SINGLE-LAYER BREAKWATER ARMOURING: FEEDBACK ON THE ACCROPODE™ TECHNOLOGY FROM SITE EXPERIENCE

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The single-layer technique appeared at the beginning of the 1980s, with the ACCROPODE™ unit, and is thus entering its third decade. At the time, this solution was a real innovation, reducing the amount of concrete and steepening armour facing slopes, hence reducing the volume of materials required. After three decades in use and more than 200 projects to date, it was important to summarize the lessons learned during this period and to inspect (above and below water) some of these structures in order to assess their behaviour and particularly to confirm the validity of the unit placing rules. In addition to the aspects related to armour stability, the focus has been given to the colonization by marine life of the structures, including the bedding layers, toe berms, underlayer, armour units. The purpose of this paper is to share the experience gained throughout the inspections undertaken since 2010 on structures built more than 10 years ago. A large panel of structures has been inspected, of different ages and at various locations worldwide.

Keywords: rubble-mound breakwater; single-layer armouring; ACCROPODE™ units; biodiversity

INTRODUCTION

The ACCROPODE™ armour unit, well known today, is a plain concrete unit designed to protect the breakwaters, in aiming to reducing considerably the use of material while implementing steeper slopes and a single layer of concrete units (Figure 1). Invented in 1981 thanks to the bases and knowledge acquired with the Tetrapod invented by the same engineering company in 1953, the technology is still currently used and more than 200 applications have been built worldwide. This versatile technology can be implemented on most of the projects of breakwaters or shore protections. The sizes used so far range from 0.8m3 to 28m3 to fit with every type of breakwater condition. The technology has improved since its birth, in particular on site when implementing the technique. The guidelines used today are the results of years of experience on the field and in the physical model laboratories.

Importance of single layer placing technique

All armour units have their own stability coefficient (Kd), but single-layer units owe their high Kd to the mobilization of forces generated partly by other units around them. The important factor for this force mobilization is interlocking. While Tetrapods have a stability coefficient for design purposes of 8, the new generation of units (ACCROPODE™II developed in the year 2000) has a stability coefficient of 16. Unlike Dolos, cube and Tetrapod units, which are placed in two layers, ACCROPODE™ units are placed in a single layer. It is hence vital for this single layer to remain stable in all circumstances and homogeneity must not be disturbed by design waves. This is why placing rules exist and must be respected both above and below the water level. Structures built using single-layer units are also sized to ensure “zero damage” when subjected to design waves while taking into account a high safety coefficient. With the single layers armours, constructional practices and design methods had to be adapted to be certain that this technique would be viable in the long term.

When the “single layer” technique was launched, unit interlocking was not understood by all stakeholders as being an absolute necessity strongly governing the stability of the structure. Usual safety margins at the design stage were much higher than now (oversizing was very frequent). Current practices tend to focus on seeking optimization, in particular in terms of unit size, mainly to reduce costs. At the beginning of the 2000s, practices and recommendations hence had to be adapted, in particular regarding the verification of underwater placing and the importance of unit keying. New practices were then defined and new technologies were introduced leading to improved mastery of underwater placing and more accurate checking of proper unit interlocking.

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Figure 1. Construction of single layer armouring made of ACCROPODE™ units.

Placing methodologies

In the first decade of ACCROPODE™ armouring use, most of the constructions methodologies and knowledge were still coming from the double layer armouring systems such as Tetrapods or Cubes. Most part of time the interlocking effect was either neglected or under estimated. This new technology was questioning the long experience acquired by the corporation of stakeholders in the protection of rubble-mound breakwaters. It took more than a decade to overcome these believes and start to change the uses. The consequences when placing units out of profile or not well interlocked were not well known since there was no specific prototype experimentation.

Some placing principles, such as placing according to the diamond shape (placing one unit between the two other in the row below) were understood. Placing according to the grid indicated on the placing plans was also adopted by most of the stakeholders. The grid was offering the possibility of monitoring the placing density (number of units per square meters) at all times. The cranes were then fitted with systems allowing for placing the units according to the chosen coordinates.

The randomness of the units' orientation was also understood and was guided by shifting the sling around the units in order to obtain a certain variation in the orientation of the units. Most of the crane operators at that time were relying on their own feeling they had when placing the units, observing the cable and how the load was hanging and reacting when in contact the other units.

Positioning systems enhancing

Until the middle of the 90's positioning systems were also much less accurate than those used nowadays. One of these systems consisted in welding a compass on the crane and a sort of plumb line on the boom in order to know the distance and the direction (see Figure 2). Polar coordinates for locating the units were then used while taking into account the accurate location of the center of the crane.

Figure 2. Compass frame welded on the crane (left) and frame for the vertical angle of the boom (right).

These systems are no longer in use today and digital systems with satellites have replaced the former mechanical systems. Most of the contractors use georeferenced coordinates. They allow for obtaining the coordinates instantly thanks to DGPS and RTK systems. As a result, the accuracy of the coordinates together with the new practices for the underwater placing have broadly improved both the quality and the productivity of the armour units placing.

Underwater placing techniques.

In the early eighties, the placing using coordinates systems was considered by most of the contractors to be sufficient to obtain a good placing quality. Underwater assistance for placing the units was not part of the mandatory requirements. The quality control procedures were not as efficient as they are today. Although it was recommended by the inventor of the technique, on most of the sites no system for checking the underwater placing quality was used.

Today, the technique improvements allow for the monitoring and control of the underwater placing all along the slope. Currently, most of the projects use an underwater assistance for implementing all types of single layer technologies. This assistance is usually carried out either by divers or electronic systems such as ECHOSCOPE™ or POSIBLOC™ tools in turbid waters or unsafe working conditions. Irrespective of the methodology used, the principle is to make sure that the units are properly interlocked and the armour layer strictly observes the placing rules.

Today, thanks to the most enhanced technologies and methodologies, it is possible to master the placing of the units at all times when placing and afterward.

Objectives of the inspections

Given this long historic process and evolution of the construction techniques, it was considered relevant to gain feedback about the breakwater single layer armours from site inspections. Priority has been given on three frequently asked questions by designers, builders and owners: is the rock toe reinforcement necessary? Is there a need under water assistance for placing the single layer units? Does marine life settle on these structures? In order to help answering these questions, it was decided to perform inspections on old ACCROPODE™ structures. This paper presents the inspection methodology and the observations made on the abovementioned three aspects.

INSPECTION METHODOLOGIES

In order to collect a maximum of pieces of information and analyze the state of the structures many years after their construction, several inspection campaigns were performed in 2012 and 2013. The inspections were conducted by the first author, expert in single layer technique and diver. The chosen structures are ACCROPODE™ armoured breakwaters built more than 10 years ago. The construction methodology was taken into account for the choice of the structures in order to identify if the use of underwater placing assistance had a visual impact on the armour units placing quality.

A total of eleven structures at different locations worldwide were inspected during this campaign (see Figure 3). The choice was also governed by the need to identify different types of environments such as warm and cold waters. It was then identified three zones with several structures to be inspected in a limited area. Four structures were inspected in the Caribbean area, fives structures in the northern side of the Mediterranean sea (South of France and Spain) and one in the Indian ocean as shown in the figure below.

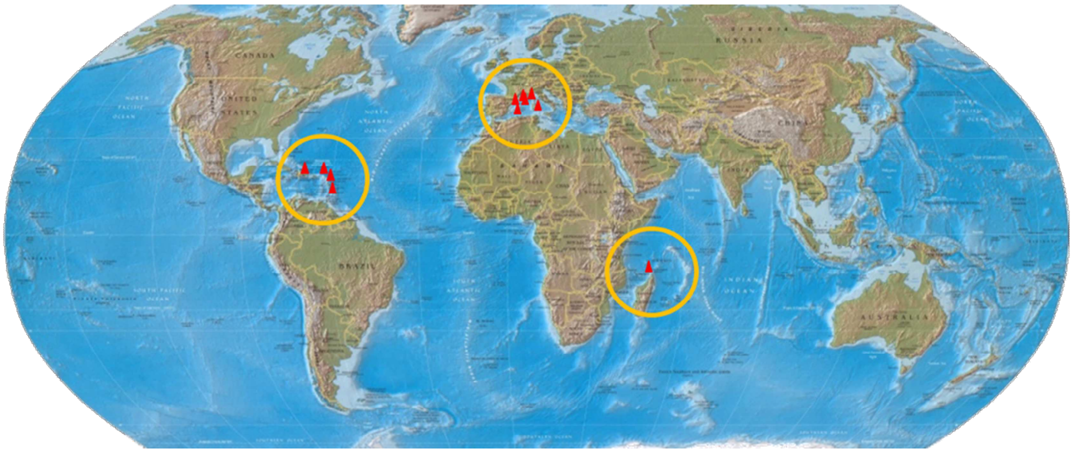

Figure 3. Location of the eleven inspected structures.

The inspections focused on the state of the units, their geometry, the pathologies observed on the concrete exposed to marine environments as well as the general behaviour of the armour layer. Eventually, part of the inspections was aiming to make observations on the biodiversity on and around the armouring in order to collect data regarding the possible future adaptations for increasing the biomass related to these structures.

STABILITY OF THE STRUCTURES

Assessment methodology

Visual inspections were performed above and underwater with a limited intervention procedure as the inspections were aiming at having a general opinion regarding the condition of the breakwater. There was no point in detailing the aspects related to the units placing nor in making an exhaustive list of defects encountered on the armour layers. In this context, the structures were not entirely inspected and for some of the longest one, parts were inspected only, considering their size. Most part of the time one or two dives maximum were performed for each structure. The general framework of the inspections was as follows:

- Data collection regarding the construction and the design
- Visual inspection from the crest
- Visual inspection from a light boat for the emerged part of the armouring
- Visual inspection by scuba diving

These four steps were followed for each structure. However, for some them it was not possible to access the top of the crest for safety and security reasons. Different parts of the structure were inspected such as the typical sections, bends, round head, crest and toe reinforcement. The following items were considered during the inspections:

- Conditions of the units (visual aspects)
- Armour layer profile.
- Armour layer integrity.
- General randomness of the armour units.
- Visual density and interlocking of the units.
- Armour unit extraction.
- Broken armour units.
- Evidences of motion, sliding.
- Toe reinforcement condition

Results of the observations

The conditions of the inspected armour layers are very varied. Some of the armour layers were found to be in bad condition, with varied levels of damage. Other structures are in very good condition.

Summary of the observations made on the structures in good condition

A certain number of similarities were observed between the breakwaters in good condition. The armour units themselves are mostly in good shape and the concrete does not show major signs of deterioration. The units are generally more worn out when located around the sea level, where the action of the waves and dry/wet alternating cycle is continuous. The armour layers are in a correct alignment. There is no evidence of misalignment of the armouring, see example in Figure 4.

The units are contained within a single layer envelope and very few units are slightly out of profile. (A unit is considered to be out of profile when it is more than 1/3 of its size out of the mean alignment).

The armour layers do not present any major loss of packing density where gap could have been seen. The units are still fairly interlocked with each other (exceptions have been seen, but most of the units are interlocked). The basic “diamond shape” pattern is generally observed (leading to one unit interlocked between two units of the row below), but not systematically. Through the year and thanks to this diamond shape arrangement, the units have not formed “columns” of units along the slope. The diamond shape acts as a spring allowing for the units to re-arrange themselves without creating arcs or bulbing profiles. Randomness of units placing is generally present, but it is not always the case in all areas of the breakwaters. Some areas present lots of similar unit orientations, but this does not seem to strongly affect the stability of the area. The units remain well interlocked even in this case and after several decades on these positions. Through the years and under wave action, the armour units tend to flatten their orientation (axis of the noses becoming vertical). This is also due to the initial placing carried out in the early eighties when the units were placed more systematically with the axis of the noses slightly vertical.

Figure 4. Le Frioul breakwater, in the South of France, built in 1984.

Very few units were found to be extracted out from these armour layers. Some have nevertheless been seen. It was not possible to identify where the extracted units were coming from in the armour layer as no obvious scars were visible. It was not possible either to determine if these armour units were extracted after the completion of the construction or during the construction itself by misplacing the units. Very few units are found to be broken. The condition of the structure’s toe reinforcement with rocks was observed to be efficient and prevents the units from moving away. The first row of ACCROPODE™ units is generally well locked in the trench or by the rock toe reinforcement. The placing of the armour units was correctly carried out by taking into consideration the importance of the interlocking above and below water. For example, the port of Port Bou completed in 1998, was built with the help of divers and it is clearly visible when inspected the structure that the interlocking of the units was a priority. This structure was significantly impacted by storms (see Figure 5, left) during its construction and since its completion. However the structure is still is good condition (Figure 5, right).

Figure 5. Storm during the construction of the Port Bou site (left) and Port Bou after completion (right).

Summary of the observations made on the structures in medium or bad conditions

The inspections carried out on these armour layers have revealed noncompliance with the basic principles of the technique. However, it is important to underline that none of these breakwaters have failed.

Structure of the concrete units

The units themselves are generally in good condition. Concrete issues are not the main cause of the damage reported on the breakwater, but they tend to increase the level of damage when they are present. Other causes are generally the starting points of damage than the deterioration of concrete.

Some of the structures present significantly worn out concrete units. The most frequent problems observed are an alteration of the cement past and aggregates (Figure 6). The shape of the units can be significantly modified due to the concrete problems. Some of the units have lost a large part of the cementitious paste that fixes the aggregates. On the opposite, it was noticed some of the units were losing aggregates. These aggregates tend to melt because of the sulfate attacks, sun and dry/wet cycles (Figure 6, right).

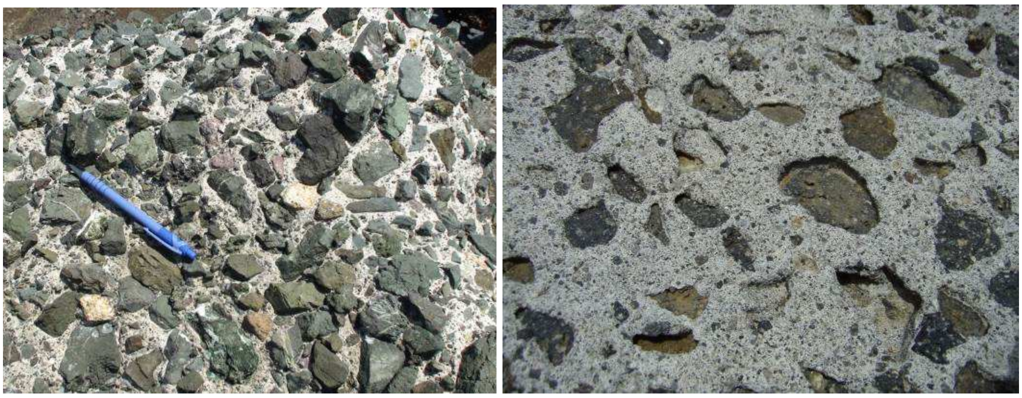

Figure 6: Concrete degradation: loss of cement past (left) and aggregates melting (right).

Most of the concrete alterations are believed to be the results of significant and repetitive movements. Most of the reported damage is believed to be caused by mechanical action rather than chemical action induced by the sea water. The armour units can be rounded and sharp edges have mostly vanished. Such action can be caused by the sand and small rocks moving continuously around the units It was the case for the former Grand Rivière port built in the 80’s (see Figure 7, right).

Such alteration can also be the result of low of packing density. When the interlocking is not sufficient, the units may be subjected to move. If these units are rocking continuously, they become worn out and scratch on the other neighboring units. As a result, the units loose small pieces of concrete and tend to be rounder (Figure 7, left).

Figure 7. Unit not interlocked, rounded shape (left). Units worn out by mechanical action of the sand and small rocks projected by the waves (right).

Interlocking factor and packing density

Several of the inspected armour layers suffer of loss of packing density. The interlocking is locally poor and some of the units are free to move. This effect was generally noticed in restricted areas only and not on the whole structure. None of the inspected structure was displaying a general loss of packing density. However, some of these areas were quite widely spread over the structure and are subjected to extend again as the connection between the low packing density area and the satisfactory interlocking area is not locked. Interlocking remains one of the key factors for the stability of the layer.

One of the common point between the armour layers in bad condition, is that they suffer of lack of interlocking between the units. The orientation of the units is generally not optimum to allow an efficient interlocking and many units can be found extracted.

Units out of profile

Out of profile units were observed on several structures (Figure 8). These units are not correctly interlocked and they do not really participate to the armouring stability. In most cases, such types of defect will end up with the extraction of the units (see Fig 9). In most cases such defect is not believed to be the result re-arrangement of the units under wave action, but clearly the results of misplacing at the construction stage. The main cause for producing such misplacing is the absence of underwater assistance when placing. Most of the armour layers placed without a proper underwater assistance present obvious lack of interlocking. In spite of remaining within the armour layer these units are generally found not to be interlocked enough with the other units. As a result, they are not linked enough and are subjected to rocking. At final stage, they are extracted.

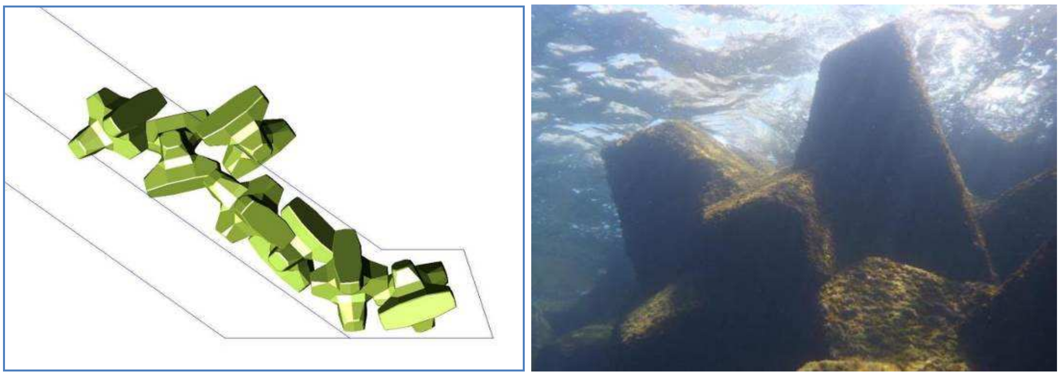

Figure 8. Units out of profile.

Extracted units

On several breakwaters, extracted units have been observed. Their number is variable from one to several units and sometimes they have been observed in groups. The extraction of one unit does not systematically imply major loss of density and damage. It was observed that the gap left by one unit is sometimes self-healed, and sometimes not. Such evolution depends on the interlocking and the possibility of the units above the gap to re arrange themselves and fill the gap. Surprisingly the units located around the gap do not systematically show evidences of movement. They seem not to having moved at all and the gap is still there. The underlayer is sometimes clearly exposed, but no sign of underlayer rock extraction have been seen on the inspected structures.

In some cases, several units have been found extracted. It has been observed several single units extracted along the breakwater but also groups of extracted units. (Figure 9, right). The armour layer where these units have been extracted are generally significantly damaged as the low packing density also leads to some units' breakage as explained above.


Figure 9. Single extracted unit laying on the seabed (left), group of extracted units (right).

Toe units stability

In the first decade of use, the code of practices did not mention the necessity of a toe reinforcement made of heavy rocks in front of the first row of concrete units (Figure 10). After several years of use, and considering the potential unstability of the first row in case of settlements, it was recommended to buttressing the first row of armour units with rocks. This issue was not predictable earlier since the feed-back from the site was very poor and no issue at the design stage was seen. Physical modeling tests did not show significant impact on the armour stability in case of absence of toe reinforcement. This practice allows to minimizing the adverse effects in case of construction defects when placing the first row of units. When the interlocking between the first and the second row of units is efficient, the units of the first row remain stable in many of cases. However, this wise practice is an additional safety for the long life of the structure (settlement of the armouring, settlement of the underlayers), until new enhanced placing methods or toe alternatives are defined.

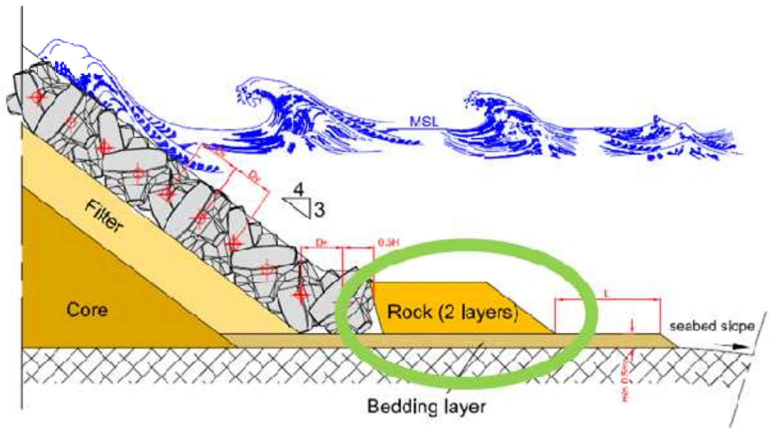

Figure 10. Basic principle for rock toe reinforcement.

The inspections have confirmed that the unsupported units can tilt over and become disconnected from the armouring. On several structures, the first row of ACCROPODE™ units was found to be no longer in contact with the rest of the layer (Figure 11). Therefore, the armour layer remains unsupported by the toe units and is sometimes “hanging” above the first row without touching it. It was not possible to determine when the isolated first row of units was extracted (at the construction or afterward). Such disconnection can take place when placing the second row of units, under storm conditions, or later when the lower layers (bedding layer for example) settle. The inspections have revealed that, the contact between the rocks and the first row of units is important to secure the units and prevent them to move away or tilt over. Specific attention is to be paid when placing the rocks in contact with the concrete units.

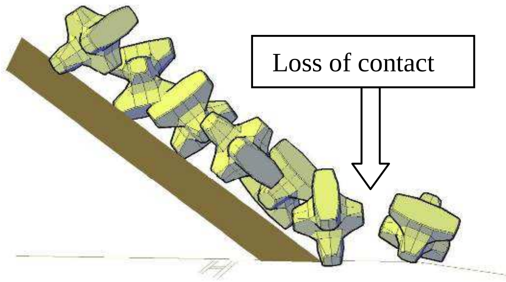

Figure 11. Example of disconnected unit at the structure's toe (left) and illustration of the disconnection of the first row of units (right).

MARINE BIODIVERSITY ON THE STRUCTURES

Assessment methodology for the observations

Basic principle

The principle for the observations regarding the biodiversity was to collect as much data as possible regarding the colonization of the structures, by marine life including the concrete armour units, the toe berm, the bedding layers and the vicinity of the structures. The observations were not aimed at analyzing into details the organisms which have grown on the units or living in the surrounding, but to obtain a qualitative overview of the flora and fauna living around. In order to do so, light explorations have been performed by scuba diving on the different breakwaters for collecting data.

In order to have an overview of the colonization of the structures, it was decided to make a difference between warm and cold waters. A choice of structures has been made taking into account this parameter with the aim of obtaining various examples of biodiversity. Hence direct comparison between the structures cannot be done, but here again, the goal was to highlight some similarities or difference when possible.

Methodology for the inspections

The inspections have been conducted either by transects or by static station for observing the fauna and flora. Depending on the size of the structure, similarly to the observations carried out for the structure stability, parts of the armouring could be observed only. The observations were always starting from the natural environment around the structure. An inventory of the species present around the structure was carried out. Then the bedding layer was inspected (when present), followed by observations on the toe reinforcement and the armour layer underwater. For the deeper water structures the total height of the armouring was split in several zones, since there are significant differences in marine growth depending on the depth. For the shallower structures the differences in terms of colonization of the armour layer along the slope were limited, hence only one or two areas were considered. Photos and videos were recorded in order to identify a posteriori the observed species. As an example, Figure 12 below shows the areas that were inspected on the Le Frioul breakwater (France).

Figure 12. Inspected areas on the Le Frioul breakwater.

Summary of the observations

All of the inspected structures have been colonized by marine life at different levels. Colonization levels not only depend on the age of the structure but on a variety of additional factors.

Vicinity of the structures

The inspected structures were built on various substrates. Some of the structures are located in sandy areas where the local biomass is limited, whereas some are located near coral reefs where biodiversity is very important. Several breakwaters are close to sea grass areas such as the protected posidonia in the Mediterranean sea or other types of sea grass (e.g. *Thalassia Testudinum*, Figure 13, right) in the Caribbean waters. Protected and rare species have been reported next to some of the structures. For example, in Le Frioul islands next to Marseille, *Posidonias Oceanica* and giant nacres (e.g. *Pinna Nobilis*, Figure 13, left) have been observed right at the bottom of the breakwater. Some breakwaters are built next to coral reefs, such as in the south of Dominican Republic or in Mayotte Island. The seabed is covered with small corals and cnidairae such as sponges. In both cases, there is a real discontinuity in terms of marine life colonization between the natural and the artificial environment created by the breakwater. As a first observation, the breakwater acts either as an attractive shelter for marine species or on the opposite remains totally artificial and poorly colonized. The differences in marine life between the natural and the artificial environment are more obvious on the sandy areas, where the number of species and taxons varies a lot. This is far less the case when the structures are placed on a coral reef. The figures here below are two illustrations of environment found during the inspections.


Figure 13. *Pinna Nobilis* protected species close to the Frioul brekwtater (left), surroundings of the Bellefontaine terminal (right).

Bedding layers

The bedding layers are generally widely colonized by marine organisms in cold and warm waters. They are generally made of smaller stones (from grams to 50kg) lying directly on the seabed. They offer a wide range of habitats where fauna such as echinoderms, fish, crustacean can hide. Small benthic organisms are highly represented and sometimes much more than in the structure surrounding. However it would be meaning less to compare strictly sandy areas and bedding layers as they are totally different habitats and do not shelter the same species. It can nevertheless be said that for sandy areas, the number of taxons identified in the bedding layer is much higher than in the natural surroundings. This is the case for instance of the breakwater of Pointe Rouge in Marseille. This is also true for smooth rocky natural sea-beds, such as in Le Frioul breakwater on each extremity of the structure. On the opposite it was noticed that the bedding layers was sheltering less species than the surrounding when built on a coral area.

Bedding layers seem to offer more shelters than any other part of the structure for numerous species. Lot of juvenile organisms, (mainly represented by fish and crustaceans) are present in this part of the structure. Small predators also hide in the bedding layers holes such as morays and groupers (Fig 14) For an example, the breakwater of le Frioul is an interesting case since toe berm at the bottom of the structure made of smaller stones is highly colonized by marine organisms. Complex ecosystems have settled and developed on these small rocks. Complete trophic chains are present on the Frioul breakwater, from the pioneers organism producers and different levels of predators. Small species of groupers come to feed on the marine organisms present on the rocks. They can find both shelter and food.

Figure 14. Grouper on the basement in Le Frioul, South of France (left), moray (*Gymnothorax Moringa*) in Saint Martin in the French Caribbean (right).

Toe berm reinforcement

Toe berms reinforcement is generally made of larger stones than bedding layers from hundred kilos to several tons. They offer larger gaps than those found in the lower layer. Larger animals have colonized these areas, but they are still mostly juvenile individuals. The same species are generally present in both bedding layers and toe reinforcement. Larger individuals than those found in the bedding layer are present in this toe berm. The number of fish or small benthic organisms is much less than in the bedding layer. This is mostly due to the fact that, the toe reinforcement is generally more impacted by wave action and currents than the bedding layer. All of the inspected toe berms have very different levels of colonization depending on their location and/or exposure to wave action. For rocks moderately to significantly exposed to wave action, the number of species is very limited. Run-up and run-down induce severe loads which prevent small organisms to fix to the rocks.

The inspected toe berms in the Mediterranean Sea are mostly covered by algae and chlorophyts (Figure 15, right). Small benthic organisms feed on these sea weeds as well as fish. The structures in the Caribbean waters are mostly colonized by fans, sponges, corals (Figure 15, left).

Figure 15. Toe reinforcement in Case Pilote (Martinique) (left) and toe berm reinforcement rocks in Pointe Rouge covered of algae (south of France)(right).

Armour layer

Artificial armour units are obviously located in the most exposed areas in terms of wave exposure. Hence, conditions for marine life to settle and grow are not optimal. Several zones were identified on the armour layers considering their exposure to waves. Sun light is also a parameter influencing significantly marine life in these areas. Such differences induce large variations between the different parts of an armour layer in terms of habitat and colonization. As a general statement and irrespective of the location, the single layer concrete armouring is less colonized by marine life than the bedding layer and the toe reinforcement. The armour layers present much larger gaps, which can barely be used by juveniles to get protected from their predators. Larger individuals and species have been observed between the artificial concrete units. Predators, like grouper or travelly, use these large gaps for hiding and hunting. As a consequence, juveniles do not remain in the armouring except in large groups.

Few crustaceans or echinoderms have been seen in comparison to the toe reinforcement and the bedding layer. They are not totally absent but less represented. Most of them are urchins feeding on the seaweeds grown on the units. The inner side of the armouring is poorer comparing to the external side of the armour layer. The underlayer of these armours layers was expected to shelter many species of marine organisms, but the shade provided by the armour units prevent most of the organisms to develop.

In the colder waters, all of the visited armour units have a thick layer of cholorophits on their exposed faces to the sunlight. The others faces in the shade, are mostly colonized by cnidarae such as sponges, small corals, anemones see fig 16 on the right side. Starfish, octopus, nudibranches, gastropods use the lower faces of the units during the day and leave for finding food at night. On several inspected armour layers, mussels have grown next to the water level see Fig 16 left side. The units act as favorable support for the larvae to settle, but they mostly are small individuals. Fishers and mussels grower frequently come to collect small mussels.

Figure 16. Mussels on the armour unit (left) and Shaded face of an armour unit colonized by anemone in the South of France (right)

In warmer waters, armour layers are generally less colonized than the toe reinforcement and the bedding layer. The armour units are less covered by sea weeds, but corals have generally found with the units a good support to grow. Coral colonies have been observed on all of the inspected structures located in warm waters. Soft and hard corals have been observed as well as spongiaridae developing directly on the concrete units. The spongiaridaes are differently represented on a given structure, in function of their exposure to the waves. Massive corals can develop in the most exposed areas of the breakwater apart from the run up/down zone. The extension of the area colonized by corals depends on the continuous agitation of the waters. Most of the structures do not present any or very few species of corals between 0 and -2m. However when the normal agitation is low, coral can grow next to the water surface and develop much better than other places on the armour layer by looking for sunlight close to the sea level. It is the case for example in the structure or Le Marigot in Saint Martin where large *Accropora Palmata* coral colonies (Figure 19, right) have been observed. Some of these colonies grown on the armour units themselves are larger than 2,5m in diameter at a depth of 1.5m below the surface. In these two areas (Bellefontaine and Le Marigot), the daily agitation is very limited. This allows corals and sponges to grow as it was observed at Bellefontaine Terminal, see Figures 17 and 18.

Figure 17. Soft and hard coral colonies at St Martin, 2m in depth (left) and colonization on the first row of units (5m depth) at Bellefontaine terminal.

Figure 18: ACCROPODE™ units covered by corals and sponges in Bellefontaine (4m in depth).

In some of the inspected sites like in the south of Dominican Republic, corals have developed below -3m because of wave agitation. Almost no coral colonies were observed on the range between the water level and 3m in depth. Most of the colonies have been observed from -3m to -12m. Examples of coral colonies are shown in Figure 19.

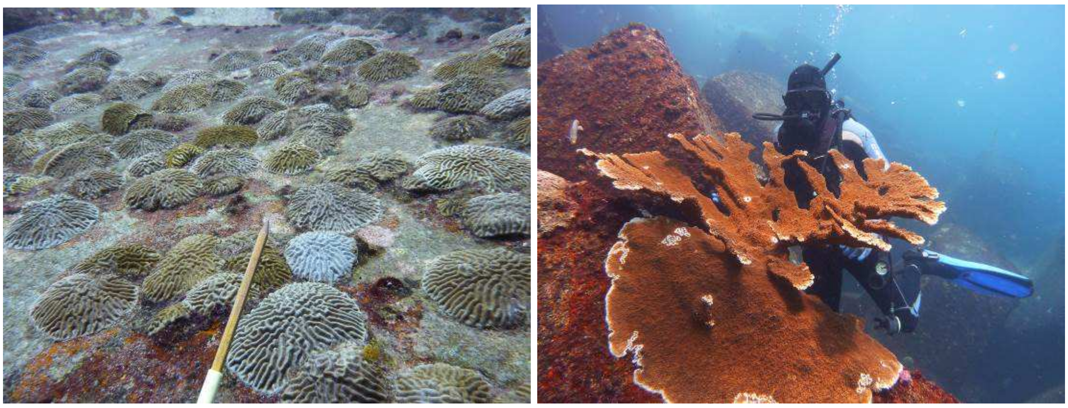

Figure 19: Massive corals at 10m below water (left), *Accropora Palmata* (right), both in Dominican Republic.

One exception however, in the lagoon of Mayotte, the protection of the airport made of ACCROPODE™ units was found to be poor. Very few species of marine organisms have been seen during the inspections. On the concrete units, few oysters have settled only. There is no toe reinforcement and no bedding layer as the armour units are directly placed on top of the shallow coral seabed. The tidal range is such, that the entire layer is emergent. In front of the structure a 5m wide strip of natural seabed looks lifeless whereas at 10m from the toe units, sea weeds, corals, several taxons of fish, crustacean are present. Green turtles have also been observed feeding around the structure.
This is probably the poorest structure seen during these inspections in terms of biodiversity whereas the surrounding environment is more than favorable. The lagoon of Mayotte is one of the richest in the world. The location of the structure, the effects of the waves on the seabed which seems to be continuously impacted, as well as the tide effects are probably amongst the reasons that explain this particular condition.

CONCLUSIONS

Stability aspects

The inspected structures are in very different conditions. They were built using different constructing methods and the local wave climates are different, it is therefore difficult make direct comparison between them. The structures that have been properly designed and built according to the technology rules are generally in good conditions in spite of the years and the storm events that may have impacted them. This suggests that, when the technology is applied properly, the single layer systems are efficient and reliable.
The structures which are in the best conditions are those where the underwater placing has been properly monitored, controlled and implemented thanks to underwater assistance. Constructing a single layer armouring without underwater assistance for controlling the interlocking and positioning of each unit leads to questioning the future stability of the protection. For the structures built without underwater assistance, the most important placing rules are generally not fulfilled. Units out of profile or low interlocking have led to extractions. When these extractions are taking place in group of units, they are likely to destabilize the armour layer. Single extraction does not systematically leads to the failure of the structure, but it must be considered a significant warning. The lack of placing randomness under certain conditions will not affect the stability of the layer. The above suggests that care should be paid to the main placing rules: interlocking efficiency, packing density and underlayer quality. A correct packing density prevents the units from rocking and being broken when rearrangement takes place. However, density must not be dissociated from interlocking: both are working together for the armour layer stability. Hence it is essential to make sure that the underwater placing complies with the basic rules.
The toe reinforcement (rock toe berm) is an essential element for the stability of the armour layer. The toe berm prevents the first row of units to be disconnected from the upper rows. As seen during the inspections, if interlocking is limited between the first and the second row, there is a significant risk that the first row units tilt over and get disconnected. The behaviour of the armouring is therefore uncertain. The stability of the toe is thus to be verified. In the cases where a rock toe reinforcement cannot be implemented, a trench or an embedded toe should be preferred.

Biodiversity aspects

Large differences of colonization by marine life of the structures have been observed. Time makes obviously a difference between the colonization levels, as larvae which settle on these structure need time to grow. Natural seabed, water quality, wave exposure and other environmental factors seem also to have a significant influence. The inspections have also shown that marine life colonization is not homogenous in the different parts of each structure. The quantity of observed species and taxons is much greater in the lower areas (toe) of the structures as far as these areas are not damaged or covered by sand for instance.

One factor that seems to significantly influence the structure’s capacity to attract marine life is the presence of small rocks forming a bedding layer at the structure’s toe. The bedding layers have been found to concentrate most of the species observed on the breakwaters, especially when built in sandy areas. To a lower extent, the rock toe berms also provide shelter to many species and individuals. The armour units themselves do not seem to offer many opportunities of sheltering for small fish to hide, since the wide interstices are often occupied by larger predators using them as hunting places. The number of species present in the armouring itself also seems to depend on the quantity of species settled in the lower areas such as the bedding layer.

General conclusions

The inspections have confirmed that the new design and construction practices set in force for both toe reinforcement and underwater assistance are essential for the armour layer stability. As a consequence, these practices must be taken into account by designers and contractors for ensuring a satisfactory behaviour of the armouring. Several aspects of the constructing methods have a significant beneficial or adverse impact on the future stability of the breakwaters armouring. They must be carefully analyzed by all parties in order to make sure that the required quality will be achieved.

The collected data related to the biodiversity is still insufficient to draw major conclusions on the possibilities to adapt the structures in order to attract and settle more marine life. A gradation of the shelters’ size, providing food, shelter and reproduction areas, is favorable to marine biodiversity. Increasing the number of varied shelters sizes in order to increase the diversity of the habitats would also help in increasing the biomass and set up long term trophic chains.

The inspections carried out help understanding where and why marine life settles on these structures, and identifying favorable/unfavorable factors for the settlement of marine organisms. New inspections should focus on a quantitative assessment of the species and individuals, in order in particular to analyse the density of species and individuals in the different parts of the armouring. This would help determining on which part of the structure particular attention should be paid in order to attract more marine life. This might eventually lead to adapting the designs of the single layer breakwaters and introduce new design practices, as already done for instance for the construction practices.