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BREAKWATERS IN A LIVING ENVIRONMENT

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ABSTRACT

Breakwaters protecting harbors and coastal areas are key to the economic and social development of many countries, but they are also infrastructures which may result in relevant environmental and social impacts. The construction of new breakwaters in developing countries, together with the dismantling, rehabilitation or repair of old breakwaters in developed countries, should be adapted to the principles of sustainability to produce efficient and resilient systems. Global mean temperatures and sea levels are rising due to climate change, and many environmental variables and numerous ecosystems are evolving. The hypothesis of stationarity, widely assumed in the last century when estimating the wave climate for the design of maritime structures, is now questionable, and new methodologies are required to design breakwaters in this changing environment. Marine life and ecosystems are affected by construction processes and structures, but the interactions are not well known; marine growth and enhanced biodiversity are usually considered positive environmental impacts of most breakwaters but materials, carbon footprint and energy consumption are negative impacts. The two main challenges in breakwater design are (1) to develop sound design methods valid in a changing wave climate and with rising sea levels, and (2) to adapt design guidelines to build-up, to repair and to dismantle breakwaters in a living environment.

KEWORDS: Breakwater, Rehabilitation, Design, Sustainability, Climate change, Marine life.

1 INTRODUCTION

Breakwaters are key infrastructures for harbors, and they are fundamental for coastal protection. During the first phase of economic development, attention is usually focused on constructing basic infrastructures such as new breakwaters for port development and maritime transportation, which is directly related to consumption, trade and industrial production. Decades later, developed countries focus attention on monitoring, maintaining and exploiting infrastructures being central issues both life cycle management as well as social and environmental impacts. Additionally, Climate Change (CC) and Sea Level Rise (SLR) have increased the design wave loads (see Isobe, 2011) for existing breakwaters and coastal structures. During the coming decades, structural damage, flood risks (see Muis *et al*., 2020) and environmental impacts are likely to increase in littoral areas resulting in higher design waves and unexpected overtopping, coastal flooding, etc. In this changing scenario, assuming the principles of the Circular Economy (CE) is a sound alternative (see Korhonen *et al.*, 2018) for both mitigating and adapting to CC by reusing concrete elements which otherwise would produce a significant carbon and energetic footprint.

During the next few decades, thousands of new breakwaters and coastal infrastructures are expected to be built around the world as a result of the economic expansion of many developing and undeveloped countries and the new requirements of maritime transportation. There is a strong correlation between global Gross Domestic Product (GDP) and international marine trade (see UNCTAD, 2022); long-term world GDP growth seems unstoppable as well as the maritime transportation and the need for additional coastal infrastructure to support maritime trade. Figure 1 shows the evolution of global maritime trade by cargo type over the last five decades. In the last 22 years, the number of Twenty-foot Equivalent Unit (TEU) transported by sea has increased 3-fold as well as the size of the largest containerships in the world; the dimensions of the largest containerships in 2023 (Length≈400 m, Breadth≈60 m and Draft≈16 m for 24,000 TEU) are conditioned by the Suez Canal characteristics, just as the locks of the old Panama Canal limited the size of the Panamax containership (5,000 TEU) in the past, and the new locks limit the New Panamax vessels (16,000 TEU). Both larger ships and a sustained increase in world maritime transportation will lead to new breakwaters, port and coastal infrastructures, most of them in hubs and developing countries. In the last two decades, the international maritime trade in tons loaded (tankers, bulk-carriers, containerships and other dry cargo) has shown an average accumulated annual increase rate of +3.8%, while the global containerized trade in TEU has been growing at an average annual rate of +4.9% and the world GDP only +2.9%. These trends in global maritime trade are pushing the corresponding port infrastructures to the limit.

Over the last seven decades, thousands of breakwaters have been built around the world following and sometimes leading the economic and social development of many countries. Numerous breakwaters have been damaged during their service time (see Edge and Magoon, 1979, and Losada *et al.*, 1991), and CC and SLR are increasing the risk to existing breakwaters. Rehabilitation, repair and reuse of materials have received limited attention in the breakwater literature, although it is obviously a relevant technical issue due to the ageing stock of breakwaters around the world and the need to adapt them to CC and SLR. The principles of CE (EMAF, 2015) seem to be a reasonable basis for the problem of rehabilitating breakwaters.

During the next few decades, developed countries will face the problem of finding a new use for port facilities and also the need to dismantle or rehabilitate thousands of breakwaters whose design lifetime will be surpassed. Accumulated damages over time, corrosion and durability issues as well as changing design conditions for many breakwaters will require much more than just monitoring programs and repair works. Meanwhile, developing countries will continue to be focused on economic development and the construction of new ports and coastal infrastructures; the construction of a new breakwater increases materials consumption and produces relevant carbon and energy footprints. The challenge is to learn from past experience and to design with nature, reducing costs and negative environmental impacts. For both developed and developing countries, new design methods and guidelines are required to balance the economic and technical needs with marine life, taking into consideration the principles of sustainability to create resilient systems in a maritime environment dominated by an uncontrolled climate change.

The consumption of materials, energy and carbon footprints caused by breakwaters (see Bruce and Chick, 2009) and the negative impacts on marine ecosystems are relevant issues in the 21st century. Our understanding of the ecological functioning of marine habitats and breakwaters needs to be improved while ecological criteria must be integrated in coastal engineering to better preserve marine biodiversity (see Bulleri and Chapman, 2010). A range of eco-engineering options has been proposed (see O'Shaughnessy *et al.*, 2020) for environmentally-sensitive coastal infrastructures, but it is not so easy to integrate the variety of available options into current breakwater design techniques, which are mostly dominated by economic limitations and construction feasibility.

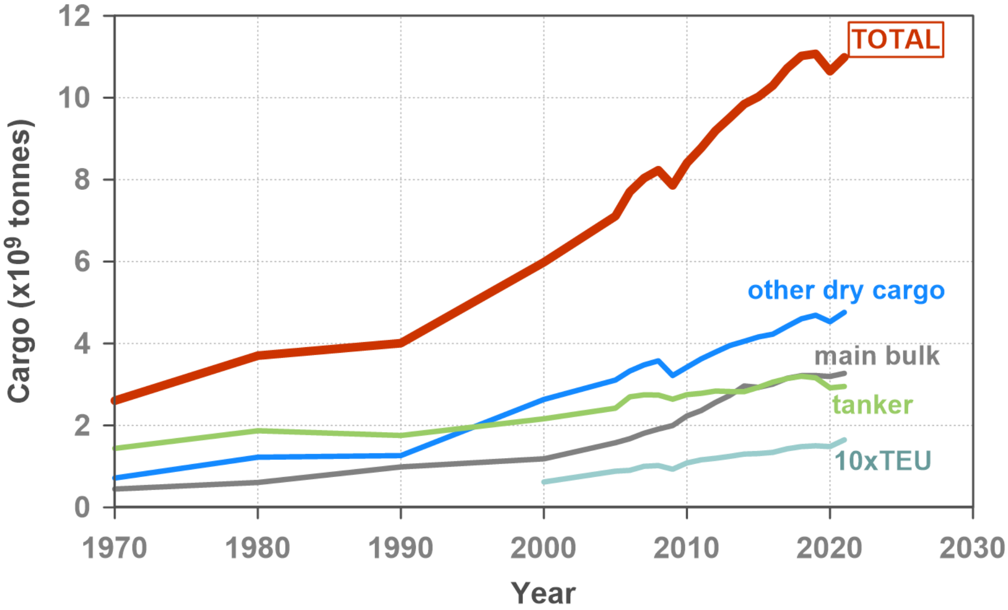

Figure 1. Evolution of maritime trade by cargo type (UNCTAD, 2022).

2 DESIGNING BREAKWATERS IN A CHANGING WAVE CLIMATE

Statistical studies of extreme values, which analyze measured or retro-fitted environmental data to estimate future extremes, are central to design civil engineering structures; usually, a stable distribution is required in time (stationarity) from which the extremes are drawn (see Gumbel, 1958). In the maritime engineering field, methods commonly used to estimate extreme storms (e.g. design significant wave height, H_{sd}) are implicitly based on the hypothesis of stationarity (e.g. Goda, 2011). However, the hypothesis of stationarity, which has been widely assumed in the past to build up sound statistical models to predict extreme variables used in the design process of civil infrastructures, can no longer be taken for granted. It is necessary to face the fact that global temperatures on Earth are rising (air and sea water), and a warming planet is inducing an environmental chain reaction which may be changing significantly, over time, the statistical characteristics of the key variables used in civil engineering design. It is easy to understand that warming air and sea water induce ice loss and a retreat of continental glaciers as well as changes in wind intensity, cyclones and precipitation; the terrestrial ice melting and thermal expansion contribute to the SLR, and changes in winds and water levels modify the sea currents, precipitations and ecosystems.

IPCC (2021) provides qualitative assessments and quantitative estimations for future projections regarding a variety of key environmental variables, such as global mean temperature and SLR. These are based on scenarios corresponding to different subjective assumptions regarding future emissions of CO_2 and other greenhouse gases. Figure 2 shows the estimation of global surface temperature given by IPCC (2021); it is widely accepted that the Earth is warming, and it is clear that future consumption of fossil fuels on our planet and other future anthropic behavior will also affect the warming process. Therefore, it is necessary to face the fact that our planet is warming without any reasonable control, and the present warming rate may increase or decrease in the long term.

Although an uncontrolled human activity is the main driver of this environmental chain reaction, and a rising global temperature on Earth is the main environmental response, coastal engineers must estimate extreme wave and wind storms and water levels to design breakwaters and other structures. IPCC (2021) qualifies as “virtually certain” that global mean sea level will rise over the 21st century (0.28 to 1.01 m) and it is highly confident that sea levels will rise for centuries or millennia, and the millennia elevations are expected to be between 2 and 22 m depending on the temperature on Earth. Fortunately, large breakwaters usually have a service time of 50 years (see ROM 1.0-09, 2010) and engineers must focus on estimating extreme water levels, waves and winds during the 21st century.

Global mean sea levels are clearly rising; they affect the highest and lowest water levels for design and depend on tectonic uplift and subsidence, as well as other regional factors. SLR during service time is routinely included in the design of breakwaters worldwide. The direct and indirect evidence of global SLR and the inertia of the process are quite clear (observations of tidal gauges, retreat of glaciers, thermal expansion, etc.); thus, the engineering community has easily adopted the inclusion of an estimation of future SLR in the design of breakwaters and other port infrastructures. The problem here is the uncertainty of those estimations, as it depends on scenarios based on assumptions regarding future behavior of humankind (consumption of fossil fuels, etc.), and these are not so easy to agree upon.

Wind, waves, and other key environmental variables are evolving with a warming planet, but the change is not obvious in many regions (see Walsh *et al.*, 2020). Wave climate characterized by significant wave height (Hs), mean wave period (Tm) and mean wave direction (Θm) is changing at the planetary scale, but the confidence level is low (IPCC, 2021) mainly because a wide range of wind-wave models are used to derive wave characteristics from surface winds or pressure fields, which increases the large uncertainty of projections based on scenarios.

In this changing climate, the future characterization of environmental stochastic variables (waves, wind, etc.) to design breakwaters will continue to be based on the hypothesis of stationarity, although some ad hoc modifications will be proposed when sufficient evidence against stationarity is found. SLR during lifetime will have to be estimated based on the predictions associated to subjective scenarios (see IPCC, 20121); a general agreement within the engineering community on the most appropriate scenario for design is unlikely to emerge, but there are also divergent opinions caused by the intrinsic uncertainty of the CC. Different designers may have different criteria to characterize environmental variables, but the engineering community needs an agreement on basic rules such as the parsimony principle which is valid in this changing environment.

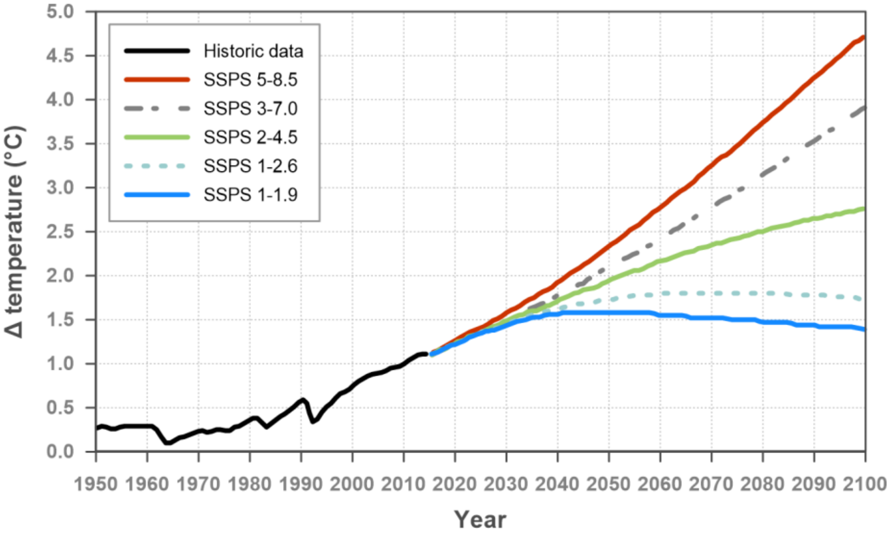

Figure 2. Global surface temperature changes relative to 1850-1900 (IPCC, 2021).

3 AGEING INFRASTRUCTURES AND REHABILITATION OF MOUND BREAKWATERS

3.1 Evolution in design and construction of mound breakwaters

De Graauw (2022) described ancient harbors and port structures; some ports were protected with remarkable ancient rubble-mound breakwaters such as those sheltering Portus and Antium (Italy), Pharos (Egypt), Thapsos (Tunisia), or Paphos (Cyprus). For centuries, rubble-mound breakwaters were built dumping rocks on the coast; the larger rocks were dumped on the slope facing the sea, and continuous maintenance works during service time were required with frequent rock dumping after storm damage. Concrete cubes or parallelepiped precast units were used instead of rocks for the largest breakwaters built in the 19th century to shelter ports for larger ships and much higher volumes of maritime transportation, especially when sufficiently large rocks were not available at the construction site. The new cranes, railways and transportation systems favored the construction of the first large mound breakwaters. For instance, 60-tonne concrete blocks were placed in the Santurce Breakwater (1888 to 1904) at the Port of Bilbao, Spain (MOPU, 1988). Trial-and-error was the design methodology during the 19th century and periodic maintenance and frequent repairs were common before the second half of the 20th century (see Sullivan, 1979).

Throughout the 20th century, many new large breakwaters were built around the world, and three main methods and research tools were developed to properly design these breakwaters: (a) small-scale physical testing, (b) wave forecasting and measurement systems, and (c) wave propagation models (refraction and diffraction). Based on small-scale physical tests with regular waves, Castro (1933) and Iribarren (1938) proposed the first valid formula to design the armor layer of rubble-mound breakwaters; rocks and parallelepiped blocks were the armor units available during the first half of the 20th century. Deterministic design storms based on subjective observations and models to propagate waves from deep water to the coast led to the first rational design methodology for mound breakwaters.

During the 1950s, the Tetrapod was invented in France, and systematic small-scale physical tests were carried out in the USA. These tests were used to propose Hudson's formula, based on Iribarren's formula, which has been extensively used by scientists and practitioners. Hudson (1959) introduced the concept of the stability coefficient, K_D (different for each type of armor unit), and the commercial success of the patented Tetrapod armor unit led to an explosion of research and innovation in this field with dozens of new types of armor units being invented in the 1950s and 1960s. The most popular of the new units was the Dolos, a slender free-usable unit invented in 1963 and rapidly popularized around the world (very high K_D estimated by different laboratories). The publication of the Shore Protection Manual (USACE, 1975) popularized the use of Hudson's formula around the world as well as the recommended cross sections of mound breakwaters in breaking and nonbreaking conditions. Wave measurement systems, observations from ships and wave hindcasting methods were developed in different countries to estimate the extreme wave climate, while refraction and diffraction models were used to calculate the design wave storms for the new breakwaters. During the 1960s and 1970s, the engineering community developed the methods and scientific background to properly design mound breakwaters (e.g. Iribarren, 1965, and USACE, 1975).

The oil crisis of 1973 led to the construction of much larger oil tankers together with larger and deeper mound breakwaters around the world. The engineering community was quite confident with the design methods and armor units developed in the previous decades, and many new mound breakwaters were designed to minimize maintenance costs during lifetime. However, numerous new breakwaters failed in the 1970s and 1980s with unexpected large economic losses, generating an intense discussion within the engineering community. During the 1970s and 1980s, Dolos-armored breakwaters failed at Sines (Portugal) and San Ciprián (Spain); Tetrapod-armored breakwaters failed at Tripoli (Libya) and Arzew (Algeria), and other large mound breakwaters failed, highlighting the relevance of the randomness of waves (not well described by the regular waves used in physical tests) and the structural integrity of concrete armor units (observed breakage of Dolosse and Tetrapods). The safety margin was increased (see USACE, 1984, compared to USACE, 1975), physical testing with irregular waves became common, more robust armor units were used and, thus, breakwater design methods improved significantly. The failure of breakwaters in the 1990s and later is not rare, but extensive breakwater damage is less frequent than in the 1970s and 1980s.

3.2 Information of breakwater failures

Allsop *et al.* (2010) highlighted the difficulty in obtaining crucial information about the major breakwaters built around the world and the extreme difficulty in obtaining reliable information of breakwater failures in recent times. Mound breakwaters constructed in recent decades have usually been designed for minimum maintenance during lifetime, due to the high cost of mobilizing the equipment required for repair works. A breakwater failure during service time usually generates huge economic losses, legal disputes among different companies and a variety of political, social, environmental and economic troubles. This social environment favors opacity and a lack of reliable technical information about breakwater failures and the corresponding rehabilitation works. Transparency about a given breakwater failure is extremely valuable for scientists and engineers, but it may be very risky for managers and politicians who are or may be responsible for the managing, designing, constructing and rehabilitating the breakwater. Fortunately, there are some large breakwater failures and rehabilitation works from the 1970s and 1980s which are relatively well documented in the grey literature. Special recognition should be given to the Portuguese government, who made available to the engineering community the details of the failure of the breakwater of Sines (Portugal), the largest breakwater built in the world by the late 1970s (see Reis *et al.*, 2011).

Edge and Magoon (1979) reviewed nine breakwater failures and the repair works in different countries; most of them were Dolos-armored breakwaters damaged in the 1970s, although there were also rock-, cube- and Tetrapod-armored breakwaters. Foster (1984) described the guidelines for breakwater designs in Australia before the 1980s and analyzed eight rehabilitated breakwaters (rocks, cubes, Tribar and Dolos armor units) damaged in that country during the 1970s and 1980s. Prior to the 1970s, most breakwaters were rock- or parallelepiped-armored structures with frequent damages and periodic maintenance; after 1970, breakwater design in Australia evolved to minimize or eliminate maintenance in order to optimize costs over the lifetime. Harlow (1980) analyzed multiple breakwater damages in the 1970s highlighting several potential causes, different from the weight of the armor units; for example, he noted the case of the breakwater of Kahului-Hawaii (Sulivan, 1979) originally built with rocks, repaired first with Tetrapod, later with Tribar and finally with Dolos.

Five large breakwaters which failed in the period 1978 to 1981 were analyzed by Burcharth (1987). Magoon and Davison (1984) organized a seminar to review prototype experiences and described a number of repair and rehabilitation case histories such as the Cleveland Eastern Breakwater (Bottin and Mohr, 1994), or the Duca di Galiera Breakwater (Fedolino *et al.*, 1994), etc. Melby and Turk (1995) also examined the damage survey and repair works of sixteen Tetrapod, Tribar and Dolos armors in the USA. Negro (2002) studied the damage and rehabilitation works of large breakwaters in Spain and other countries during the 1970s, 80s and 90s.

Analyzing in detail specific rehabilitation works, Losada *et al.* (1991) reported on the damage and repair works to improve the cube-armored breakwaters located near the Cudillero and Luarca fishing villages on the Northern coast of Spain. Stadler *et al.* (1995) analyzed the causes and damage to a 10.5-tonne rock armored breakwater in Ashkelon (Israel) and proposed a flexible design approach for urgent rehabilitation based on prototype monitoring. Pillay *et al.* (1998) reported the damage and repair works to the Dolos armored south breakwater at the entrance to the Port of Richards Bay (South Africa). Melby (2001) examined the Yaquina north jetty (Oregon), which was damaged and repaired many times, while Melby (2005) proposed a Core-Loc armored composite-berm structure as the final rehabilitation for a multiple-repaired breakwater at Lajes (Azores). Reis *et al.* (2011) studied different alternatives to the new rehabilitation of the Sines west breakwater based on a historical perspective of the original project and emergency repairs from 1973 to 1981 as well as the rehabilitation works from 1989 to 1992; re-using materials was the critical factor including high density 90- and 105-tonne Antifer blocks. After accumulated damage over the years, Podowski and Smith (2012) described the rehabilitation of the breakwater protecting the Kaumalapau Harbor (Hawaii) using large Core-Loc units.

3.3 Upgrading, repair and rehabilitation of mound breakwaters

The information from all breakwaters downgraded during lifetime and the guidelines of Life Cycle Management (LCM) given by PIANC (2008) can be used as a framework to prioritize breakwater repairs (Marujo *et al.*, 2019). In addition to the natural degradation of infrastructures in a breakwater's lifetime, CC and SLR are increasing the design wave loads on existing breakwaters and damages are likely to increase. In this scenario, assuming the principles of the Circular Economy (CE) is reasonable (EMF, 2015); reusing concrete elements and materials may be relevant to reduce carbon and energy footprints in the short term and a sustainable development in the long term.

The best international practices for cost-benefit analysis of infrastructure investments include estimating the financial risks, cash-flows and cost-benefits of a variety of agents from Administration to clients during the lifetime (see MEIPOR, 2016). However, it is difficult to estimate specific costs and risks associated with repair and rehabilitation works of breakwaters damaged after extreme wave storms. Models of accumulated damage and levels of damage (initiation of damage to destruction) are necessary to define the appropriate strategy for conservation and repair (e.g. ROM 1.1-18, 2018), but time and mobilization costs to repair a damaged breakwater are usually very high, and both stoppage and repair costs after failure critically depend on the repair strategy which should be defined in advance to reduce costs.

Monitoring breakwaters during construction and service lifetime is the basis for any rational strategy for maintenance, repair or rehabilitation. Most coastal structures built in the world have received some monitoring (see Magoon *et al.*, 1983) from a general visual inspection of the emerged part to specific surveys and studies focused on describing the evolution in time of environmental variables and structural characteristics. Additionally, technology, sensors and surveying techniques (e.g. multibeam echosounders, side-scan sonar, LIDAR, etc.) have evolved over time, reducing the monitoring costs which tend to improve and change the post-construction monitoring programs. Figure 3 shows a conceptual sketch of the evolution of quality over time for a typical breakwater with an original lifetime of v=50 years and a probability of failure during service time of Pf=0.1; the return period (Tr) equal to the inverse of the annual probability of failure (ypf) for all failure modes is used to measure the quality.

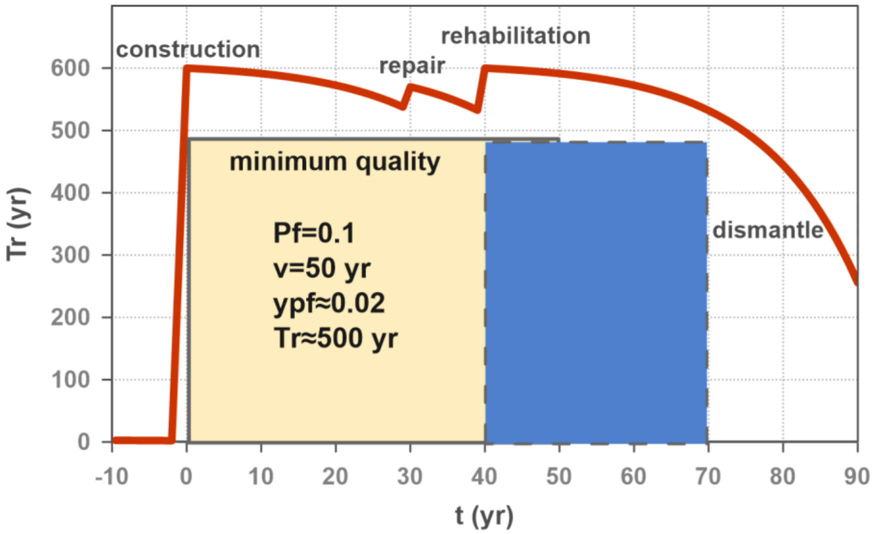

Figure 3. Sketch of quality versus time for a typical breakwater with an original lifetime of v=50 years and a probability of failure during service time of Pf=0.1.

There is an increasing number of both breakwaters in service whose original lifetime is exceeded or close to being exceeded in the coming years, and low-cost, high precision surveying techniques (e.g. UAV LIDAR for the emerged part of the breakwater); this favors the use of a variety of new breakwater monitoring schemes and surveys (see Ueno *et al.*, 2021, Sousa *et al.*, 2022, and Bajo, 2022). This selection of available monitoring techniques range from simple visual inspections of the emerged part and not so simple underwater visual inspections (photographs and videos) by divers. The monitoring of the emerged part of the breakwater is relatively simple using airborne, terrestrial and drone LIDAR or photogrammetry. The monitoring of the submerged part of the breakwater is not so simple using multibeam echosounders, side-scan sonar, etc. In addition, sub-bottom profilers, electrical resistivity tomography, CPTU, SPT, dissipation and other tests may be used to characterize the breakwater structure and the foundation in a given monitoring program. When the repair or rehabilitation of a given breakwater is likely to occur in the near future, the main objectives of the monitoring program are usually to detect structural integrity failures (armor units breakages, crown-wall damages, etc.) and to generate a 3D model using the DTM obtained from the surveys of the emerged and submerged parts of the breakwater.

The evolution in time of the structural characteristics of a given breakwater is obviously key to any monitoring system for the breakwater. The other relevant aspect is the characterization of the environmental variables affecting the structure; specifically, waves attacking the breakwater and water levels, which may be affected by climate change and sea bottom erosion. Most breakwater damage is usually caused by large waves, and the direct measurement of waves at the toe of the structure is very expensive and unfeasible in the long run; however, publically-available reanalysis results such as those given by the ERA5 database from Copernicus-ECMWF provide hourly data for many environmental variables in a regular latitude-longitude grid of 0.5x0.5 degrees (including significant wave height, mean wave period, mean wave direction, etc.). Deep water reanalyzed wave characteristics can be propagated to the toe of the structure to estimate the waves attacking the breakwater in the past (since 1940) when using ERA5 database.

In addition to characterizing the evolution in time of the breakwater structure (DTM) and estimating waves attacking the structure during lifetime, other specific studies may be carried out to better estimate the evolution in time of the risk of failure. A reliability study of upgrading alternatives (see Galiatsatou *et al.*, 2018) includes the analysis of Ultimate Limit States (ULS) and principal failure modes such as erosion of the armor layer, scour and toe berm failure, excessive overtopping and erosion of rear-side slope, sliding and tilting of crown wall, geotechnical failures, and so on. Damages accumulated in time tend to amplify the effects with a global probability of failure which usually grows exponentially with the accumulation of damage. Overtopping, pressure on crown-wall, scour depth and other variables can be measured to estimate the actual response of the structure to wave attack and better estimate the corresponding risk of failure.

During the construction phase (see Grau *et al.*, 2023), execution control and payment are key elements, and a continuous monitoring system is mandatory for quality control. During the first years of the service time, monitoring breakwaters is common because design errors and latent defects must be detected and corrected. Later, if no relevant defect or design error is observed during the first years, the monitoring of the infrastructure tends to be sidelined during service time, and a good performance of the breakwater is usually taken for granted during lifetime and, sometimes, forever. Obviously, infrastructures downgrade over time and a minimum structural quality is required to perform adequately.

A sustainable monitoring program must be defined from the very beginning, and it needs to be followed for a given explicit lifetime. During the first years with the breakwater in service, the main objective is to detect design errors and latent defects; later, the main objective changes to detect degradation of elements which could require intervention (repair or re-habilitation). When the breakwater is in service so long that design lifetime is nearly surpassed, the breakwater must be re-analyzed to estimate again the risk of failure as well as to ensure compliance with new requirements, as these usually change over time. The old breakwater has to be either re-designed for a new lifetime or re-habilitated for a new purpose or completely dismantled; the alternative to neglect the natural downgrading of old breakwaters which are in service after their lifetime is unacceptable because risk of failure increases over time without any control.

4 MARINE STRUCTURES IN A LIVING ENVIRONMENT

4.1 Breakwater design in a living environment

Adapting design guidelines to construct breakwaters in a living environment is now a relevant challenge. Climate change and the accumulation of pollutants caused by human activity have been degrading ecosystems around the world, and both are threatening the existence of the human species on Earth in the long term. Oceans are the final destination of many pollutants produced by humans, and maritime ecosystems are deeply affected by climate change and other anthropogenic impacts; the annual retreat of 1% to 2% of coral reefs in the last decades (see Rinkevich, 2014) and the corresponding worldwide degradation of ecosystems are the clearest indicators of the poor health of marine life.

The loss of biodiversity is accelerating on a planetary scale (see Ceballos, 2015), and humans must change our collective behavior to avoid extinction with many other species; the stability of ecosystems and biodiversity are vital objectives to be taken into consideration in human activities. New breakwater design guidelines are required to account for the effects on ecosystems and biodiversity, as well as to collaborate in the global effort to revert the fate of humans in the present accelerating degradation process of the biosphere. The main challenge is to identify clear rules to improve the marine ecosystem's response to coastal infrastructures and to include them effectively in current construction and design guidelines.

The construction of coastal structures is usually considered a necessary infrastructure (social and economic development, efficient transportation, etc.) with a negative local impact on the environment (energy and carbon footprint, etc.). However, some coastal structures such as artificial reefs have been built given their positive impact on the marine life; for centuries, artificial reefs were used in Japan to attract fishes and fifty years ago (see Nakamura, 1985) they were built to improve the fisheries (nursery grounds, increased fisheries productivity, etc.). Artificial reefs have also been built with many other purposes in mind (see Baine, 2001) such as providing recreational diving areas in the USA or preventing trawling in Europe, and sometimes these were built using questionable materials such as old ships and cars (see Medina and Serra, 1987). Any artificial structure, including breakwaters, placed on a sandy bottom can attract some fishes, but it is not clear if the global effect for the marine ecosystem is positive or negative. Browne and Chapman (2011) focused attention on the worldwide "armoring" of the shoreline and the need to design infrastructures that sustain natural biodiversity.

The need to sustain marine biodiversity is clear, but it is not so clear which design rules are applicable to coastal structures to promote long-term marine biodiversity. The experiences and research on this topic are limited, but a lack of knowledge should not prevent us from doing our best to promote biodiversity for our coastal structures; some results and common-sense reasoning may lead to intelligent design rules to follow.

4.2 General design rules in a living environment

The complexity of ecosystem evolution in relation to the local climate and environmental conditions requires a continued research effort to find clear and simple design rules to apply when designing and constructing maritime structures. In this section, general rules are given in reference to materials and concrete to use, as well as to formwork modifications and other changes to enhance marine biodiversity.

- **Rocks, concrete, steel and other materials**

  Designers of coastal structures should take into consideration that some materials are better than others to develop marine habitats (see Burt *et al.*, 2009, and Grasselli *et al.*, 2024). The use of rocks similar to native rocks and cliffs seems to be the best alternative to facilitate marine colonization and sustain biodiversity, and natural rocks different from autochthonous rocks seem to be the second-best alternative.

  After natural rocks, which are not always available at a given construction site, mass concrete is a good alternative; the energy and carbon footprint is relevant but concrete is durable in sea water and has some resemblance to natural rocks. Steel has a much higher carbon footprint and a lower durability than mass concrete, but steel has a very high tensile strength which is a key factor for some coastal structures; iron is not hazardous to health and it is a common material in Earth's crust.

  Finally, heavy metals, plastics, rubber and other materials and pollutants have different levels of toxicity for living organisms and one should take into consideration that they can significantly modify the marine ecosystems reducing biodiversity.

- **Cement in mass concrete**

  Mass concrete is the most common artificial material used in coastal structures (armor units, etc.), and the cement used for concrete is the component with the highest cost, energy and carbon footprint; aggregates in concrete usually have a minor impact on economic cost and carbon footprint. There are many non-harmonized standards in different countries such as the EN206 and EN197 in Europe for the selection of Portland, composite or blended cement in concrete manufacturing (see Escudero *et al.*, 2024). The characteristic tensile strength (f_{ctk}) related to the characteristic compressive strength (f_{ck}) at 28 days is a key variable for the structural integrity of mass concrete elements. Characteristic tensile and compressive strengths are related to the water-to-cement (w/c) ratio and the content of cement in concrete; the lower the w/c ratio and the higher the content of cement, the higher the characteristic tensile and compressive strength.

  Massive armor units up to 60 tonnes only require concrete with $f_{ctk} \geq 1.5$ MPa and $f_{ck} \geq 20$ MPa (see Medina and Gómez-Martín, 2016), although European standards for maritime structures require $f_{ck} \geq 30$ MPa ($f_{ctk} \geq 2.90$ MPa), a w/c ratio lower than 0.5 and more than 0.30 tonnes of cement per m^3 of concrete; with these limits, massive armor units up to 150 tonnes can be manufactured. European standards for concrete are good for safety, but they are too conservative to reduce CO_2 emissions because large elements of mass concrete (massive armor units, crown walls, etc.) could reduce the cement consumption while maintaining structural integrity.

  There are different types of cement depending on the proportion of clinker in the cement and additional supplementary cementitious materials (e.g. fly ash, silica fume, slag, etc.); the carbon footprint mostly depends on the proportion of clinker in the cement: CEM I (Portland), CEM II and CEM III have average carbon footprints (in tCO_2/tonne) of 0.86, 0.68 and 0.48, respectively (see Haist *et al.*, 2022). Cement production is responsible for about 8% of the global anthropogenic CO_2 emissions (see Schiefer and Plank, 2023), and coastal structures should favor the use of CEM III to CEM II and CEM I to reduce the global carbon footprint. The availability and prices of different types of cement change from one construction site to another, but the rule is clear: it is preferable to use low-carbon footprint cements such as CEM III/B 42.5 N-LH/SR recommended for maritime structures with a very low carbon footprint and adequate cementitious materials with better bioreceptivity (Hayek *et al.*, 2021). It is necessary to note that the price of a specific cement in a given construction site does not take into account the global damage caused by CO_2 emissions, because some countries do not have a market for carbon permits and the countries with a scheme of carbon permits (e.g. EU) offer huge free carbon permits to cement producers; an additional cost of 90€/tCO_2 (typical EU carbon permit price since 2022) would raise the price of the cement between 50% (CEM I) and 20% (CEM III).

- **Concrete surface roughness and colonization**

  It is not clear how the type of concrete affects colonization (see Becker *et al.*, 2020). Colonization of concrete in the sea and biodiversity is usually better than in sandy areas but not as good as around natural rocks; thus, Evans *et al.* (2021) recommended eco-engineering approaches to mimic features of natural reef topography. Hayek *et al.* (2021) found a clear impact of surfaced design (type of roughness) on the biofouling, and Hall *et al.* (2018) used arrays of holes and grooves on granite armor rocks to increase diversity and abundance of marine organisms on coastal structures.

  Sella and Perkol-Finkel (2015) monitored proprietary concrete mix, surface texture and design of concrete armor units in the Eastern Mediterranean, observing a clear increase in biodiversity associated with complex concrete surfaces (holes and crevices) compared to smooth surfaces. Macro and micro roughness of concrete surface creates niches for different marine species, favoring colonization, biofouling and an increase in biodiversity in the long-term (see Figure 4).

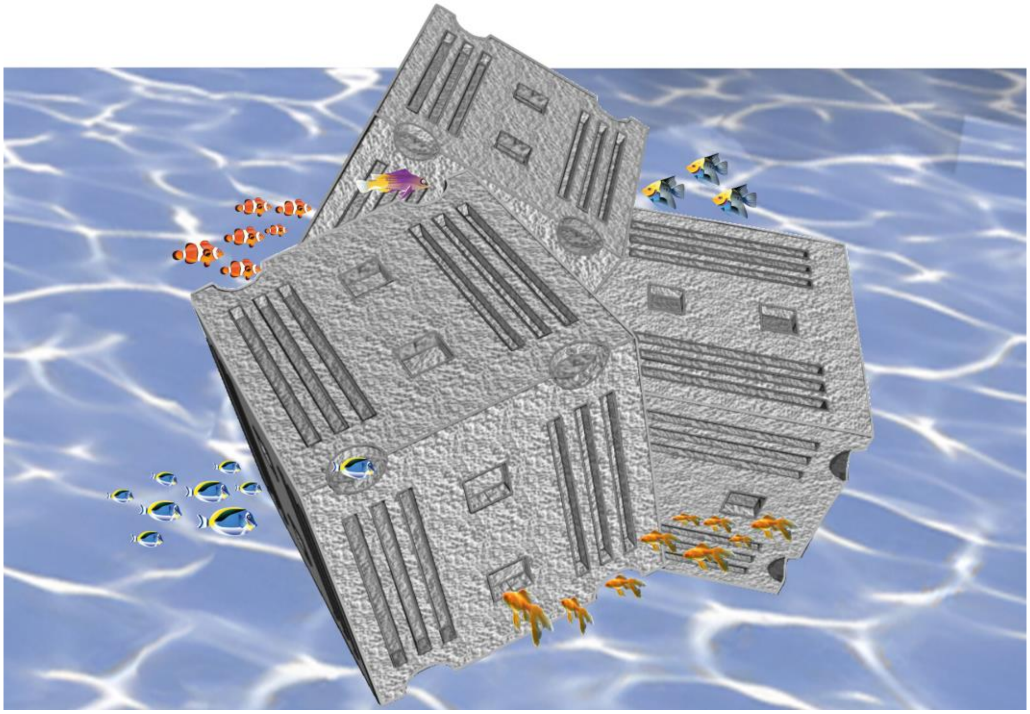

Figure 4. Macro and micro roughness of concrete surface creates niches for different species.

5 SUMMARY AND CONCLUSIONS

Thousands of new breakwaters and coastal infrastructures are expected to be built around the world in the coming decades, and developed countries will face the problem of dismantling or rehabilitating thousands of other breakwaters whose design lifetime will be surpassed. Both the construction of new breakwaters and the repair of old breakwaters must be adapted to the principles of sustainability in a living environment. The challenge is to learn from past experience to design with nature; new design methods and guidelines are required to balance the economic and technical needs with complex marine ecosystems in a maritime environment dominated by an uncontrolled climate change. Our understanding of breakwaters and the ecological functioning of marine habitats needs to be integrated to better preserve marine biodiversity and to avoid human extinction in the long term.

Coastal engineers require the estimation of extreme waves, wind storms and water levels to design breakwaters and other structures. Global mean sea levels are clearly rising and affecting the highest and lowest water levels for design, and estimations of SLR during service time is routinely included in the design of breakwaters worldwide. However, the uncertainty of SLR is high, because it depends on scenarios based on assumptions regarding the future behavior of humankind. Wind, waves, and other key environmental variables are evolving with a warming planet, but the change is not obvious in many regions. In this changing climate, the future characterization of stochastic variables to design breakwaters will continue to be based on the hypothesis of stationarity, although some ad hoc modifications will be used when sufficient evidence against stationarity is found.

Breakwaters always downgrade during lifetime and dismantling or upgrading breakwaters is an economic, technical and environmental challenge in many countries. The safety and functionality of long serving infrastructures cannot be taken for granted, but systematically monitored during service lifetime; breakwaters in service require a rational strategy for maintenance and repair to guarantee the expected level of safety and functionality. Breakwaters near their service lifetime have to be re-designed for a new lifetime or re-habilitated for a new purpose or completely dismantled; the alternative of ignoring the natural downgrading of old breakwaters in service after their lifetime is unacceptable because the risk of failure increases over time.

Climate change and accumulation of anthropogenic pollutants have been degrading ecosystems around the world and both are threatening the existence of many species on Earth. Oceans are the final destination of many pollutants and the loss of biodiversity is a clear indicator of the poor health of marine life; humans must change our collective behavior to avoid extinction in the long term. New breakwater design guidelines are required to take into consideration the effects on ecosystems and biodiversity in order to collaborate in the global effort to revert the fate of humans in the biosphere. The need to sustain marine biodiversity is clear, but it is not so clear which design rules are applicable to coastal structures to promote long-term marine biodiversity.

Some general design rules applicable to coastal structures to enhance marine biodiversity include:

1. Natural rocks are better than mass concrete; concrete is better than steel, and ferrous materials are better than heavy metals and other artificial materials which may have a relevant negative impact on marine ecosystems.
2. For concrete mixing, cements with a low proportion of clinker (e.g. CEM III) are better than cements with a high proportion of clinker (e.g. CEM I), and adequate cementitious materials produce better bioreceptivity. The price of a specific cement in a given construction site does not take into account the global damage caused by CO_2 emissions.
3. Macro and micro roughness of concrete surface create niches for different marine species favoring colonization and increase of biodiversity.

Due to the limited knowledge of the complex interrelation between maritime constructions and ecosystems, and the need for clear design rules to improve biodiversity, it is imperative to systematically integrate the monitoring of marine ecosystems with the structures to guarantee the functionality and safety of structures during their lifetimes while improving the effect on the marine living organisms.

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