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THE CHERLOC PROJECT: AN EXPERIMENTAL CASE STUDY OF MARINE STRUCTURES COMBINING ENGINEERING AND BIODIVERSITY

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ABSTRACT

A topical issue for coastal structures is the development of innovative solutions combining functional requirement and ecological improvement. The CHERLOC collaborative project seeks to meet engineering design needs for coastal structures while preserving the ecological habitat of coastal areas and develop biodiversity on marine infrastructures. The aim of the project is to perform in-situ coastal protection experiments designed via a cross-disciplinary engineering, biodiversity and societal approach. Two pilot sites were set up in the Normandy region Ouistreham and Cherbourg. The Cherbourg site involved the installation of new artificial concrete block armour along a damaged trunk section of the existing Eastern port breakwater. These blocks are more specifically a new block armour known as “Double-Cube (DC)” and a new generation of toe blocks called ACCROBERM™ II, which are designed to replace “classic” toe rocks and limit direct and indirect environmental impacts. The design aimed to achieve a limited footprint on the seabed and an enhanced cavity. This paper gives an overview of the design conditions of the experiment, details the construction aspects of the pilot site, and points out the first lessons learned and the outcomes regarding stability and biodiversity surveys after more than one (1) year of the experiment.

1. Introduction

An increase in the use of rigid marine structures to replace natural structures leads to several unwanted environmental impacts (Bulleri and Chapman, 2010; Chapman and Underwood, 2011; Firth et al., 2014; Floerl et al., 2021). Artificial structures are usually built from manmade materials, affecting ecological colonisation (Bulleri and Chapman, 2010). Indeed, hydraulic conditions and constraints on the sourcing of materials frequently imply the use of concrete blocks instead of natural rocks (Giraudel et al., 2022). According to Moschella et al. (2005), a lack of complexity may be a key factor in the settlement of artificial structures, and this is thought to be the reason for low biological diversity in this kind of substratum.

Coastal hardening processes of this kind, although difficult to reverse, can be mitigated through ecological engineering. The current trend is to aim for a combination of improved structural sustainability/efficiency and ecosystem development (Firth et al., 2020). Coastal engineering is thus required to consider environmental aspects at the same level as technical needs. A topical issue for coastal structures is how to develop innovative solutions that combine functional requirements and ecological understanding to provide cost-effective ways to maintain or enhance biodiversity (Floerl et al., 2021).

Ecodesign aims to stimulate a new reflexive approach to works requiring intrinsic enhancement of nature in order to reduce ecological losses on pre-existing species, habitats and ecological functionalities (Pioch et al., 2018, Salgues, et al., 2020). It consists of integrating environmental objectives into the technical design of a structure so that it provides useful functions for biodiversity. To do so, it is important to know the natural processes of colonisation by marine organisms in natural habitats in order to compensate for the absence of these sometimes observed on artificial structures (Firth et al., 2014). In practice, incorporating physical heterogeneity at a range of spatial scales offers the greatest potential for improved coastal engineering (Coombes et al., 2015). Small (<10cm) and medium (1-10m) scale changes provide important refuge for many species (Firth, 2014).

To this end, the CHERLOC collaborative project seeks to meet the engineering design needs for coastal structures while preserving the ecological habitat of coastal areas. The aim is to perform in-situ coastal protection experiments using artificial blocks in a cross-disciplinary engineering, biodiversity and societal approach.

2. The CHERLOC Project

The CHERLOC project involves six French partners (ESITC Caen, ARTELIA, MARC SA and the University of Normandy via three laboratories M2C, BOREA, CERREV) working in a consortium of coastal engineers, marine structure specialists, marine biologists, social experts and a contractor. The CHERLOC collaborative project seeks to meet engineering design needs for coastal structures while preserving the ecological habitat of coastal areas. The aim is to perform in-situ coastal protection experiments using artificial blocks in a cross-disciplinary engineering, biodiversity and societal approach.

Two pilot sites have been set up in the Normandy region, i.e. Ouistreham and Cherbourg (Figure 1). The new artificial blocks used a part of a new generation of armour blocks called “Double-Cube (DC)” and a new generation of toe blocks called ACCROBERM™ II, designed for coastal structures and breakwaters and to replace “classic” toe rocks and limit direct and indirect environmental impacts.

The project began with baseline surveys on both pilot sites and 2D physical modelling to verify the hydraulic stability of the blocks and finalise the block arrangements to be adopted on the sites. The 2D tests were performed for different block arrangement configurations and extreme wave conditions up to a 100-y wave event (offshore wave

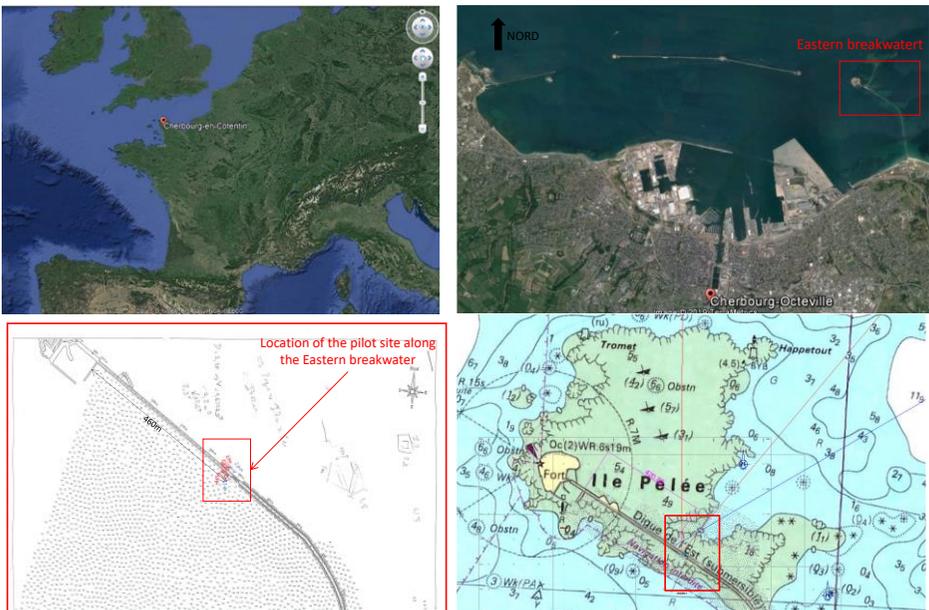
height: $H_{mo}=5.80\text{m}$) with high water levels. This preliminary step completed in autumn 2020 allowed block fabrication to begin at the prototype scale, and preparation of the rehabilitation works to get underway based on the new solution.

3. Cherbourg pilot site

3.1 The site

The main pilot site is located in Cherbourg harbour and involves the installation of new concrete armour blocks along a damaged trunk section of the existing Eastern breakwater. Furthermore, multi-measure monitoring was engaged to verify their structural stability, functional role and to gauge their benefits for the marine environment.

Figure 1 Location of the Cherbourg pilot site (France) and its exposure to wave actions. Source: *Google Earth, Nautical chart (SHOM)*.



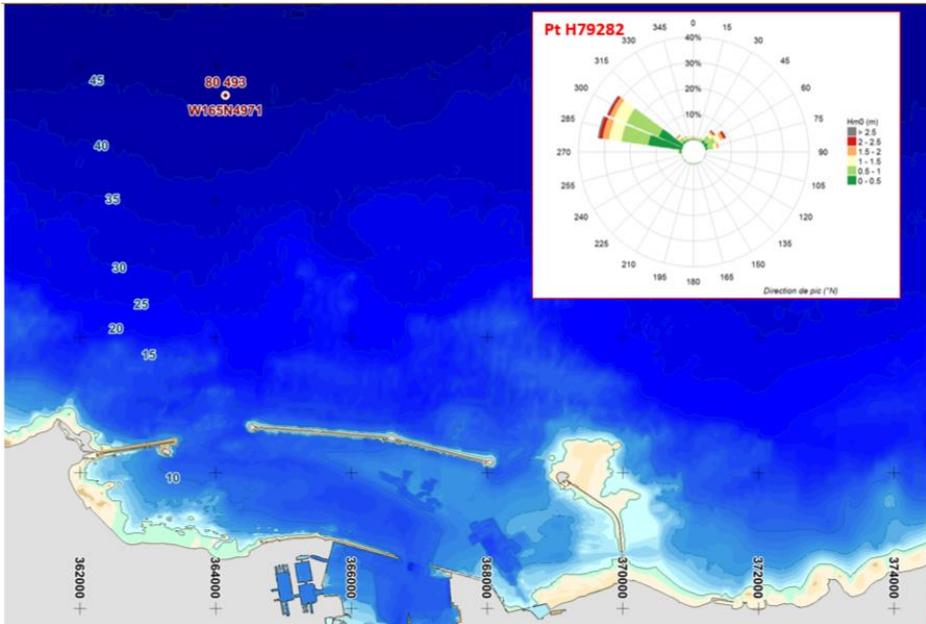
The innovative solution developed for the rehabilitation of the existing breakwater attempts to (re)develop habitats within the area enclosed by the port infrastructure.

The Cherbourg harbour is surrounded by three external breakwaters, i.e., the Querqueville breakwater to the west, the offshore breakwater and the eastern breakwater (Figure 1). The Cherbourg pilot site is exposed to two main directional wave sectors (Figure 2):

- the Channel sector accounting for 25% of sea states,
- the Atlantic sector accounting for 75% and including the roughest sea states.

The bathymetry around the pilot section of the eastern breakwater is uneven, shallower to the west than to the east. The breakwater is in fact surrounded by a relatively high tidal reef, which is completely exposed at low spring tides (see bathymetry on Figure 1 and Figure 2). This shallowness has some effects on the wave propagation and refraction towards the structure, making the incident waves almost perpendicular to the breakwater when coming from the west.

Figure 2 Local bathymetry at the pilot site and offshore main directional wave sectors (inserted detail)



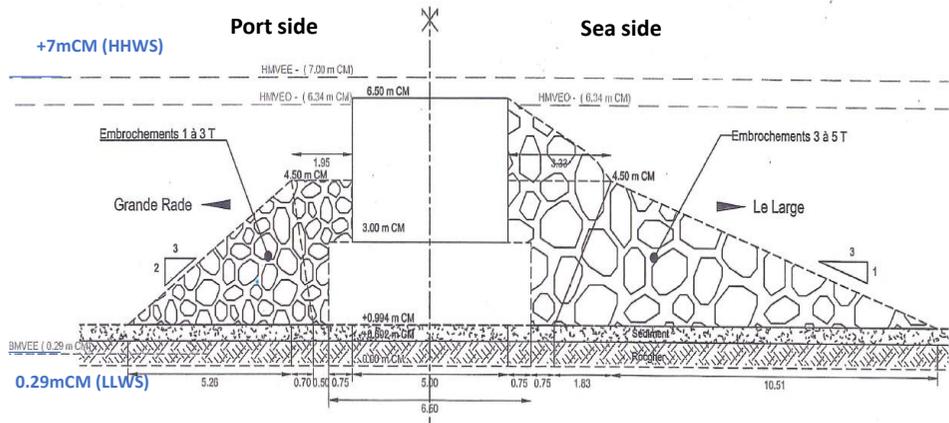
The Eastern breakwater, levelled at +6.5m CD (Chart Datum), is tidally submerged and directly exposed to northwest and northeast waves. This implies re-orientation of the offshore waves at the site in addition to significant dissipation of wave energy at low tides. Thus, the nearshore wave conditions, at the toe of the breakwater, are largely dependent on tidal water levels varying for instance from +0.25m CD to +7.30m CD for 10-year water levels and from +0.10m CD to +7.50m CD for 100-year water levels. The extreme water levels were derived from statistical studies conducted jointly by the SHOM and CEREMA; however, the extreme values of these elevations do not include the impact of Global Sea Level rise that was taken into account in the dedicated wave study performed for the CHERLOC project.

3.2 The original Eastern breakwater

The original Eastern breakwater design consists of a masonry wall covered by a slope rock protection. Nowadays, such design led by the old work methodology, is no longer

appropriate; but knowledge of it is essential for effective maintenance and rehabilitation in line with the original harbour appearance. Figure 3 shows the cross-section of the original Eastern breakwater consisted. However, this profile of the structure is now theoretical as nowadays the breakwater no longer corresponds to this configuration.

Figure 3 Cross-section of the original, now defunct, mixed breakwater (top) and the damage observed during the baseline survey in 2020 (bottom)



The Eastern breakwater was damaged on several occasions and the most recurrent problem is missing rocks, observed especially on the seaward side, where the rock slope protection has been either partially eroded or completely removed. It is not uncommon to see large rocks (3-5t) that have been extracted and transported far away from the armour layer.

After several repairs, a long-term solution must be found to keep the marine structure in good condition and stable. In light of the damage to the eastern breakwater, it was decided to rehabilitate the most damaged 30-m trunk section of the breakwater using an innovative solution described below.

Since the hydraulic conditions at the Cherbourg site are relatively severe, the use of artificial concrete blocks instead of natural rocks was suggested, firstly to ensure the stability of the structure and secondly to limit the seabed covering and to attempt to preserve/enhance the biodiversity.

4. The rehabilitation solution using ACCROBERM™ II toe blocks

4.1 A new toe armour block

The design of the repair solution aimed to ensure hydraulic stability with a design life of a few years (typically 10-y was considered for this repair and innovative experiment) and attempt to offer environmental advantages. To meet this brief, the innovative repair solution involved new artificial blocks consisting of new massive armour blocks known as “Double-Cube (DC)” and a new generation of toe armour block called ACCROBERM™ II.

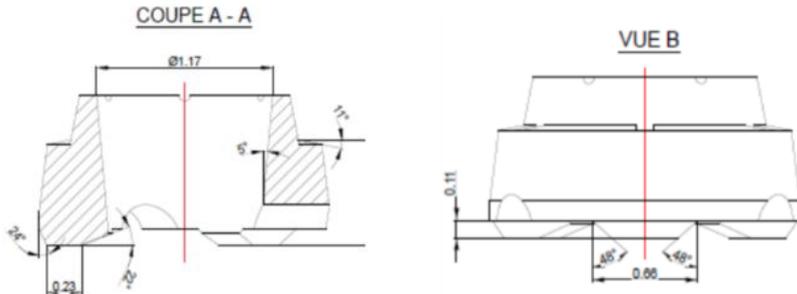
This later toe armour block is designed for coastal structures and breakwaters, and to replace “classic” toe rock and limit direct and indirect environmental impacts, especially with a reduced seabed footprint and an enhanced cavity. This hole-shaped block is cylindrical with a low centre of gravity and an annular shape designed to be filled with rocks. The stability of the ACCROBERM™ II toe block is ensured by the rock filling which can use different rock categories arranged in accordance with the specific site in order to create a heterogeneous environment and attract larvae, both juveniles and adults, creating a new artificial ecosystem or recreating the pre-existing ecosystem.

Figure 4 - ACCROBERM™ II toe blocks filled with rocks (at the bottom of the repair solution) interlocked with Double-Cube blocks placed on the slope



The aim of this new ACCROBERM™ II block is to provide two functionalities, i.e., both a toe block and a support for biodiversity by providing new habitats including micro-habitats.

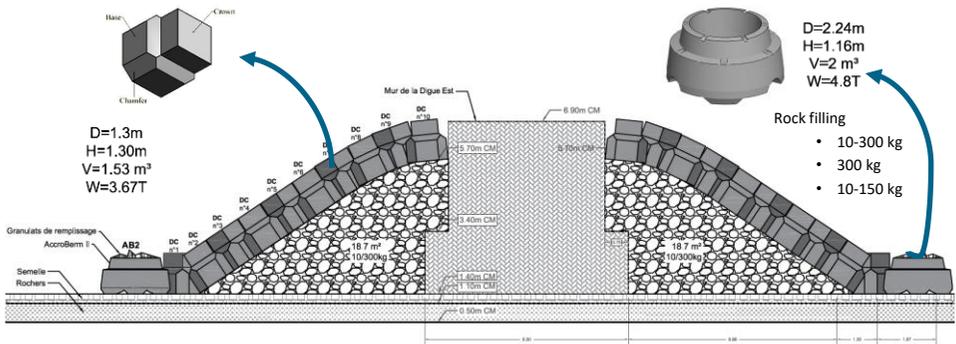
Figure 5: Details of the new ACCROBERM™ II toe block



4.2 Development of the repair solution

Prior to the in-situ experiments in Cherbourg, the repair solution had already been developed (Figure 6).

Figure 6 Cross-section of the repair solution



This development phase followed a series of steps and an experimental protocol:

- Design/sizing of both new blocks for their integration into the existing damaged structure, especially the ACCROBERM II™ toe armour blocks,
- Sizing of rockfill specifications in collaboration with the ecologists and in accordance with the environmental conditions; placement of ACCROBERM™ II blocks is envisaged by testing three categories of ballast rocks: 10-150kg, 10-300kg and 300kg. This flexibility in filling should allow for changes in gaps/cavity and thus adapt to the local ecological environment,
- Verification of the hydraulic stability of the ACCROBERM II™ blocks in a wave flume (2D physical model) under storm conditions and with different design sea levels (see Figure 7),

- The physical modelling conducted in the ESITC wave flume verified the stability of the blocks. The 2D tests were carried out for different block arrangement configurations and extreme wave conditions of up to 100-y waves with a high water level (Figure 7),
- These series of 2D tests confirming the sizing of the blocks allowed block fabrication at the prototype scale to begin.

Figure 7 2D tests for Cherbourg pilot site (ESITC wave flume)



- Design of formwork for manufacturing of the ACCROBERM II™ blocks,
- Trials for lifting and placing the blocks, and works preparation (see Figure 7),
- Biological investigation including a fauna/flora baseline survey prior to the rehabilitation works,
- Effective start of the rehabilitation works.

5. Experimentation

The rehabilitation works began in June 2021, involving the use of both land-based and nautical equipment. The repair solution considers both the seaward and harbour sides of the breakwater. The works were scheduled according to the tides and meteocean conditions since the artificial blocks were transported by barge from their storage platform in Cherbourg harbour to the offshore Eastern breakwater (pilot site). A comprehensive fauna/flora survey and ecological observations were performed, based on a 3/6/9/12-month strategy using the usual observation techniques (Figure 8 and Figure 9).

The ecological study carried out an inventory of the benthic diversity (flora/fauna) recorded before the rehabilitation works and during one year after the installation of the blocks in both sites.

Figure 8 Algal ecological survey for Cherbourg pilot site (BOREA – University Caen Normandy investigations).



This survey was performed during four sampling campaigns conducted on the hard substratum of the half-tide zone (Figure 8 and Figure 10). The samples collected were sorted and analysed. The objective is to perform a comparative study of the biodiversity found on marine structures protected by existing rock materials and on the planned new concrete armour blocks, using ecosystem approaches for macroflora, macrofauna and microalgal biofilm. In addition, every quarter a monitoring of the artificial blocks was made at each site and thus during one year.

Figure 9 Faunal ecological survey for both sites (M2C – University of Caen) for soft-bottom substratum (above) and hard-bottom substratum (below).



6. Preliminary results

6.1. Stability confirmed by in-situ storm events

In December 2021, during the first year of survey, the Cherbourg pilot site was subjected to a series of relatively severe storm events. These storms (i.e., ARWEN on 27th November 2021 and BARRA on 6th to 8th December 2021) caused some damage to the rubble mound rock armour (existing structure) while the repaired part with concrete armour blocks remained stable (see Figure 10). For this study, and in order to assess the in-situ stability, we performed storm reconstruction for the whole of 2021 using the existing SWAN wave

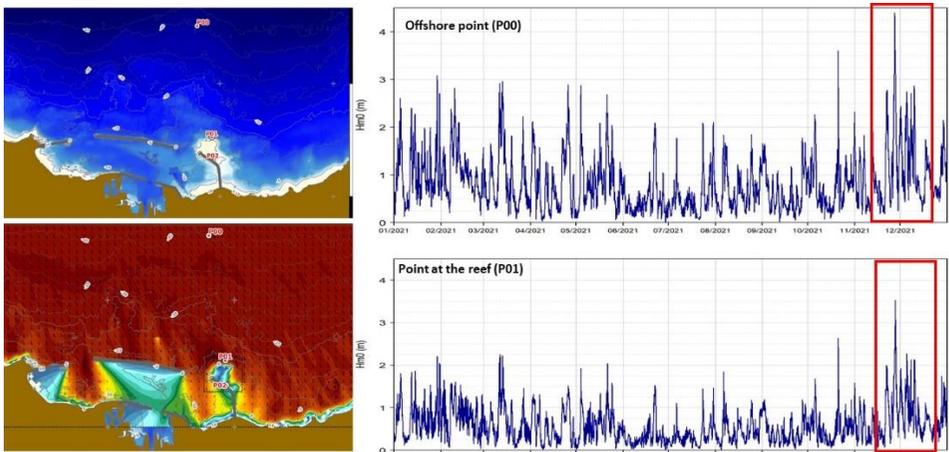
model based on the Ifremer NORGAS-UG model and database. The large model was run with a 100m mesh grid integrated with a local model for the project area (20m mesh grid) and the repaired trunk section of the Eastern breakwater.

- Following this reconstruction (see Figure 11), the storm events that occurred in December 2021 are characterised as follows:
- the extreme value of the time-series at the offshore point (P00) corresponds to about $H_{m0}=4.5\text{m}$,
- the extreme value of the time-series at the nearshore point (P01) corresponds to about $H_{m0}=3.5\text{m}$,

Figure 10 Cherbourg Experiment in December 2021 after the aforementioned storm events which appear to have a 5-10-year return period



Figure 11 December 2021 Reconstruction of storm events based on the existing wave model made for the Cherbourg project



These values match with the storm event of 27th November 2021 and if we consider the values at the offshore point which was not affected by the water levels, the return period of this storm might be considered as around 5 years. Further investigations, considering more accurately the water levels on the reef, are ongoing in order to estimate the characteristics of the waves (especially Return Period) at the toe of the eastern breakwater.

6.2. Ecological

Figure 12 shows the change in time of the wildlife diversity (fauna taxonomic richness) from four sampling campaigns, two before the rehabilitation works with concrete armour blocks and two after. This wildlife diversity parameter is measured in a 0.1 m² framework (Figure 9) during one year and four months on different stations along the breakwater. A difference in taxonomic richness is observed for different stations and sampling periods. Samplings on the breakwater (both internal and external sites) showed the smallest variation in richness. The greatest taxonomic richness was observed in the lower half-tide artificial block on both harbour side and the seaward side.

There is a dominance of the barnacle crustaceans *Semibalanus balanoides*, which represent 80% of the individuals sampled on all stations (Figure 13). This animal species is a fast growing pioneer species that provide a spatial heterogeneity on the support they colonise. This spatial heterogeneity provide support for epibiotic organisms. Although the diversity index is low, the ecological status of the site is classified as very good.

Figure 12 Mean faunal taxonomic richness measured during 1 year and 4 months

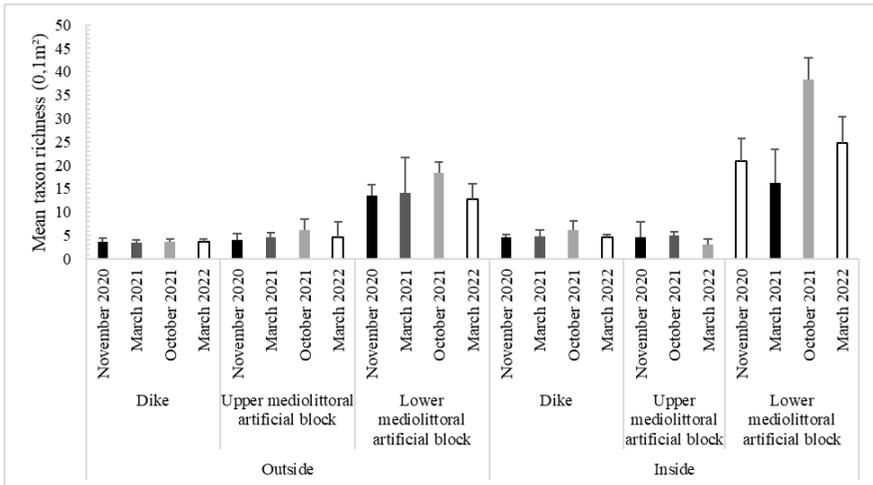
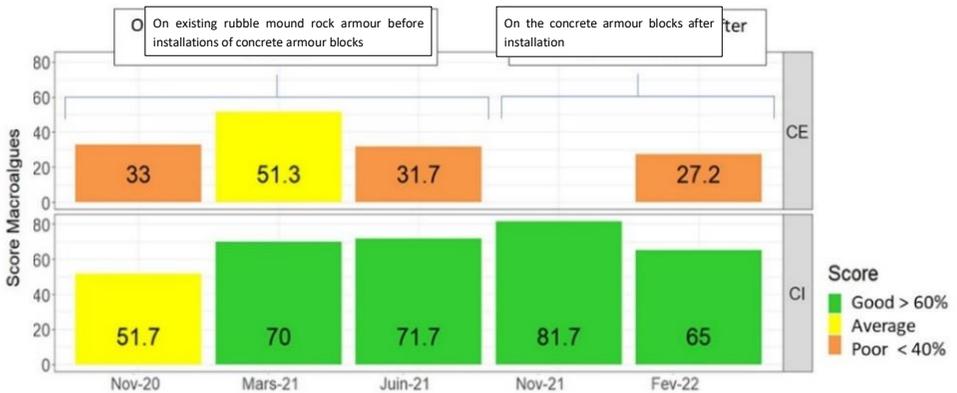


Figure 13: Barnacle crustaceans *Semibalanus balanoides* observed on site.



Figure 14 shows the scores in the evaluation of the qualitative state of macroalgae. It is possible to observe seasonal variations on the Cherbourg sites. On the new experimental blocks, the first macroalgae were observed from November 2021, but with insufficient diversity to establish a qualitative state at this stage. Also, a significant increase in microphytobenthic biomass over time was observed at Cherbourg.

Figure 14 Scores for the evaluation of the qualitative state of macroalgae present on the rock armour around the study sites. (CE = Cherbourg External Site, CI = Cherbourg Internal Site)



Algae species (*Fucus spiralis*, *F. serratus* and *F. vesiculosus*) dominate the upper parts of the site. The lower part of the site outside Cherbourg harbour is devoid of algae. The lower part of the site inside the large Cherbourg breakwater is dominated by a colony of gigartinales; *Chondrus crispus* and *Mastocarpus stellatus* with respectively 2% for both in October, then 20% and 3% in March. The qualitative state from a macroalgal standpoint of outside and inside the large Cherbourg harbour are respectively Average (51/100) and Good (70/100). Figure 15 shows the monitoring design on the hard bottom benthic communities surrounding and on the experimental breakwater with a low colonisation by some animals such as the barnacles and the gastropods.

The *Patella* spp. found rich microphytobenthic and macrophyte biomass (micro and macro algae) on the ACCROBERM™ II concrete blocks at the end of the first year of survey showing the establishment of a trophic network between primary producers and grazers. The presence of *Patella* spp is crucial as they have a key role in growing biodiversity as they are rich nourishment of biggest predator, i.e. crustacean species.

Figure 15 Monitoring of the hard-bottom benthic communities around and on the experimental breakwater

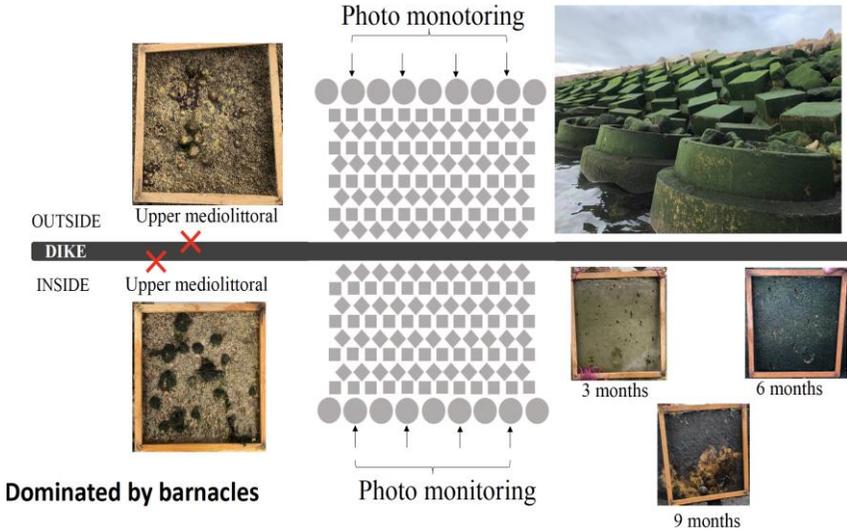


Figure 16 Picture of the gastropod *Patella* spp. scraping the microphytobenthos and macroalgae on the ACCROBERM™ II blocks in June 2022.



7. Preliminary conclusions and next steps

Based on the preliminary results, we can conclude that the pilot project shows:

- Good hydraulic stability of the new artificial blocks against a five-year return period storm;
- Biological development in the lower part of the rehabilitated breakwater as expected.

These developments are in line with the observations made by Giraudel et al. (2014) during extensive underwater surveys on single-layer breakwaters in existence for more than 10 years. The observations considered both the residual stability of breakwaters and their colonisation by marine life. Significant differences in marine growth were noted depending on the depth and in different parts of the breakwater. In general, and irrespective of the locations, the quantity of taxa observed was higher in the lower parts (i.e., toe, lower armour layer) than the upper parts of the breakwater.

However, to contribute to a better understanding of such developments, continuous monitoring is required to achieve reliable results and conclusions. This is also important as the Cherbourg site is relatively specific regarding toe blocks resting on hard-bottom seabed. For these reasons, multidisciplinary and multi-year monitoring will continue for the Cherbourg experiment.

In addition, note that other similar trials are scheduled for 2023 in another port development where a small number of ACCROBERM™ II blocks will be placed along two trunk sections at the toe of a single layer breakwater; these toe block arrangements are treated as an experiment for testing eco-design on marine structures. This forthcoming pilot site considers soft-bottom seabed for which the ecological development is different.

8. Acknowledgment

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