

SAFETY OF MONOLAYER BREAKWATERS

O. Juul Jensen¹, L. Uguccioni¹ and T. Gierlevsen¹

¹Department of Marine and Foundation Engineering, COWI A/S., Denmark

ABSTRACT

The authors present their concern for the use of (interlocking) monolayer armour units with high porosity, also referred to as bulky monolayer units. It is based upon their long experience in the study and design of all types of breakwaters and revetments including vast experience in hydraulic model tests of such structures. The paper thus relies on this experience including the involvement in the study of damaged breakwaters and a study of what appears on the subject in the public domain. The paper finally presents the authors' own conclusion and proposal on new guidelines for the use of such units; with the aim of arriving at safer design in the future, thus avoiding or significantly reducing the too high number of damaged breakwaters that the coastal engineering profession has witnessed. It also presents ideas for safer design of large, exposed breakwaters in deeper water, where such monolayer units should be avoided.

1 Introduction

The decision to write this paper has been taken following many years of concern for the state of the art of design and use of monolayer breakwaters and communication about this subject. The safety of rubble mound breakwaters with special emphasis on monolayer armour systems and units was already dealt with in Juul Jensen (2013), which was based upon increasing concerns about monolayer armour units, breakage of such units in structures, discussions with SOGREAH and later CLI, and the authors general experience with monolayer breakwaters and damage of same. Readers of the current paper are encouraged to read also the 2013 paper.

In the following, the stability coefficient K_D from the well-known Hudson formula will be used as a measure of the hydraulic stability of the armour units, as this is the parameter used by all the patentees or licensees of monolayer units. (In this paper patentee and licensee are taken to be the same). Previously, the patent holders Concrete Layer Innovations (CLI) and Delta Marine Consultant (DMC) indicated K_D factors of 15 or 16 in their design recommendations for the breakwater trunk sections on a flat or gently sloping seabed. Over time, however, CLI have introduced stricter recommendations for AccropodeTM units with respect to the criteria for acceptable movements and displacement of armour units in physical model tests as well as general recommendation of lower K_D values for breakwaters with a foreshore steeper than 1:100. Likewise, the patentholder of Xbloc®, DMC, have recently updated their guidelines and are now recommending safety factors that lead to relative larger armour units (i.e., essentially a smaller K_D) for given design wave conditions. Hence, it appears that a sort of acknowledgement by the patent holders has been made regarding previous design approach not being sufficiently safe. Further, since 2013 a new patented product, the Cubipod® developed by SATO in Spain, has gained popularity.

In Juul Jensen (2013), it was concluded that there was an unhealthy competition going on between the different patentees about who could offer a product that would further reduce the consumption and volume of concrete for a specific armour layer. Unfortunately for our profession, this trend is still going on, and potential customers are still "promised" products with performances that are often not met.

2 The development of double and monolayer armour units

Before the introduction of monolayer units, mainly double layer concrete armour units were used, starting with very simple units like cubes and rectangular blocks which have seen many successful applications, some of which have now been in service for more than 100 years. Then, a major breakthrough took place in 1950 with the invention of the Tetrapod in France. This was followed by many other units, of which the Dolos by Merrifield in South Africa in about 1963 was a major new development. This was thought to be a good armour unit, also for large, exposed breakwaters, until nature proved otherwise by catastrophic failures in Sines and San Ciprian. This spurred a lot of important research and had a major influence on the future armour unit technology. Other pattern-placed monolayer units were also developed: Tribars, Cobs, SHEDs and Seabees. Later this was followed by the introduction of the first real randomly oriented monolayer unit, the AccropodeTM I in France in 1981, again followed by the Core LocTM in USA in 1996, the AccropodeTM II in 1999, the Xbloc® in Netherlands by DMC in 2001 and finally the Cubipod® in Spain by SATO and first used in the port of Malaga in 2011.

For most of these types of concrete armour units, the engineering profession has witnessed daring optimistic designs resulting in damage and sometimes catastrophic failures. However, new insight into the nature and behaviour of the particular armour units under complex wave loading was gained. For all these units (except Cubipods®, where, to the authors knowledge, no damage with breakage of units has occurred to date), the damage experienced led to a more conservative and more safe use of the units in question. Core locTM is an exception, and to the authors knowledge no new recommendations are given, and it appears that the unit is not used in practice anymore. It however still appears on the licensee's (CLI) homepage.

The authors consider monolayer units a very good and valid addition to breakwater technology. However, as will be explained in this paper, the authors believe that there are limitations to their use for large, exposed breakwaters. In the authors' opinion, more care and diligence should be invested into the design when using such units. Further, for very large and severely exposed structures, monolayer units are normally not the safe solution. Juul Jensen (2013) presented the main author's experience with rubble mound breakwater armour layers and reached the conclusion that not enough attention was being paid to the use of the highly promoted monolayer systems. Particularly the size of these units relative to the incoming design wave condition (for simplicity expressed by the Hudson stability coefficient K_D) was, and still remains, a source for concern.

During the following nine years since the 2013 paper, additional experience was gained by the authors from studies and analysis of monolayer armoured breakwaters and

revetments, often in an expert role for assessment of damage to large breakwaters and revetments, carried out under Non-Disclosure Agreements (NDAs). For this reason, while project details have been kept confidential, the main overall observations and new experience gained has been presented in the hope that this can be a valid contribution to the coastal engineering profession. Thereby, future projects can avoid making the same mistakes as before so that more safe breakwaters are obtained for the owners. The authors' ideas on how to obtain a safe breakwater design and when monolayer systems should and should not be used will likewise be presented.

3 Brief history of breakwater armour unit and major failures

The design of rubble mound breakwaters has since about 150 years ago and until the 1930's mainly relied on practical experience and "trial and error" procedures and the use of quarry rocks and concrete armour units like cubes or elongated cubes/rectangular blocks as armour. In the 1930s the approach became more scientific with further development of the understanding of ocean waves and the relationship between the wave height and the size (weight) of the armour units. Iribarren (1949) in Spain was one of the pioneers, and then Hudson (1959). Since then, researchers and designers relied upon an estimation of waves at the site and the use of empirical formulae for the determination of the size of armour units. In many cases it was still a "trial and error" process, where the breakwater was designed based upon limited knowledge of the wave conditions, which in many cases resulted in a too weak design, and in other cases in overdesign. When damage occurred, a breakwater was repaired by adding more armour units, and thereby it became stronger and stronger if the rock or concrete blocks were large enough. Some of the earlier breakwaters with artificial units were armoured with cubes or rectangular blocks, and as for rock breakwaters, the repair is often relatively easy. It can be done by adding more armour units for reinforcement and strengthening. One example of such breakwater with blocks from 1930s is shown in Figure 1

Figure 1 Example of breakwater armoured with large rectangular blocks (Port of Algiers, Algeria).



In the 1950s, the use of the new armour unit developed in France, Tetrapod, took off and many successful projects were implemented. However, damage also occurred for

Tetrapods. An example from Arzew EL Djedid, Algeria (1981) is shown Juul Jensen (2013).

In connection with the development of Port d'Antifer in Normandy (France) the Antifer Cube for two-layer armoring was developed in 1973. It is a tapered cube with grooves tapered the other way, so they can easily be cast in forms without bottom and top and easily taken out of the formwork. These blocks are robust and have been used for very exposed deep-water breakwaters like in Mohammedia in Morocco and Zeebrugge, Belgium. But from the senior author's personal experience from numerous model tests when at DHI (1975-1994), there is an apparent tendency that these units may reorient themselves in the armour layer and form a rather smooth "pavement", which increases run-up and overtopping. This does not happen so easily for rectangular blocks/elongated cubes for example with relative dimensions $1 \times 1 \times 1.33$. When these are placed randomly, the armour layer becomes more irregular.

On February 26, 1978, the major failure of the Dolos breakwater in Sines, Portugal occurred. This was followed in 1980 by the failure of the Dolos breakwater in San Ciprian in Spain. The main author has not been involved in these projects, however, reference is made to extensive literature available on the Sines breakwater case.

The Sines failure was a very serious wake up call for the coastal engineering profession. The use of slender fragile concrete armour units had been carried beyond its limits. The breakwater was built with 42t Dolos units in two layers and the design wave condition was $H_s=11\text{m}$ with $T_p=16\text{s}$. This corresponds to a stability coefficient of $K_D=23.6$. The failure resulted in a lot of attention in the coastal engineering profession and many papers and studies have been made to explain and document what went wrong. The severe damage occurred in a storm with $H_s=9\text{m}$ and $T_p=19\text{s}$. The Dolos units used in Sines were about twice as heavy as any other units used at the time of design in 1976. In hindsight, this was a very daring design and "nature" proved that there was a limit to the use of slender Dolos units in the harsh wave climate of the Atlantic.

In Algeria the large new industrial port, Port d'Arzew el Djedid, was built using Tetrapods as main armour. The main author was part of a team studying the damage. This breakwater failed in 1981 during a severe storm with about $H_s=7\text{m}$, and the breakwater suffered very severe damage. It is 2,000m long, in 25m water depth and was armoured with 20m^3 Tetrapods (two layers) on a slope of 1:1.33, see the details in Juul Jensen (2013). Subsequent model test investigations showed that the breakwater armour layer must have been constructed with a relatively high porosity and loose packing density, although a standard tetrapod placement grid was used. The wave impact during the storm led to compaction and settlements, in both prototype and model, within the entire armour layer, which again led to the breakage of the units and hence the loss of interlocking and failure of sections of the armour layer. For $H_s=7\text{m}$, the corresponding K_D is as low as 5.5, so this would be regarded as safe at the design stage.

The failures of Sines, San Ciprian and Arzew el Djedid breakwaters spurred a lot of interest and became the subject for many papers and discussions in coastal engineering conferences. Research was performed on the wave loading, strength and fatigue of slender units like the Dolos and Tetrapods. Different lines of research developed, in Denmark (Dolos), in the Netherlands (Tetrapods), and in the USA (mostly Dolos). The paper by Burcharth et al (2000) resumed the research and presented an empirical formula for breakage of Dolos as well as Tetrapods.

Furthermore, it became apparent for the coastal engineering profession that the forces and hence stresses in such armour units increase with their size, whereas concrete have the same strength and properties no matter how large armour units it is used for. It further became evident that extreme care should be exercised in the interpretation of results from small scale model tests, where the fragility of the units could not be modelled. Minor rocking of a number of units and settlements within the whole armour layer which appeared of little consequence in the model could in the prototype mean breakage of units and possible failure of the breakwater, even when it had two layers of armour units.

In the early 1980s this led the coastal engineering profession in three principally different directions:

- Some projects took up or continued the old and well proven technology of using large concrete blocks in two layers as armouring. The main author had his own experience around 1982 from the large breakwater for Puerto de Carboneras, Spain, See Juul Jensen (2013). In Spain, this tradition has been continued until today and new large deep water and exposed breakwaters are with success using two layers of large, massive concrete blocks as armouring, for instance at La Coruña.
- Others continued the use of Dolos and Tetrapods, but with significantly lower stability factors, i.e., larger armour units relatively to the design waves.
- Some designers resorted to the use of Dolos and Tetrapods with steel bar reinforcement. In literature there are a number of references to such projects; but the use of reinforcement has not been widely applied. The reason is both higher costs of the armour units, and further the apparent problem with the risk of corrosion in the marine and salty environment.
- Others focused on monolayer units, see the following section.

4 The development of monolayer units

After about 30 years of the use of Tetrapods and a few other armour units, SOGREAH in France developed the first new type of monolayer armour units and registered a patent on the Accropode™ unit in 1981.

SOGREAH's invention of the Accropode™ started the use of monolayer armour units, and later the Core Loc™ was introduced by US Army Corp of Engineers in 1995, followed by the Accropode™ II in 1999. In 2001 the XBloc® was patented and brought onto the

marked by Delta Marine Consultants of The Netherlands. As for the other monolayer units, XBloc® “promised” in the beginning stability coefficients as high as $K_D=16$ for the trunk and very high porosity leading to a small reduction in the volume of concrete in comparison with any other armour unit, ie. an apparent economical advantage for the owner. Looking at the shape and design parameters of the XBloc® and the Accropode™ II, they are quite similar, and should in the authors opinion perform similarly, when exposed to severe wave loading.

In the period between 2005-2010 the Cubipod® was developed at the Universitat Politècnica de Valencia by Professor J.M. Medina and others. The Spanish company SATO now holds the patent of the Cubipod®, which is a cube with 6 pods (stubs) sticking out on each of the six sides of the unit, see Figure 2 and Medina et al (2016).

Figure 2 Armour units: Accropode™ I, Core Loc™, Accropode™ II, XBloc® and Cubipod®

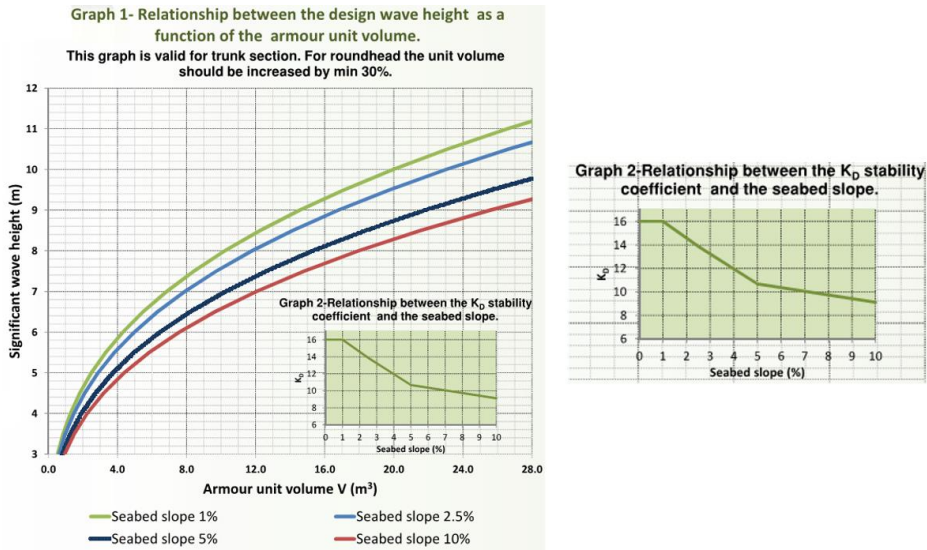


Cubipod® is bulkier and more robust than the other monolayer units (see Figure 2) and does not gain its hydraulic stability from interlocking. This can also be seen in the apparent porosity of an armour layer, which is approx. 40% for Cubipod®, but approx. 54-58% for the other units. Cubipod® is also the only unit where the patentee, SATO, is advocating/promoting their use in both one and two layers of the armour, see Cubipod Manual, Medina et al (2016). This manual presents the recommended K_D factors for the use in one and two layers, and somewhat surprisingly a K_D as high as 28 is presented for a two-layer solution for trunk sections. It appears that the $K_D=28$ was derived from hydraulic model tests and corresponds to a situation with “initiation of destruction”, see Gomez-Martin et al. (2014). Hence, this very high K_D is inconsistent with the definition of K_D for practical breakwater design, which is based on “initiation of damage”. It is the authors opinion, a robust breakwater design should be based on “initiation of damage”, and it seems potentially misleading to present such a high K_D if the assumptions behind it are not clearly communicated, and without warning against using this K_D blindly. Otherwise, the unprepared and unexperienced designer may be misled into using such high and unsafe K_D values. For one-layer solutions, SATO recommends $K_D=12$, based on the normal definition as “initiation of damage”. In COWIs application of Cubipod® for the new Western Breakwater in Hanstholm (Denmark) $K_D=11.7$ was documented by physical model tests for 22t high density Cubipods® in one layer (based on a design $H_{1/3}=9.0\text{m}$ measured at the toe of the breakwater), see Lauridsen et al. (2023).

The recommended K_D factors for trunk sections interlocking monolayer units like Accropode™ and Xbloc® units are generally as high as 15 to 16.

In addition, in their specifications and promotion material, see CLI (2012) - Accropode™ II Design Table, CLI are presenting a curve to be applied for breakwaters on steeper seabed slopes, see Figure 3. Crucially, however, CLI and others are not providing a definition on where the determining wave height, H_s , shall be measured. This aspect is further addressed in Section 6.

Figure 3 CLI graphs for the determination of K_D for structures on a sloping seabed. CLI (2012).



XBloc® have also now introduced reduction/safety factors to be applied for the design. Table 1 shows the latest recommendations as taken from DMC’s homepage. The largest factor is 2.0 for very steep seabed of 1:10 or low crested breakwaters or low core permeability. It is stated in the specifications, that if more than one aspect/item applies, the highest factor should be applied. In conclusion this means that even for a very exposed breakwater on a very steep slope, the resulting K_D would be as high as $16/2=8$. It is uncertain and up to the designer’s discretion how to apply the factors.

Table 1 Excerpt from DMC's design guidelines table with XBloc® correction factors for local phenomena that affect the required unit size.

Phenomenon	Effect on Armour Stability	Correction factor on unit weight Xbloc
Frequent occurrence of near-design wave height during the lifetime of the structure	Rocking of units, which can occur for a small percentage of the armour units during the design event of a breakwater, can occur frequently during the lifetime of the structure. Therefore, rocking should be carefully assessed during the physical model tests.	1.25
The foreshore in front of the structure is steep	A steep foreshore can lead to adverse wave impact against the armour layer.	1.1 for a steepness between 1:30 and 1:20 1.25 for a steepness between 1:20 and 1:15 1.5 for a steepness between 1:15 and 1:10 2 for a steepness greater than 1:10
The structure is low crested	Armour units placed on the horizontal crest and high on the slope are less stable than units placed lower on the slope, where interlocking is increased by gravity and the above-lying units. In case of a low breakwater the crest area sustains wave impacts and as a consequence a larger unit size is applied.	2 for a relative freeboard < 0.5 1.5 for a relative freeboard < 1
The water depth is large	For typical nearshore breakwater cross sections, the ratio between the highest wave heights in the spectrum and the significant wave height is in the order of 1.2 – 1.4. For breakwaters in deep water, this ratio can be up to 1.8 – 2. As the largest waves in the spectrum cause the largest loads on the armour layer, the stability of the armour layer is reduced compared to breakwaters in lower water depths. Furthermore, a breakwater cross section in deep water typically contains a high rock toe which can affect the wave impacts on the armour slope. Therefore, rocking should be carefully assessed during the physical model tests.	1.5 for water depth > 2.5 x Hs 2 for water depth > 3.5 x Hs
The core permeability is low	A low core permeability can lead to large pressures in the armour layer and reduce the stability of the armour layer. The permeability of the core depends on the materials used and the distance at the water line between the armour layer and the impermeable layer.	1.5 for low core permeability 2 for an impermeable core
The armour slope is mild (<1:1.5)	On a mild slope, the interlocking of the armour units is less effective and as a consequence the stability is reduced.	1.25 (slope milder than 2:3) 1.5 (slope milder than 1:2)

Preliminary designs are made using the Hudson stability coefficient (K_D) specified by the patentees, but without clear definition of the design wave height to be used in combination with the specified K_D if the seabed is not horizontal. The design specifications by the patentees then call for physical model tests to verify the design, which is important so bathymetric variations and influence of design wave conditions can be accounted for in the design.

5 Physical Model Testing

The patentees specify procedures for design verification by physical model tests. However, according to the authors' long experience with physical model tests, this procedure is associated with uncertainty and challenges, as described in the following:

- First and foremost, model armour units in the model do not break as they may in the prototype. Assume a typical model test in scale 1:60. A model unit is then typically ~4 cm. It is very difficult to observe units exercising limited rocking and displacement during wave action. If a model unit is moving/rocking ~10% of the size of the unit, or 4 mm (~25 cm in prototype) it is extremely difficult to detect in a model even using video and overlay photos before and after testing.

- Often model armour units may rock during a test and be in the same position after the test, so it is not detected by still photos. Further, the rocking occurs during severe run-up or run-down and the armour layer is covered with waves and turbulent water with air entrainment. This often makes the water unclear, and it is virtually impossible to observe rocking units.
- Some of the observed damage to actual breakwaters can only be explained by accepting that such small movements and rocking may introduce excessive stress in the prototype units, which may break, even for wave conditions below the design event. However, the rocking criterion defined by the patentees of the interlocking units is for design wave conditions only and not for more frequent wave conditions. These more frequent events may in fact be equally relevant when considering breakages due to rocking in view of imperfections in placement and settling (re-compacting) of the armour units after construction.

Figure 4 shows an example from a prototype with broken units and openings in the armour layer (left) and results from model tests of same structure with detection of rocking units (right).

Figure 4 Broken units in the prototype (left) and rocking units registered in model tests (right). Revetment with Accropode™ I (6.3 m³).

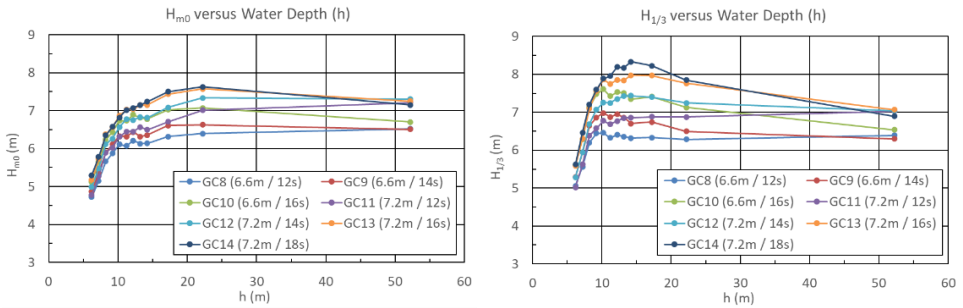


6 Design waves and the influence of seabed profile and slope

All design assessments and calculations relate to the waves that hit the structure. It is therefore important to define how and where these waves are determined in relation to the structure in question. If the seabed is horizontal there is not much uncertainty. However, for a sloping seabed, the waves undergo transformation by shoaling and breaking and for very steep foreshores the effect of non-linear shoaling becomes very important, see e.g. Allsop & Durand (1998). Reading design guidelines of the monolayer unit patentees, it is uncertain how the design waves in front of the structures should be determined for the recommended K_D values to be reliable. There can be a significant difference between using the wave height at the toe of the structure and the wave height at some distance from the structure, and for relatively steep seabeds this will result in two different armour unit sizes. An example to illustrate the importance of design wave definition when using the K_D recommended by the patentees, is the Hanstholm breakwater case mentioned earlier and presented in Lauridsen et al (2023). Based on the

design $H_{1/3}=9.0$ m determined in the model tests at the toe of the structure, $K_D=11.7$ was found. If instead K_D had been determined based on $H_{1/3}=9.5$ m a bit further away from the structure, then it would have resulted in $K_D=13.8$. Therefore, it is insufficient when the patentees present K_D values without also defining the associated wave height to be used for design. The designer must also remember that in shallow water and particularly on steep seabed slopes, the significant wave height based on spectral analysis (H_{m0}) can be much different from the time domain value ($H_s = H_{1/3}$), which is the parameter to use in design based on the patentees' design guidelines. To illustrate this aspect, Figure 5 shows the results from model tests of the wave propagation on a steep seabed with an average slope of 1:27, carried out in a large wave flume. Note, how $H_{1/3} = 7.2$ m is amplified up to a maximum of 8.3 m, $T_p = 18$ s in a water depth of 14 m when the waves propagate towards the shore. The amplification is clearly larger the longer the wave period, T_p . Note also that H_{m0} peaks at 7.7 m but in a water depth of 22 m, while in 14 m depth, it is only 7.1 m.

Figure 5 Results from wave transformation tests on a sloping seabed (1:27). H_{m0} vs. water depth (left) and $H_{1/3}$ vs. water depth (right).



It is the authors' opinion, that when the patentees recommend certain stability coefficients K_D , it needs to be accompanied with a firm definition of the design waves in front of the structure for which these K_D are valid. The definition of design waves and the K_D are interrelated, and it is insufficient to specify K_D and not give any guidelines on the associated design waves. Ideally, the patentees should agree on a common definition, for instance they could settle for defining and measuring the waves in front of a structure at a distance of $0.5L_{p0}$ (L_{p0} being the deep-water wavelength corresponding to T_p) in front of the toe of the structure (i.e., where the armour layer meets the toe).

7 Armour unit placing density and its consequences

For single-layer units placing and positioning of armour units is carried out using a pre-calculated grid to secure the distribution, placing density and position of the units in the armour layer. Further, for all types of armour units, the armour layer may settle in the direction of the slope (re-compact) during wave loading (see Figure 6) and this may result in breakage of armour units. This effect is significantly more critical for the bulky

interlocking armour units with high porosity (Accropode™ I and II, XBloc® and Core Loc™) than for massive non-interlocking units (Cubipod®).

Figure 6 Example of damaged Core Loc™ Breakwater where the whole armour layer settled due to compaction and sliding on the rock underlayer.



The units are placed using x-y grids prepared and delivered by the patentees. Thereby, a certain packing density of units (i.e. number of units per 100 m²) is specified. For Accropode™ II units, for example, specifications indicate acceptable tolerance between 95 and 105 % of the specified packing density. Since the specified placement density is far from the maximum theoretical density, experience shows that the whole armour layer can settle (by sliding on the underlayer), which may result in overload and thus breakage of individual armour units. This behaviour has been observed even in the aftermath of wave conditions considerably below the design wave condition. Further, the specifications call for ideal placing of each unit, so the individual unit rests on the underlayer and is in good contact with neighbouring units. These are theoretical requirements that are not always realistic to achieve for all the many units to be placed in the armour layer. Even for the most careful and diligent contractors using special systems for the checking of the positions of the units, like POSIBLOC™ or similar, in the authors' opinion and experience, the ideal placing is not always possible and there will inevitably be placement imperfections. It is a limitation of the interlocking monolayer units, that a contractor cannot achieve the highest placement density of the units that would prevent them from rocking and moving during wave action. In many cases, the whole armour layer may be compacted during wave action and as a result, it appears as if a downwards movement on the underlayer has taken place. The photo in Figure 6 shows an example for a Core Loc™ armoured breakwater where this has happened after exposure to approx. the design waves of $H_s=5.2$ m. The units are relatively small at 3.6 m³ and not many units were extracted from the armour layer, but some broke in the settling process.

As an example, a comparison of the porosity and concrete consumption for Accropode™ II, Core-Loc™, X-bloc® and Cupipods® for a 5 m³ unit is presented in Table 2. It appears that for the same slope (eg. 1:1.5) there is very little difference in the concrete consumption, while the first three units have very high porosity, say 54 to 59 %, while

Cubipods® is at 40%. The reason while Cubipods® with lower porosity has comparable concrete consumption is the fact that the layer thickness due to the bulkiness of the unit is much lower for this unit.

Table 2 Comparison of a 5 m³ unit for: Accropode™ I and II, Core-loc™, Xbloc® and Cubipods®

Unit	Volume (m ³)	Dn (m)	Layer thick. (m)	Porosity (%)	Concrete (m ³ /m ²)
Accropode	5	1.71	2.33	53.59	1.079
Core Loc	5	1.71	2.6	58.95	1.067
X-bloc	5	1.71	2.4	58.7	0.99
Cubipods	5	1.71	1.71	40	1.03

In addition to the above considerations, it can be mentioned that for Accropode™, the CLI design tables show a slightly increasing porosity with increasing size (volume) of the armour units, which therefore means that the risk for movement and breakage increase with the size of unit. This is contradictory to the principle of similitude between two armour layers constructed with different sizes of the units.

8 Repair procedures for monolayer armour layers and their effect/consequence

The difficulties in repairing interlocking monolayer breakwaters by replacing broken units with new ones is an aspect that is often not recognised when selecting monolayer units and not understood by the owners when commissioning a breakwater.

When breakage occurs in a monolayer breakwater armour layer, it is often near the Still Water Level (SWL) or below it, as this is where the largest wave impacts/drag forces occur on the arm of a unit during wave run down. It will often be required for broken units to be taken out and new units installed. This is achieved by removing all the units above in a V-shape, i.e., basically following the placement pattern of 45 degrees to each side of the location of the broken unit. For monolayer breakwaters with 18 to 20 rows of armour (which is typical for many applications), this would require the stripping of about 10 rows of armour, which (as each row is offset horizontally by ½ of the size of the unit) corresponds to: 1+2+3+4+5+6+7+8+9+10=55 units to remove and put back in place again. Therefore, if there are many broken units and they need to be replaced with intact units, it would be complicated and the costs would be very significant. Furthermore, it is highly likely, that with a high probability the settlement and rocking process resulting in the damage would just repeat itself, since the replacing would have to be done using the same procedures as the original construction. In the authors' opinion it is thus highly questionable whether such repairs may make things worse than leaving a limited number of broken units in the layer.

Practical experience as also presented by (Giraubel et al, 2014) seems to indicate that a limited to a low percentage of broken units, when evenly distributed, does not necessarily endanger the overall stability of the armour layer. However, broken units in an armour

layer are often a source of dispute, since it is not what the owner and their lawyers, in their interpretation and understanding, have paid for, i.e. expecting a flawless structure.

Breakwaters armoured with Cubipods® or rectangular blocks or Antifer Cubes (massive non-interlocking concrete armour units) would be easier to repair in the case of damage, as the standard repair solution is to supplement new units directly into the armour layer where there is a need of reinforcement with new units, reinforcing the toe/berm if so required.

9 Recent examples of damage to monolayer armoured breakwaters

The paper Juul Jensen (2013) presented several examples of breakwaters armoured with monolayer units where damage had occurred. The reasons for the cases presented were primarily that the units were too small relative to the waves and consequently rocking and settlements within the armour layer occurred, which triggered the damage. Since 2013 more projects with damage and broken units have come to the authors' attention, both through publicly available information and literature, as well as through involvement as expert consultant (under NDAs) in some cases. Only publicly available information is referred to in the following.

A new example with broken Core Loc™ is shown by Hendrikse (2014), see Figure 7. Here, it is apparent that the armour on the slope has settled due to wave action while the armour on the crest is in place, and a horizontal rift has opened in the armour layer.

Figure 7 Movement of Core Loc™ units with large settlements (Hendrikse et al., 2014).



Other monolayer breakwaters with damage are mentioned in literature. Giraubel C. et al (2014) present examples of damage to Accropode™ breakwaters. These examples show, in line with the opinion of the authors of this paper, that damage to monolayer breakwaters is not a rare occurrence. This, however, does not necessarily mean failure of the armour layer and structures in question.

Figure 8 shows an example where the Accropode™ type I units have been subject to significant wear and tear by mechanical action of sand and smaller rocks. It is therefore important for a project that the toe and berm are designed so that other rocks cannot move up onto the lower part of the armour layer. Sometimes armour units are displaced completely out of profile as seen in the example shown in Figure 9. It is not known whether in this case the displacement was due to bad placement during construction or due to extraction by waves of the unit from its original position. Other times armour units may be extracted completely out of the armour layer and settle on the seabed as shown in the example in Figure10.

Figure 8 Accropode™ I with unit not interlocked and wear and tear of the units from movement of smaller rocks (Giraubel C. et al., 2014).



Figure 9 Example of units displaced out of profile (Giraubel C. et al 2014).

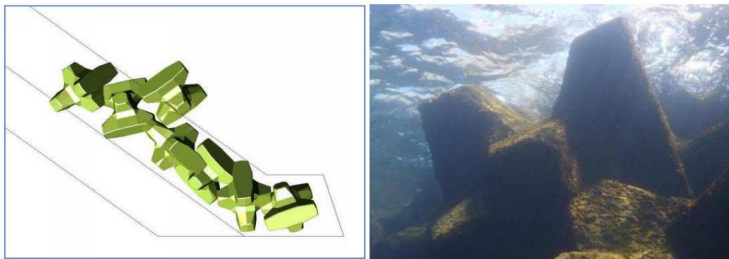


Figure 10 Example of single extracted unit on seabed (Giraubel C. et al, 2014).



Another recent example of broken Accropode™ II units is reported in press, www.clicanoo.re (2021), www.clicanoo.re (2022) and www.linfo.re (2022), and it concerns the revetment protection of the new littoral road along the north shore of the French Island, La Réunion in the Indian Ocean. The revetment is exposed to the large waves generated by the passage of tropical cyclones, up to 10 to 15 m H_s in deep water. It is reported that the revetment is armoured with about 23,000 Accropode™ II units, as well as smaller number of Xbloc® units, and that 150 units were damaged in 2018 by the severe cyclone, Dumazile (www.clicanoo.re, 2021). Further, it was reported that 775 out of the 23,000 units were not correctly placed. Recently in 2022 the island was again hit by cyclone Batsirai and according to www.clicanoo.re (2022) this resulted in the damage (breakage) of an additional ~60 units. A total of 210 broken units would represent 0.9 %, say 1 % of the total of 23,000 units. The size of the units is reported by www.linfo.re (2022) to be between 14 and 26 t. A characterization of the two cyclones based on information in the general media reveals that the two cyclones in category 4 were quite severe and offshore waves with H_s of 10 to 12 m were mentioned in relation to the second cyclone from 2022. This project is reported to have been under construction in the period from approximately 2014 to 2018, so initial damage would have occurred towards completion of construction. Nonetheless, such a percentage of broken units by two cyclones events that are not reported in the media to have exceeded design conditions, is worthy of note. This is also reflected by comments in the press from the owner and authorities regarding reliability of the structure.

10 A strategy for safer design of monolayer breakwaters

The question today is then what to do to obtain the required safety of monolayer breakwaters with armour units within reasonable cost. The authors believe that the experience of damaged structures (which seems to continue) dictates that significantly new and stricter design requirements are required, especially for large and exposed breakwaters. In the written comments to the discussions in the 2013 Conference, the following was proposed by the main author. The use of a safety factor of 1.15 to be introduced, understood in the following way:

- The factor of 1.15 should be applied on the size/dimension of the armour given in the design tables: As $(1.15)^3$ is 1.52, this means a factor of about 1.5 on the weight of the armour in connection with an upper limit to the K_D factor of say, $K_D=10$ for flat sea bed slope. However, with this design value, practical examples and experience show that if the units are large there will still be a relatively high probability that a small percentage of the units will break within the armour layer. The percentage is in most cases expected to be a few percent. If the owner/designer aim for no or very few broken units, it would be prudent to apply yet an additional safety factor of say 1.5 on K_D , which would reduce the basic design value for K_D to $10/1.5=6$. This is for breakwaters and revetments on almost flat slopes. In case the seabed is steep, and the waves are breaking, the K_D factor may need to be further reduced. The reduction of K_D from say 15 to 6 corresponds to a factor of 2.5 on increase of weight and about 1.35 on increase of size of the units.

- The same factor should be applied on the number of rows of the units which today is about 20. Hence the maximum number of units up the slope is $20/1.15$ or 17 units. Since the units are 1.15 times larger, the 17 larger units would cover the same distance up the slope as the 20 smaller units. In addition to the above points from the 2013 discussion, the following is also proposed:
 - For all types of armour units, monolayer or double, the settlements observed within the entire armour layer indicates a packing density that is rather loose, and that wave action tends to compact the armour layer that consists of large single elements. Therefore, the designer and contractor should aim for decreasing the porosity within practical limits.
 - Finally, a limit should be put to how large the interlocking monolayer units should be. The authors would personally estimate that maybe 6-8 m³ (say a maximum weight of about 16 t) should be the maximum for interlocking units.
 - As presented in the paper, there seems to be some universal traits of breakwaters and their design and in the present competitive world where many projects are made under design and build contract with ever increasing focus on costs as well as reduction of carbon emissions, the competition is fierce. Hence, if a small saving on the concrete volume can be achieved by keeping the size of armour unit to the absolute minimum and with many rows of units up the slope, it may be a decisive factor on selecting the final design and contractor. This is done despite the fact, that the design may not have the required safety for the breakwater to be in service without damage for the intended design life. Focus is more on fulfilling contractual obligations and win the job, than on providing the best long-term solution.
 - There is no doubt that monolayer units are good inventions and should be used for projects where they suffice. But for deep water breakwaters in exposed locations and with extended armour layers (many rows of armour units up the slope) monolayer units are in the author's opinion not the right choice of armour. Therefore, the designer should look for more robust alternatives with a higher safety margin and where repairs can more easily be undertaken when damage occurs – because a severe design storm resulting in some damage will eventually occur.
 - However, the total volume of concrete in the armour layer is only proportional to the $V^{1/3}$ (V being the volume of one armour unit). In other words, an increase in armour weight with 50% corresponding to a change in K_D from 15 to 10, only increases the total volume of concrete in the armour layer with 14%. It is in this context forgotten that at the same time the number of units to cast, store, transport and place in the breakwater decreases with 24%. Larger units may require larger filter/underlayer rocks, but often for the armour layer the larger volume of concrete is offset by the reduced number of units to be placed and the shorter construction time. In a specific project it was cheaper to use larger units as the breakwater could be completed in one season instead of two, which resulted in a significant cost reduction.

- The monolayer units (Accropods™ II, Core Loc™, Xbloc® and Cubipods®) are patented, and the patentees are promoting their specific unit and design. It is normally the contractor that is having the contract for the use of the patent for a specific type of monolayer armour unit. The payment for the use of a patented unit may consist of a fee for the use calculated as a fee per m³ of concrete used and a fee for other services like assistance with model tests and for inspection visits during the project execution. To the authors' knowledge, the patentees refrain by the service contract from taking any responsibility for the design for which the unit is used. Therefore, the consultant/designer for a specific breakwater or revetment design has the full responsibility for the choice of units, the size (weight) of the units, the general composition including underlayer, the concrete mix/composition and for the construction methods and procedures and further for the design basis data such as design waves and water levels etc. It is therefore very important that a designer has adequate experience and knowledge of all aspects of the use of the type of unit chosen.
- Ultimately, applying above considerations, for a relatively flat seabed (slope of 1:100 or flatter) with armour slope 1:1.5 and a maximum armour weight of 16 t, the corresponding limiting design waves H_s can be back-calculated by Hudson formula to be $H_s = 5.2$ m. This would apply to the interlocking monolayer units with high porosity over about 50%.

11 Conclusions

The paper has presented the authors' personal experience and opinions on the use of monolayer armour units. It is important to state that the opinions are entirely at the authors' own account.

Monolayer armour units are a very valid technological contribution to coastal and breakwater engineering. However, they have their limitations and are sometimes being oversold and used in less robust solutions, which may not meet the requirements or the owner's expectations at a specific site. The consequence of all this is that many owners think that they buy a perfect product without flaws and the patentees indicate that their technology has minimal or no maintenance costs - while reality often is different and broken units may and will occur.

It is the authors' opinion that each project is unique, and one should, beyond the capital and maintenance costs of a breakwater, take a closer look at the assets protected by the breakwater (or revetment) and the consequences if operations behind the breakwater need to be stopped because of damage to the structure. As consultants and designers, it is our duty to make these aspects clear to the owners, so they are aware of the risks and costs for the project in question. Likewise, merits and limitation of the use of monolayer armour units should be part of the conversation between designers and owners when considering technologies to be used for the project.

The patentees of the different monolayer armour units have prepared specifications for the use of their products. It is acknowledged that in recent years, the patentees for some

armour units have introduced safety factors that will increase the safety of breakwaters if applied; but there is no stringent and logical way for their use. Further, a uniform definition of the design waves in front of a breakwater is urgently required.

Model tests are recommended by the patentees for design verification, as these are very important to address the uncertainties related to the actual wave conditions hitting the breakwater at complex and steep seabed slopes. However, as explained, small scale model tests are associated with uncertainty as it is very difficult to observe the very small movements and rocking of units that in the prototype may lead to damage and broken armour units. In an armour layer exhibiting even limited settlements, the individual units will have moved slightly and in this process, the forces between units may be excessive and lead to breakages.

The paper presents the authors' conclusions based upon experience from damaged breakwaters and proposes a limit for the use of interlocking monolayer units in terms of size of unit (K_D value), number of units on the slope, and consequently a limit on the maximum design wave for which the units should be used. In the coastal engineering community, there is often the opinion that if the strict requirements of the patentees are followed, breakwaters can be designed and built for more severe wave conditions than those proposed by the authors in this paper. This is based on the perception that many of the damages and failures that have occurred are due to incorrect placement of the armour units. While the authors agree with the importance of correct placement of the armour units, they also believe that especially at deep exposed locations constructing a breakwater with each and every armour unit in an ideal position and placement - especially under water – is not practically possible. Further, even if all units had been placed “correctly”, the fact remains that the breakwater armour layer will have looser than optimal packing density. Hence the risk for settlements that for large units may result in armour overload and breakage remains. In the authors' opinion, the armour solutions that currently constitute more robust design options for very exposed breakwaters, often in deep waters, are:

- Double layer solutions using robust massive armour units like rectangular units or Antifer Cubes, although this means increase in concrete consumption and capital expenditure costs (see eg. Juul Jensen (2013) for examples of such applications);
- Use of Cubipod® as monolayer armour unit, see an example in Lauridsen et al (2023). Compared to the bulky monolayer units, the Cubipod® has the advantage of being a massive unit less prone to breakages due to rocking or movements in the armour layer. Additionally, Cubipod® can also be placed in two layers.

It is the authors' experience that often the patentees' promotion of their products is done with a very optimistic view on the stability and performance, thus “promising” the owner a zero or close to zero-damage solution with no or minimal maintenance requirements (designed to withstand the design wave without sustaining damage). However, the number of damaged breakwaters over the years is now so large, that it cannot be left unquestioned by our coastal engineering/breakwater profession. It is our hope that this paper will lead

to the necessary discussion among professionals, with the aim of arriving at safe and practical design guidelines that will enhance the robustness of future breakwaters, so there will be a significant reduction in the number of damaged monolayer breakwaters.

Since practical experience from construction of breakwaters is so important for the understanding of the behaviour of monolayer units, it is highly encouraged that the data and information from built breakwaters be made public for the coastal engineering community. This includes especially damaged breakwaters, but also if there are cases where the breakwater armour has been exposed to design conditions without significant damage. In particular, it would be relevant, in the aftermath of design (or close to design) events, to obtain such information from breakwaters for which specialised companies have certified that all units had been placed in an optimum way.

12 Acknowledgements

This paper recapitulates the experiences of the authors and in particular, of the main author's experience from more than 45 years working with breakwaters design at a hydraulic laboratory (DHI) first as well as a consultant with COWI A/S. By not acknowledging specific persons here, we do not risk of forgetting any. So instead, we would like to acknowledge all the colleagues, clients like owners and marine contractors with whom we have interacted over all these years and from whom we have gained important knowledge and experience on breakwaters and coastal engineering aspects. We would also like to acknowledge all the important exchange of knowledge and ideas with individuals in the academic world and colleagues in the coastal engineering community, that is so important for consultants working in the field.

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