Safety of Breakwater Armour Layers with Special Focus on Monolayer Armour Units

(Discussion Based Upon Four Decades Experience of Breakwater Damage)

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Introduction

Rubble mound breakwaters and revetments have for more than 100 year been constructed using concrete blocks of various types, shapes and sizes for the main armour layer. There has been a development from very simple units like cubes and rectangular blocks that were much used for more than 100 year. Then a major breakthrough took place by the invention of the Tetrapod in France around 1950. This was followed by many other units, of which the Dolos from South Africa in about 1963 had a major influence on the future armour unit technology. Later this was followed by the introduction of the first randomly oriented monolayer unit, the Accropode in France in 1981, again followed by the Core-Loc in USA in 1996, the Accropode II in 1999 and more recently by the Xbloc in Netherlands in 2001. The paper deals mainly with the author's personal experience from almost four decades including cases with damaged breakwaters and the lessons learned.

Summary

There seems to be a trend over many years that for new concrete armour units, daring designs are developed and constructed until breakwaters were damaged and new insight into the nature and behaviour of the particular armour units under complex wave loading was gained. For all these units (except perhaps Xbloc where no damage to the authors knowledge has occurred yet), the damage experienced led to more conservative and more safe use of the units in question. This paper presents some of this historical development and the lessons learned as experienced by the author. Based on this the situation today is assessed. The personal experience ranges from the severe damage to the Bilbao Breakwater armoured with rectangular blocks to Tetrapod armoured breakwaters, where especially the Arzew el Djedid breakwater in Algeria is an important case study.
The paper also makes reference to the most important breakwater failure in Sines Portugal; where the breakwagter armoured with Dolosse failed in 1978. More recently in the last decade, we have also seen damage to monolayer armoured breakwaters although the general rules of the inventor/patentee had been followed. These monolayer armour units are all very good and valuable inventions, but according to the author's opinion, in some cases, their use is associated with too high risk of future damage. It is the hope that the paper can assist in initiating the necessary discussion in the coastal engineering community about the safety of these breakwaters.

Brief History of the Development of Armour Units, Their Use and Breakwater Damage

Designers of breakwaters have since the 1930'ies 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 also on a "trial and error" process, where the breakwater was designed based upon limited knowledge about the wave conditions, which in many cases resulted in a too weak design. The breakwater was then repaired after damage and hence it became stronger and stronger. 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, as it can be done by adding more armour units for reinforcement and strengthening. One example of such blocks from 1930'ies is shown in Figure 1.

In the 1950'ies the use of the new armour unit, Tetrapod, took off and many successful projects were implemented. However, breakwater damage occurred for also with Tetrapods. An example from around 1979 is shown in Figure 2.

Other pattern placed armour units were developed like Tribars (1958), COB (1969) and SHED (1982). These are monolayer/single layer units. They will not be dealt with further in this paper, as the author has no personal experience in their application.

On February 26 1978, the major failure of the Dolos armoured breakwater in Sines, Portugal occurred. This was followed in 1980 by the failure of the Dolos armoured breakwater in San Ciprian in Spain. For some years these events brought much attention to the coastal engineering community world-wide. The author has not been involved in these projects, so the following is from the extensive literature on the Sines breakwater case and the then newly found knowledge of high fragility of slender concrete armour units like Dolosse ((Edge & Magoon, 1979) and (Burcharth, Full Scale Trials of Dolosse to Destruction, 1980)).

Figure 1 Example of breakwater built in the 1930'ies and armoured with large rectangular blocks.

Figure 2 Damaged tetrapod breakwater in El Kala, Algeria.

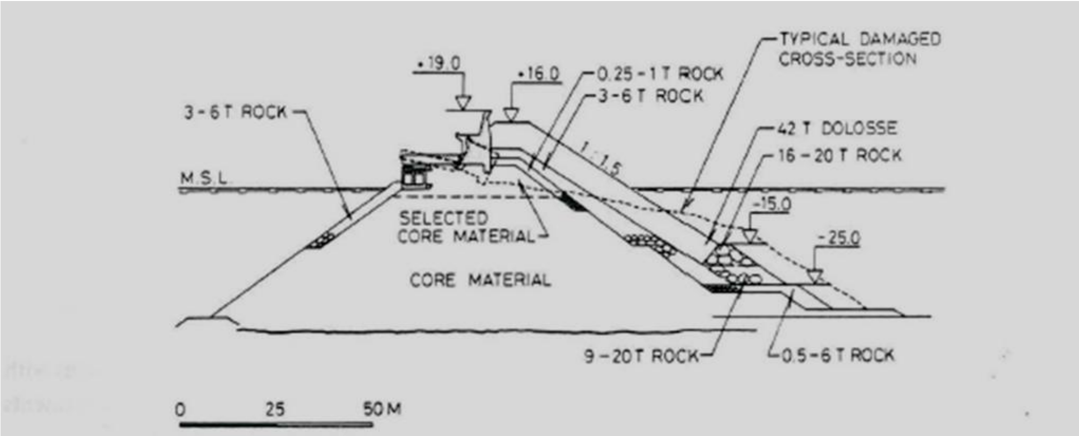

Figure 3 Sines Breakwater profile and damage (Burcharth, The Lessons from Recent Breakwater Failures, Development in Breakwater Design, 1987).

Figure 4 Sines breakwater failure seen from behind the superstructure.

The Sines failure attracted 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 breakwater was built with 42t Dolos on a slope of 1:1.5 and the design wave condition was: H_s=11m with T_p=16s. This corresponds to a stability coefficient of K_D=23.6. The severe damage occurred in a storm with H_s=9m and T_p=19s (corresponding to K_D=13). Dolos was a non-patented armour unit and not reinforced. In addition the first Dolos had a quite slender waist ratio, that was later increased The Dolosse used in Sines were about twice as big as any other units used until 1976, where the breakwater was designed. In hindsight, this was a very daring design and nature proved to the coastal engineering profession that there was a limit to the use of slender Dolosse in the harsh wave climate of the Atlantic. For the Sines breakwater as for other Dolos armoured breakwaters that failed, the limited concrete strength of the large Dolos had not been taken into account in the design. It also became clear that the construction process in reality gives a quite loose packing density and that for so high stability coefficients the Dolosse are rocking under heavy wave attack. This lead to substantial breaking of the armour units and compaction of the armour layer, especially below SWL and eventually resulted in total failure of the breakwater. It was proven, as also proven by other breakwater failures and damages that so large concrete armour units are too fragile and brittle and will break under wave loading and the armour layer settlements that happen due to the loose packing density.

In Algeria a large new industrial port, Port d´Arzew el Djedid, near Oran, was built using Tetrapods as main armour. This breakwater failed in 1981. It is 2,000m long and in 25m water depth and armoured with 20m^3 Tetrapods (two layers) on a slope of 1:1.33, see the cross section in Figure 5. During a severe storm with only about H_s=7m, the breakwater suffered very severe damage, see photos in

Figure 6. Although the breakwater is in the same water depth for its entire length and should be exposed to almost the same wave impact, the damage was varying along the breakwater trunk and also the roundheads were severely damaged. The total displacement of the armour layer in many sections lead to undermining of the very heavy and 4m thick superstructure, which was also heavily damaged, see Figure 6. Subsequent model test investigations showed that the breakwater armour layer must have been constructed with a relatively high porosity and loose packing density and that the wave impact during the storm led to compaction and settlements of the entire armour layer, see (Abdelbaki & Jensen, 1983). This must have led to the breakage of the units and hence the loss of interlocking and failure of sections of the armour layer. For H_s=7m, the corresponding K_D is as low as 5.5; so this would be regarded as safe at the design stage. It is interesting to compare with the breakwater in Figure 2, where some of the 4m^3 Tetrapods had rolled shoreward over the rock armour without breaking, while most of the 10m^3 units broke after having been exposed to the same rolling.

It became apparent for the coastal engineering profession that the forces and hence stresses in such armour units increases 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 and where the armour layer in the model would be intact after the tests. Minor rocking of a number of units and settlements of the armour layer looked innocent in the model, but in nature it would mean breakage of units and possible failure of the breakwater.

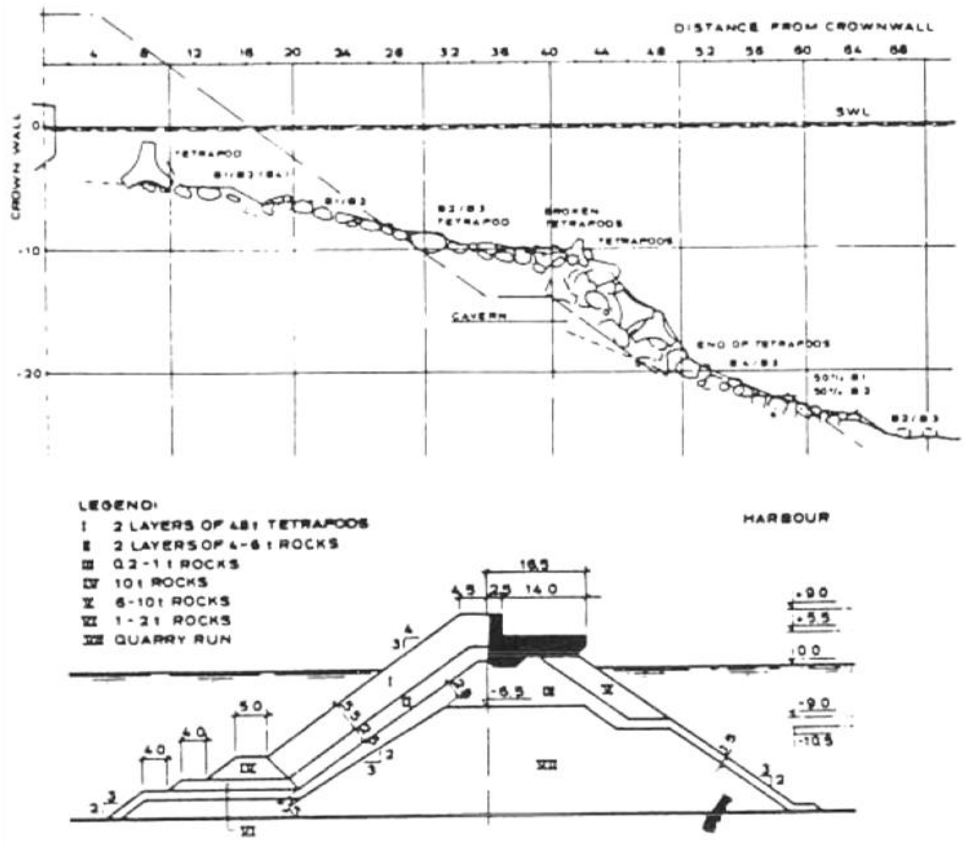

Figure 5 Arzew el Djedid breakwater cross section and most damaged profile.

Failures such as the one for Arzew el Djedid and Sines breakwaters spurred a lot of interest and became the subject for many papers and discussions under coastal engineering conferences, e.g. (Sørensen & Jensen, 1985) and (Maddrell, 2005). Studies, especially those by Professor Burcharth of Aalborg University documented the fragility and limitations of unreinforced Dolosse; see e.g. (Burcharth, The Lessons from Recent Breakwater Failures, Development in Breakwater Design, 1987) and (Burcharth, Structural Integrity and Hydraulic Stability of Dolos Armour Layers, 1993).

Arzew el Djedid and Sines and the other failures around that time led the coastal engineering profession in three principally different directions:

1. Some projects were taking up or continuing the old and well proven technology of using large concrete blocks in two layers as armouring. The author had his own experience around 1982 from the large breakwater for Puerto de Carboneras, Spain, see below. In Spain, this tradition has been continued until today and new large deep water and exposed breakwaters are with success using two layers of rectangular concrete blocks as armouring (Burcharth, Symposium Design and Construction of Deep Water Maritime Works, 2007).
2. Others continued the use of Dolosse and Tetrapods, but with significantly lower stability factors, i.e. larger armour units relatively to the design waves. One example from the early 1980'ies is the breakwater for Wudam Naval Base in Oman, where the Dolos Breakwater after hydraulic model tests where very first rocking was the acceptance criterion, was designed using K_D=9 and 6, respectively on the trunk and roundhead. This breakwater has to the author's knowledge now been in service without problems for about 30 years.
3. Others started looking into the invention of new monolayer armour units and SOGREAH took patent on the Accropode in 1981.

Figure 6 Photos of Arzew el Djedid breakwater damage. Above, most damaged sections and below, section with settlement of entire armour layer and broken units.

SOGREAH's invention of the Accropode started the use of monolayer armour units, and later on the Core-Loc was introduced by USACOE in 1995 followed by the Accropode II in 1999 and latest in 2001 the Xbloc has been patented and brought onto the marked by Delta Marine Consultants. As for the other monolayer units, Xbloc promises high stability values, K_D=16 for the trunk and high porosity and thus a reduction in the volume of concrete in comparison with any other armour unit, see Figure 12. Looking at the shape and design parameters of the Xbloc and the Accropode II, they are almost the same and one would assume that they would behave almost the same when built into a breakwater armour layer.

Bilbao Breakwater Failure, Spain

It was not only Dolos and Tetrapod breakwaters that were damaged in the late 1970'ies. A special case of breakwater damage occurred. In this, the breakwater Digue de Punta Lucero in Port of Bilbao, Spain, the author got heavily involved in finding repair solutions.. This breakwater had an armour layer of 82t rectangular blocks on a slope of 1:1.5. The armour layer itself was not sufficiently stable, but damage to the rock toe at level -10 m also contributed significantly to the severe damage to the armour. Figure 7 shows the profile of the damaged breakwater and a photo of the severe damage as seen from the port side. The toe at level -10m had 6-9 t rock and no horizontal berm. It appears in the photo how the breakwater failed and a total breach in the breakwater developed, also cutting the pipelines from the berth for super tankers to the nearby refinery. The damage interrupted the supply of crude oil by super tankers to northern Spain for some months and had serious economic implications both with respect to the costs for repairing the breakwater and the consequential damage and associated costs due to effected operation of the oil terminal. Long series of physical model tests were carried out at DHI to study the reason for the failure (Jensen, 1984). The test runs for different wave heights ranging from H_s= 7 to 11m were repeated a number of times for each wave height, and quite a high scatter was present. The model also showed that for larger waves, H_s=10 m, the armour layer failed in an unusual mode, where the toe got damaged and the entire armour layer slid down the front face of the breakwater during the action of single large wave.

Long and detailed studies followed and the breakwater was repaired using the same type of armour units, large rectangular blocks, but larger than before and on a flatter slope of 1:2. Furthermore, a proper berm was introduced at a lower level and finally the superstructure was made heavier and it projected less above the armour and would thus be less exposed to large wave impacts, see (Jensen, 1984) for further details of these studies. Figure 8 is a present Google Earth photo of the armour layer in front of the largest oil berth. The armour layer looks intact but possibly with a few spots where blocks might have been displaced.

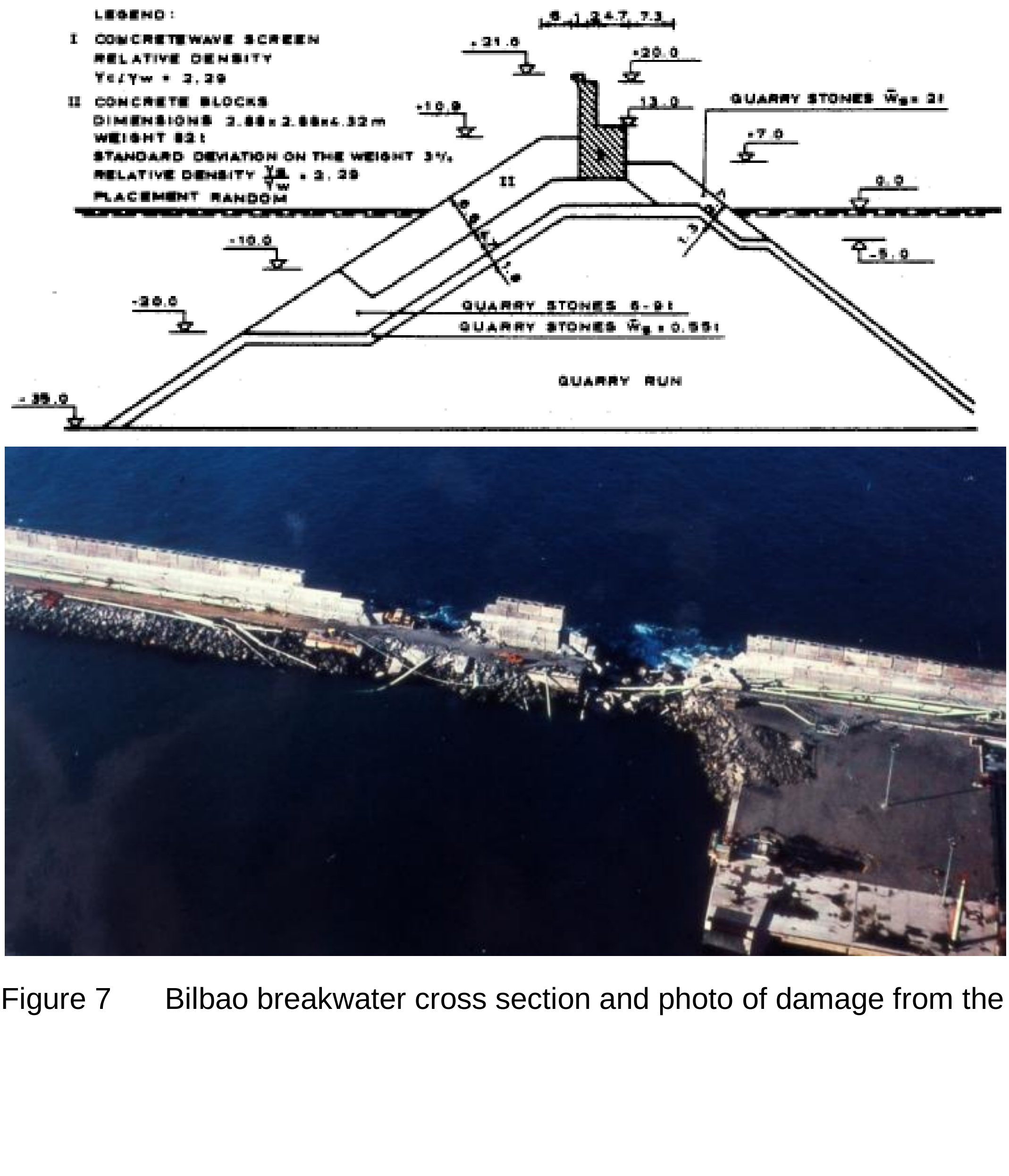

Figure 7 Bilbao breakwater cross section and photo of damage from the port side.

Figure 8 The armour layer on the Bilbao Breakwater 2013 (Google Earth).

Puerto de Carboneras, Spain

In 1981 after some of the major failures described in this paper had become common knowledge to the profession, the author got involved in the studies for a new port in Spain, Puerto de Carboneras. The breakwater protects a berth for the import of coal for the power plant seen to the left on the photo in Figure 9. At that time it was clear that there was doubt about the use of both Dolos and Tetrapods for such major breakwaters. The design wave height was about the same as for the Arzew el Djedid in Algeria on the other side of the Western Mediterranean. The author, the team at DHI and the designer, Christiani and Nielsen – Copenhagen developed a new concept shown in Figure 9.

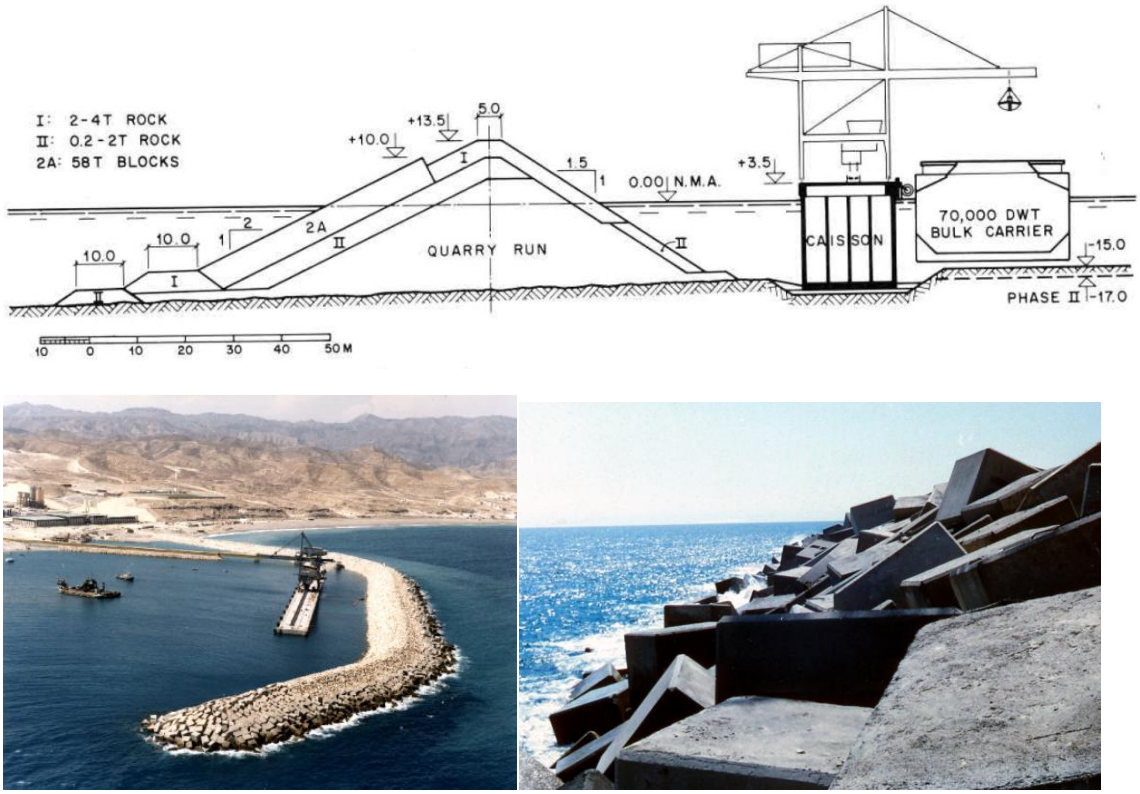

Figure 9 Puerto de Carboneras Breakwater. Cross section in deep water and photos of the port and armour layer.

First, it was clear that the breakwater had to be separated from the traffic and the conveyor belt from the berth. Therefore, contrary to other breakwaters nearby, the breakwater was developed as a pure rubble mound structure without a superstructure. As rock could be quarried in the mountains nearby, it was relatively cheap, but the size which could be obtained in large quantities was limited to 2-4 t. Therefore the crest of the breakwater on the major deep water section was made in such high level of +13.5m, that 2-4 t rock could be used on the crest and rear side of the breakwater. Model tests proved that the transition from the main armour of 58t rectangular blocks to the rock could take place at level +10m. There are two berms on the breakwater, the upper with 2-4 t rock and the lower outer/lower placed directly onto the sand sea bed with 0.2-2 t rock. The outer berm/toe is allowed to sink into the bed and form a solid foundation for the upper berm that has a 2m thick layer of quarry run underneath. The relatively small stones of 0.2-2 t were also used as filter under the 58t armour units. Model tests in 2D and 3D were used for design verification and to the authors knowledge the breakwater has now been in successful service for 30 years. This is verified by the Google Earth pictures available on the Internet.

Other Robust Armour Units

In connection with the development of Port d´Antifer in Normandy, France, a new armour unit was developed in 1973, The Antifer Cube. It is a tapered cube with grooves tapered the other way, so they could easily be cast in forms without bottom and top and easily taken out of the formwork. These blocks are robust, but there is an apparent tendency that they reorient themselves in the armour layer and form a "pavement" that is relatively smooth for wave run-up. This does not happen so easily for rectangular blocks for example with relative dimensions 1 x 1 x 1.33. When placed randomly the armour layer becomes more rough (see Figure 9) which reduces run up. Figure 10 is from Port of Zeebrugge in Belgium, where Antifer Cubes were successfully used. In comparison with Figure 9, the outer surface of the armour layer appears more smooth.

Figure 10 Antifer Cubes in the Port of Zeebrugge.

Experience with Monolayer Armour Units

Since the introduction of the Accropode as the first monolayer unit in 1981 followed by the other types of monolayer systems, several hundreds of applications have been constructed. Many successful projects have been made, but in some cases problems have occurred. The patentees and promoters claim in their material that K_D values as high as 15 or 16 applies for mild sea bed slopes (see Figure 12 below), and that model tests shall be carried out for final verification.

Many consultants are confident that if following these guidelines they will end up having a safe breakwater with long term stability. The author, when involved in designs, always attempts to limit the K_D not to exceed about 10 on the trunk of normal monolayer breakwaters.There is today, as there has always been, a tendency to get the units as small as possible with the humble ambition to reduce or limit the total volume of concrete to the absolute minimum and thereby attempting to reduce the capital costs of the breakwater. 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 often 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 stones, but often for the armour layer the larger volume of concrete is offset by the reduced number of units 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, which resulted in a significant cost reduction.

Damaged Monolayer Breakwaters

Also monolayer armoured breakwaters have suffered damage, and it appears that the stability factors and procedures previously used are in some cases not leading to safe and robust designs. It is clear that until now, the damage occurring to these projects is less severe than what was experienced previously in Spain, Portugal and Algeria, and shown in the examples above. But it is however worrying for our profession, that there still today seems to be a fierce competition to minimise the size of armour units. The examples, from nature and practical applications, shown in Figure 13 and 14 are visualising that more safety has to be built into such breakwaters.

The design of a breakwater requires a set of design data on water depth, water level and wave conditions (H_s, T_p and direction) and often the joint probability for combinations of WL and H_s is required for the design. Traditionally, the designer of a breakwater made an estimate of the wave height with a Return Period of 50 or 100 years. Such an estimate was based upon measurements or wave hindcast. However, no matter how the estimate was made, it was associated with scatter and uncertainty. Further, it did not always consider the importance of the breakwater, the value of the structures itself and the property it was build to protect, and the resulting costs if it is severely damaged or even failing. The Bilbao Breakwater mentioned above was such a case where the breakwater was under-designed, although it protected very expensive property and the berths behind were vital to the economy of northern Spain.

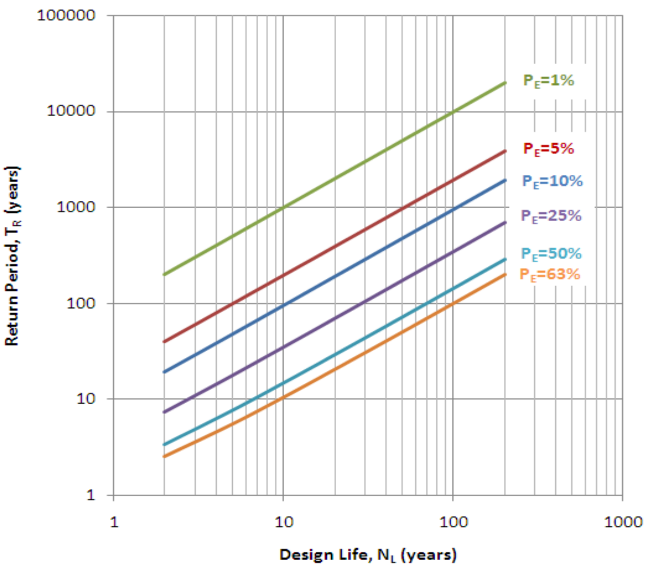

Figure 11 Relation between design life, return period and encounter probability.

The encounter probability (P_E), i.e. the probability that the design sea state is occurring during the structural lifetime, N_L, should rather be used in assessing a breakwater design instead of a selected return period, T_R. as it also includes the probability for exceedance of the design event within the defined structural lifetime of a project (Burcharth, The Lessons from Recent Breakwater Failures, Development in Breakwater Design, 1987).

Another aspect that seems not to be fully realised by all designers and owner is the very large difference in these monolayer armour units compared to the traditional rock or concrete cubes or rectangular block armouring, when it comes to the possibility for maintenance and repair. Since the stability of a monolayer breakwater depends on the interlocking between individual units, it is not effective to add new armour units directly to supplement the armour layer. Instead, it is necessary to remove the whole armour layer down to the place where the unit is missing or broken before it can be replaced with another intact unit. For other rubble mound breakwaters with rock armour or double layer concrete units, especially rectangular blocks, cubes or Antifer cubes it is possible to repair a damaged armour layer by adding new units. This difference also advocates for putting more safety into monolayer breakwaters to avoid ever having to do repairs. The promoters and their technical guidelines further mention that the number of rows of units up the slope should be limited to around 20. This is introduced to reduce the probability for settlements of the entire armour layer and the dramatic consequences of such settlements as experienced for both double layer units (Tetrapods and Dolosse for example) and Accropodes and Core-Locs. However, it is not until a few years ago that the acceptance criteria for scale model tests of monolayer breakwaters have been made severely stricter in order to reduce the risk of breaking units in the prototype breakwater. The author has during the years had several discussions with the patentees on this subject, based on the findings and thoughts presented in this paper. Model tests are always prescribed as the mean to study breakwater designs. But although the tests are using very strict criteria for displacement/rocking of units, it is suspected that there may be scale effects involved in the settlements observed in nature and model respectively.

COMPARISON OF MONOLAYER ARMOR UNITS (data for sea bed slope 1:100)					
		Accropode I	Accropode II	Core-Locs	Xbloc
K_D recommended, trunk	-	15	16	16	16
K_D recommended, roundhead	-	11.5	12.3	13	13
Example 10m^3 units	m^3	10	10	10	10
H_s max, for design	m	7.80	7.95	7.95	7.95
Block height	m	3.09	3.25	3.56	3.11
Weight (2.4 t/m^3)	t	24	24	24	24
Armour layer thickness	m	2.78	2.93	3.27	3.00
Number of units per unit area	units/100m^2	13.70	13.40	13.30	12.50
Porosity	%	50.83	54.30	59.41	58.7
Max. number of rows up slope	-	20	20	20	20
Max. size of unit in design table	m^3	28	28	11	20

Figure 12 Comparison of monolayer breakwater armour units: Accropode I, Accropode II, Core-Loc and Xbloc.

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" contracts with ever increasing focus on costs, the competition is fierce. Hence, if a small saving 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 appears to be an unhealthy practice. Some designs end up being designed for too high a probability of movement of the units, which may lead to a reduced safety for the breakwater to be in service without damage for the intended design life.

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 is in the author's opinion not the right choice of armour and the designer should look for more robust alternatives with a higher safety margin and where repairs can more easily be undertaken if damage occur – because a severe storm resulting in damage may eventually occur.

Figure 13 Example 1: Accropode breakwater with approx. K_D=15 after exposure to design event. Note broken units and openings, non-interlocking units.

Figure 14 Example 2: Core-Loc breakwater with approx. K_D=16. Note settlement of entire armour layer creating gap at wave wall and some breakage.

Conclusion

As demonstrated in this paper there is in the authors opinion a need for an open discussion on the safety of breakwaters and especially those armoured with monolayer systems. It is the authors hope that this paper will assist in initiating such a discussion.

All the experience gained over many years should be brought to the attention of the coastal engineering profession dealing with breakwater design and construction companies, clients and owners we serve. If we do not take full notice of what was experienced in the past and what has again shown up in a number of monolayer projects, the profession will end up doing too many unsafe breakwater projects, which will eventually result in increased cost for the owners.

And as I do not expect similar very severe breakwater failures in the future, but smaller incidences, it may be difficult for new generations of breakwater engineers to gain similar first hand experience. However, although there are good manuals and books on the subject that we did not have 30 or more years ago, I strongly recommend wherever possible to get first hand experience including field experience whenever possible.

Every new generation of coastal engineers should not have to do their own mistakes, since what we experienced in the past has shown ample ground for being more cautious in the design and construction of breakwaters.

Acknowledgements
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