

Uniform Placement

If armour layers can be constructed in the dry friction type armour units are very promising. It is interesting to note that the development of hollow cubes started with relatively complex and slender shapes (Cob and Shed) while later inventions were mainly focused on a simplified shape with respect to casting and placement (Seabee, Diahitis, Hollow Cube etc.) and not on improved stability and hydraulic performance.

Thus, it can be concluded that friction type armour is a highly efficient armouring technique in its current state of development. New types of armour units can be easily designed by modifying the shape of existing hollow blocks and it is very likely that these new armour units will be as efficient as existing hollow blocks. However, it is very unlikely that major improvements can be achieved.

Random Placement

The performance of randomly placed armour units is varying significantly between the different types of units that have been discussed in the previous section. Therefore new armour unit developments may provide significant advantages as compared to existing concepts, at least for specific applications (like Core-Loc as a repair unit for Dolos armour).

The current market leaders for randomly placed armour units are Accropode and Core-Loc. The shortcomings of these two blocks with respect to placement (Accropode), casting and structural stability (Core-Loc) have been discussed in the previous section. Future armour unit developments shall try to compensate these drawbacks.

A confrontation of single and double layer armouring clearly indicates:

- Single layer armour is more cost efficient due to the reduced number of armour blocks (concrete savings and lower costs for fabrication and placement of blocks).
- Double layer armour does not provide additional safety against failure – except for compact armour units with large structural stability and limited interlocking (Cube, Antifer Cube, etc.) – because the second layer tends to rock and thus the structural integrity of the armour units is jeopardized.

Therefore, future developments of interlocking armour untis shall only consider single layer armouring.

The structural stability of future armour units shall be similar to Accropodes. It will not be necessary to improve the strength of Accropode units. However, the structural strength of Core-Loc is considered insufficient and shall be improved by future developments.

It is very unlikely that a compact armour block – with similar structural stability as an Accropode – can provide significantly more interlocking than Core-Loc and Accropode. With respect to the fact that armour layers are frequently over-designed in order to minimise the placement costs the target stability factor for future armour unit developments shall be of order $K_D = 15$ (as for Accropode and Core-Loc). Developers shall not focus too much on an improved interlocking but on a balanced structural and hydraulic stability. An alternative concept however might be more slender armour units with stability coefficients that are at least one order of magnitude larger ($K_D \geq 100$) like the A-Jack.

The placement is considered as one of the main shortcomings of Accropode and Core-Loc. The interlocking of individual armour blocks is highly uncertain. Therefore large safety margins for K_D values are required for design. Future armour unit developments shall be focused on a simplified placement procedure. The interlocking of the armour units shall be almost independent of the orientation of neighbouring blocks in order to allow for a placement that is virtually random. This feature that has been called ‘automatic interlocking’ is applicable to armour units that can easily find a stable position in a matrix of armour units. Automatic interlocking is essential for an easy and fast placement of armour units as well as for a self-repairing armour layer after settlements or displacements. With automatic interlocking armour units it might be even possible to place several armour units simultaneously. Such a placement would be very fast and cost efficient.

A typical feature of Accropode and Core-Loc are three different faces (the anchor, the face with two legs and the face with one leg). Each block within the armour layer is in contact with four other blocks. Thus the interface and consequently the interlocking between an individual block and the surrounding blocks may vary significantly. If the number of different front faces is reduced the number of possible interfaces between armour blocks will be also reduced and consequently the uncertainties related to interlocking will decrease. A more predictable interlocking will allow reducing the safety margins for design and will thus lead to a more efficient design.

Blocks with only one type of front face (like cubes) tend to settle and to form a densely packed, almost uniform armour layer, which is unfavourable from a hydraulic point of view (wave run-up, excess pore pressure etc.). However, a block with only two different front faces, which can easily find a stable position on the slope, might be a promising alternative for Accropode and Core-Loc (even if the K_D factor will not be larger than 15).

It is further believed that a relatively simple armour unit shape will increase the automatic interlocking capacity while the absolute interlocking (K_D factor) will be limited. Thus, a simple bulky shape is most favourable with respect to structural stability and casting. Attempts to optimise interlocking shall consider automatic interlocking as well as K_D factor.

The casting of Core-Loc is more difficult than for Accropodes. However, a simple shape will facilitate the fabrication of moulds and thus contribute to a more flexible and efficient construction.

Further aspects that are mostly considered in the development of armour units are:

- Storage area: The required storage area mainly depends on the number of armour layers placed on the slope and on the number of layers in the storage area (typically 1 – 3, depending on the block shape).
- Roughness and porosity of the slope: The void ratio of the armour layer mainly depends on the packing density of armour units and the roughness is governed by the size of armour units. The shape of the armour units is of minor importance.

The authors consider the above two items of minor importance for the development of highly efficient concrete armour units.

ACKNOWLEDGEMENTS

The support of Delta Marine Consultants b.v. and HBG civiel b.v. within their ‘Knowledge Management and Innovation Programme’ is gratefully acknowledged.

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