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Artificial reef management – a decommissioning review

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ABSTRACT

Artificial reefs (ARs) generally aim to achieve one or more objectives such as improving fishing or diving opportunities, improving surfing by changing wave patterns, and protecting a coastline from storm surge erosion. Although the history of ARs is rich, it is only between 1970s and 80s that large-scale programs have been developed by national or local governments. As the AR programs progress, several issues have been accumulated such as attraction vs. production issue, overfishing, pollution from materials used to construct ARs, marine pests colonized in ARs, conflicts between stakeholders, potential negative environment impact, and lifespan management. Regarding the last issue, it is not likely to often recover ARs because of its cost and the secured lifespan. However, AR history shows that some ARs have been recovered due to environmental issues, heavy storms, and research purposes. This study focuses on the decommissioning of ARs, reviews historical cases, and summarizes the decommissioning procedure. For the purposes, the general and specialized practices in AR management are discussed through literature and experience reviews.

1. INTRODUCTION

Artificial reefs (ARs) generally aim to achieve one or more objectives such as improving fishing or diving opportunities, improving surfing by changing wave patterns, and protecting a coastline from storm surge erosion. These objectives can be subdivided into enhancing commercial fishing or recreational fishing, assisting in the rehabilitation of degraded fisheries, providing underwater tourist attractions for diving, supporting aquaculture or marine ranching, and providing erosion protection. Accordingly, an AR can be defined as an underwater structure installed on the seabed for the one or more purposes above, whereas a fishing device or fish aggregating device (FAD) is a moored or free-floating device to attract and/or aggregate fish, with a limited purpose, providing recreational fishing opportunities. The geometric scales of FADs are generally smaller than most ARs.

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Although the history of ARs is long, it is only between 70s and 80s that large-scale programs have been developed by national governments. As the national AR programs progress, several issues have been accumulated based on the associated scientific observations as follows. First, considerable scientific uncertainty remains whether ARs increase biological production or simply redistribute fish stocks from surrounding areas – the so-called attraction vs. production debate (Bohnsack, 1989). Significant differences have been found in the biological productivity of different AR types (Lindberg, 1997; Hunter and Sayer, 2009; Wilson et al., 2001; De Troch et al., 2013). These observations suggest that a reef design (e.g., material, structure, and porosity), placement model, and the surrounding environment (current, hydrology, and sedimentology) are all critical in determining how successful an AR will be in achieving its aims (Marsden et al., 2016). To resolve the attraction vs. production debate, several solutions have been suggested, such as no-take zones or protected reefs (Pitcher and Seaman, 2000) and marine protected areas (Claudet and Pelletier, 2004). As a result, today it is widely acknowledged that ARs involve both attraction and production (Broughton, 2012).

Second, ARs are usually designed to increase the aggregation of fish at a particular site as well as increasing catch rates. According to the concentrated population rate, ARs may be overfished (Bohnsack, 1989, Wilson et al., 2001). In other words, the populations may be attracted from surrounding areas (e.g. natural reefs) to the location of an AR, where they may be more easily targeted by fishing activities. This issue is basically connected to the first issue – the attraction vs. production debate. Consequently, the overfishing issue gives a negative effect on the production argument. To prevent the overfishing, it is recommended to regulate fishing intensity near ARs. It should be noted here that once fishing mortality exceeds the population of biomass attributed to enhancement by an AR, there is a net loss in fishery resources (Stephan, et al., 1990).

Third, pollution from materials used to construct ARs has been a problem. Some cases include the breakdown of tires and the leaching of toxic chemicals from shipwrecks, which are all deployed as ARs. A representative toxic chemical is polychlorinated biphenyls (PCBs) that are mixtures of synthetic organic chemicals with the same basic chemical structure and similar physical properties ranging from oily liquids to waxy solids (Artificial Reef Subcommittees, 2004). Due to their non-flammability, chemical stability, high boiling point, and electrical insulating properties, PCBs were used in hundreds of industrial and commercial applications including electrical, heat transfer, and hydraulic equipment; as plasticizers in plants, plastics, and rubber products; in pigments, dyes, carbonless copy paper and many other applications. Concerns over the toxicity, bioaccumulation, and persistence in the environment of PCBs led prohibitions on their manufacture, processing, and distribution.

Fourth, Marine pests are plants or animals, usually introduced from overseas, that have a significant impact on marine industries and the environment (Lafferty and Kuris, 1996). They can include mussels, crabs, seaweeds, sea stars and other marine species (Mountfort et al., 2012). Marine pests may be introduced in various ways, including in ballast waters, attached to the hulls of international ships, or imported deliberately as aquarium or aquaculture species. ARs have the potential to provide habitat for and may be colonized by marine pests. There is also the potential for marine pests to be spread by boat activities around ARs.

Fifth, the design, materials used and placement of an AR and accordingly its ecological role and impact vary according to its intended purpose. There is a risk that the AR may not meet its intended objectives. Selecting a placement model of ARs is a representative example (Yoon et al., 2016). Depending on a placement model, the wake region of the model can be varied and accordingly the efficiency of the design and placement is distinguished (Kim et al., 2014a, 2014b; Jung et al., 2016; Kim et al., 2016; Yoon et al., 2016). Thus, it is necessary to consider the wake region distribution of a target AR set, group, and complex because the wake region facilitates an energy saving, rest, stopover, and/or spawning ground for marine species (Kim et al., 2014a).

Sixth, the needs of various stakeholder groups in relation to ARs should be considered and accordingly balanced. Otherwise, different users (e.g., fishers and SCUBA divers) may have potential conflicts owing to their different requirements for type, use, locations, and management of ARs. Thus, it is necessary to identify conflicts between uses. For example, researchers are eager to resolve the attraction vs. production debate through a long-term monitoring at a site, but the local residents or fishers try to immediately take a benefit from the reef site. This kind of conflicts is likely to be extended among developers and/or users because of the recent development in multi-functional ARs such as facilitating ARs in offshore wind farm (Langhamer, 2012). Multi-functions not only generate multi-expectations, but also cultivate different requirements.

Seventh, getting to the bottom of marine biodiversity, sedimentary habitats are not well understood and less than 1% of marine benthic species are known (Snelgrove, 1999). Besides, we have explored less than five percent of the ocean (Snelgrove, 2010). In most cases, ARs are deployed in areas with sandy or silty sediments, and consequently the ecosystems are poorly understood. It is known that scour, which is caused by water motions around ARs, provides more available space for invertebrates and fish (Kruer and Causey, 1992; Sherman et al., 1999). However, comparatively little scientific research has been conducted on seafloor sediment habitats and their conservation values are less well known. The deployment of ARs represents a modification of these habitat types. Thus, it should be considered as a potential negative environment impact.

Eight, even small ARs are expensive to install and remove. In general, ARs are installed using free-fall (downward movement due to gravitational force) and physical guidance usually done by divers, wires, and cranes. Geospatial survey is also included in the installation stage typically using side scan sonar (Manoukian et al., 2011). It is also natural to investigate the environmental conditions in the target site such as wave, current, temperature, turbidity, and salinity (Harris, 2009). It is not likely to remove ARs because of its cost and the lifespan of ARs. However, AR history shows that some ARs due to their negative environmental impact have been removed, and damaged ARs due to heavy storms have been rehabilitated (London Convention and Protocol/UNEP, 2009). Because of the high cost, installation should be carefully planned and subsequent management of an AR should be effectively prepared.

Finally, depending on the nature of the materials used, ARs will have a specific operational lifespan. For example, it is seen that the reinforcing concrete reefs, fully immersed for 20 to 25 years in waters, have sound physical and chemical properties

(Kim et al., 2008a, 2008b). However, some materials such as ARs utilizing automobile shells and tires experienced rapid deterioration in waters and highly unstable movement (Brock and Norris, 1989). Thus, appropriate ongoing maintenance is demanded to ensure longevity of some AR materials. There is the potential for ARs which have reached the end of their operational lifespan to become rubbish on the seabed. The decommissioning of ARs will need to be considered as part of any proposal.

Among the issues above, this study focuses on the decommissioning of ARs, reviews a historically renowned case, and summarizes the decommissioning procedure. For the purposes the general and specialized practices in AR management are surveyed through literatures and introduced here with some discussions.

2. DECOMMISSIONING CASES

2.1 Overview of tire ARs

Tires are manufactured primarily from artificial rubbers. A typical tire rubber compound consists of several parts including rubber, fillers, extenders, etc., and two basic types of tire construction exist such as bias-ply and radial. It is known that the use of waste vehicle tires as artificial reefs (ARs) began in the United States in the late 1950s or early 1960s (Matthews, 1983). A scrap tire (waste tire) can be defined any used or processed tire that has been removed from a motor vehicle and has not been retreated or regrooved. Not only in the United States but also in other countries, scrap tires have been used for construction of ARs for example in Thailand (Pramokchutima and Vadhanakul, 1987), Malaysia (Ch'ng and Thomas, 1990), Philippines (Alaca et al., 1981), Singapore (White et al., 1990), Brunei Darussalam (De Silva, 1988), Australia (Pollard, 1989), and Israel (National Research Council, 2002). Fig. 1 shows the typical scrap tires combine in many ways for various-sized ARs such as tires stuffed, tires triangle, and tires rosette (National Research Council, 2002). Because of their low density and tendency to trap air, scrap tires are secured together in a bundle using steel rods or cables and embedded in a concrete base for use as a reef module.

The utilization of scrap tires as an AR material was undertaken to accomplish two objectives: developing fishing reefs (Stone and Buchanan, 1970) with relatively low cost and providing a possible solution to the growing solid waste disposal problem (Stone, 1982). The basic idea of using scrap tires was to create three-dimensional habitat for public fishing reefs by binding tires with connectors (e.g., wires) and sometimes with a strong substrate (e.g. concrete) (Collins, et al., 2002). After 50 years in AR practice of scrap tires, achieving these two objectives is no longer attractive to coastal states, local governments, the tire industry, and citizen groups primarily because of environmental issues associated with the AR material and the dramatic shift in scrap tire management and technological advances. Scrap tires have been gaining increased value in the market place owing to their recycling in energy recovery, road applications, devulcanization, pyrolysis, gasification, and new plastic products (Ramos et al., 2011). Besides, it is reported that tires are the least suitable as fewer corals recruited to tires than the other materials in Kaneohe Bay (Fitzhardinge and Bailey-Brock, 1989), and corals are not observed on tires for between 16 and 24 months after immersion in the Philippines (Alcala et al., 1981) and after 3 years immersion in the Persian Gulf

(Downing et al., 1985). Thus, the industry no longer views the AR deployment as a low-cost disposal alternative.

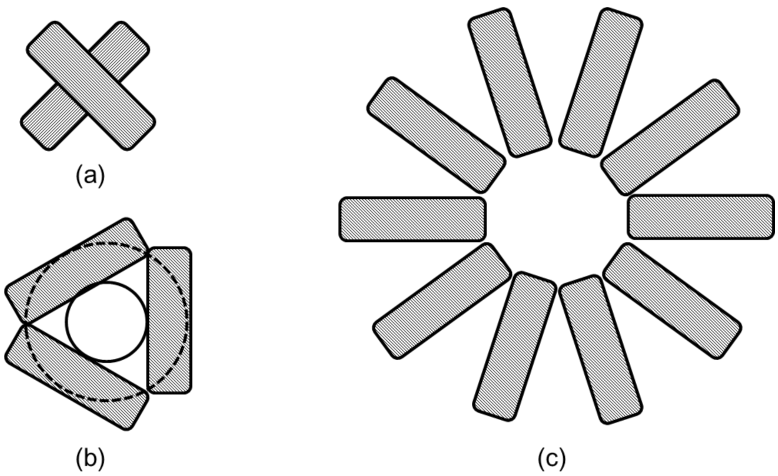

Fig. 1 Scrap tires combined in many ways for various-sized ARs: (a) tires stuffed, (b) tires triangle, and (c) tires rosette (modified from National Research Council, 2002)

2.2 Decommissioning of tire ARs

It is shown that ARs constructed of high-density, heavily ballasted tires with strong bases show stronger stability in comparison to un-ballasted tires, which often fail (Myatt et al., 1989; Morley, 2008). In 1967, approximately two million unballasted tire bundles were deployed at approximately 1.8 km offshore of Broward County, Florida. Within a few years, the bindings on the tire bundles failed and accordingly they lost their substrates by even normal currents (D. E. Britt Assoc., 1974, 1975). The tires have since moved extensively, travelling kilometers from their original locations to beaches and deeper waters offshore. Many of the loose tires have also physically damaged benthic reef fauna on natural reefs.

Consequently, tire deployments in Florida were ended by the 1980s and a large-scale removal plan of the tires was initiated in 2001 by Dr. Robin Sherman of Nova Southeastern University, who was awarded a US$30,000 grant by the National Oceanic and Atmospheric Administration (Morley et al., 2008). She was able to coordinate the removal of only 1,600 tires from the reef, and a cost estimated at $17 a tire (Florida Department of Environmental Protection, 2007). Subsequently, in 2002, Florida and Broward County environmental officials began the long and difficult process of removing the tires. An original estimate (between US$40 and 100 million) led the Florida Department of Environmental Protection to arrange a deal with those companies who were involved in the tire construction. Because the concern of the destruction of more marine habitats, initiated by environmental groups, Florida did not follow through on the plan. Consequently, the Florida legislature authorized US$2 million in 2007 for the decommissioning, military divers began to retrieve 62,000 tires in 2008, and a two-year project was commenced in 2015 to clear 90,000 tires from the site (Associate Press, 2015). This indicates that an inappropriate choice of an AR material causes significant negative environment impact and accordingly huge effort to remove them.

2.3 Overview of cube-type ARs

Considering the area and facility volume of cube-type ARs as a fraction of all ARs installed in Korean coastal waters from 1971 to 2013 (Yoon et al., 2016), the cube-type ARs account for 64.5% of the total area and 67.4% of the total facility volume. These numbers illustrate the popularity of cube-type ARs in South Korea, mainly due to their simple shape, good workability, and low cost (Yoon et al., 2016). The reefs are made from concrete and reinforcing bars, and typically measure 2m×2m×2m, for an apparent facility volume of 8m^3, and a weight of 33.34kN (3.4tons). It is recognized that the reefs are suitable for fisheries and the protection of migratory fish, owing to the relatively large void at each surface (Kim et al., 2014b), as shown in Fig. 2. It should be noted here that, based on the Korean regulations, an AR should have a facility volume greater than 800m^3 (Yoon et al., 2016). Considering a standard volume of 8m^3, at least one hundred cube-type ARs should be installed to create an AR-set. Because of their relative ease in manufacturing and handling, several cube-type ARs have been used in other countries such as Malaysia (Yaakob et al., 2016), China (Liu et al., 2012), Philippines (Munro and Balgos, 1995), and Japan (Nakamura, 1985).

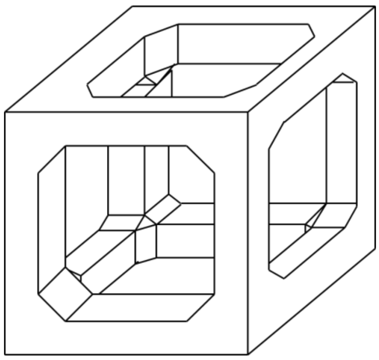

Fig. 2 Cube-type ARs (adopted from Kim et al., 2008a)

In terms of management, ARs have been classified into scales by module, set, group, and complex (Grove and Sonu, 1985), which describe the hierarchies among the scales. These scales are usually established through AR placement models, such as the intensively sacked placement model (ISPM), flatly concentrated placement model (FCPM), and flatly distributed placement model (FDPM) (Yoon et al., 20016). ISPM and FCPM are usually implemented for smaller ARs to attract fish, whereas FDPM is implemented for larger ARs to attract fish or to establish marine forests (seaweeds) in smaller ARs. In general, the cube-type ARs, relatively small ARs for fish, are constructed in ISPM. Thus, their initial deployment has been realized with layers – intensively stacked. In a sense, it is necessary to investigate the initial settlement of the first (bottom) layer owing to the initial free fall and subsequent collision between following ARs. Moreover, it is demanded to investigate time-dependent, subsequent long-term settlement (or vertical movement) and/or horizontal movement according to several environmental forces.

2.4 Decommissioning of cube-type ARs

After installation, it is necessary to investigate the condition of an AR for further management of concrete reefs. The cube-type ARs immersed in seawater for 18–25 years were investigated (Kim et al., 2008a, 2008b), and their physical and chemical degradation characteristics were identified through destructive and non-destructive tests. The reefs were physically and chemically robust, and the original estimated service life was sufficient for a further service period in water depths between 28m and 32m. Fig. 3 shows the decommissioning procedure such as search by a vessel, confirmation by side scan sonar, observation by divers, and recovery for scientific investigation, which were all carried by Kim et al. (2008a, 2008b). Fig. 4 shows the sites for the decommissioning of the cube-type ARs. From each site, four reefs were decommissioned. Fig. 5 shows the destructive and non-destructive testing tools to evaluate the physical and chemical states of the decommissioned ARs.

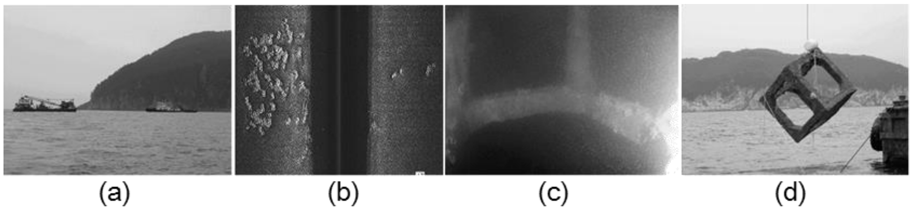

Fig. 3 A decommissioning procedure: (a) search, (b) confirmation, (c) observation, and (d) recovery of an AR (adopted from Kim et al., 2008a)

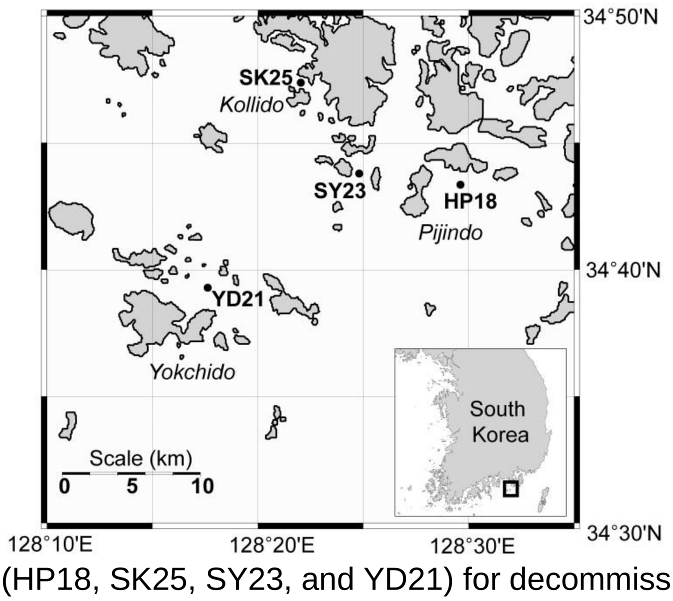

Fig. 4 Target sites (HP18, SK25, SY23, and YD21) for decommissioning of the cube-type ARs (adopted from Kim et al., 2008a, 2008b) in South Korea. The numbers used in the target sites (i.e., 18, 25, 23, and 21) indicate the ages of the recovered ARs.

(a) Testing tools for physical deteriorations

- Visual inspection
- FE-SEM (field emission scanning electron microscope)
- Tensile strength test
- Core compressive strength test
- Schmidt hammer test
- Ultrasonic velocity test
- Others on water absorption rate, apparent density, and pore volume

(b) Testing tools for chemical deteriorations

- Recording pH
- Chloride concentration
- Potential
- Composition

Fig. 5 Destructive or nondestructive testing tools used for evaluating physical and chemical states (deteriorations) of the ARs decommissioned from the target sites shown in Fig. 4 (Kim et al., 2008a, 2008b)

Unlike the decommissioning of the tire ARs in Florida, the recovery of the cube-type ARs in South Korea aimed at research purpose i.e. evaluating physical and chemical states (deteriorations) of the ARs in the seawaters. From the physical tests, the following results were observed (Kim et al., 2008b). First, visual inspection showed three micro cracks, four fractures possibly due to mechanical impacts, and three spots of exposed reinforcements; however, these are not severe enough to cause structural malfunction of the concrete reefs. Second, from the results of FE-SEM, CSH (calcium silicate hydrate), mono-sulfate, and pores were observed in all of the specimens extracted from the recovered concrete reefs; however, it is not easy to quantify the difference in composition profiles with respect to the different ages, 18, 21, 23, and 35 years. Third, it was found that the tensile strength of reinforcing bars separated from the concrete reefs varied from 43 to 55kg_f mm^{-2} (1kg_f = 9.81N) so that some of the reinforcing bars have lower strength than the minimum standard value of 45kg_f mm^{-2} (441N mm^{-2}). However, it is believed that the tensile strengths do not present significant problems since the reefs are usually not under severe external loading conditions. Moreover, the yield strength and elongation ranges are within the standard values. Fourth, based on the concrete compressive tests (i.e., core compressive strength test, Schmidt hammer test, and ultrasonic velocity test), it is found that the concrete reefs have experienced some deterioration but not severe enough for any failure. Fifth, other tests on water absorption rate, apparent density, and pore volume did not give any negative indications of the physical state of the reefs. Based on the observations, it is shown that globally the cube-type ARs have sound physical properties.

In addition, from the chemical tests, the following results were observed (Kim et al., 2008a). First, from pH measurement, the concrete reefs are still alkaline although they have been immersed in seawater for 18 to 25 years. Second, chloride concentrations range from 8 to 20kg m^{-3}; hence, it is believed to be sufficiently high to cause corrosion. Besides, the range might cause leaching of $Ca(OH)_2$. Third, the overall values of diffusion coefficients are small, and the coefficients are slightly lower in the older concrete reefs in comparison to the 18-year-old reef. Fourth, it is observed that the chloride ion concentration ranges from 8.5 to 17.0kg m^{-3} at 30 years, with 80mm cover depth. This range is believed to cause corrosion of reinforcing bars. In other words, with other cover depths of 40 and 50mm, reinforced concrete reefs are at risk of corrosion. Fifth, the composition measurement shows that the concrete reefs have been experiencing concrete strength reduction and degradation at time passes. Sixth, corrosion tests show that the reinforcing concrete reefs have more chance of having corroded bars only when the concrete cover has broken and cracking has occurred. Otherwise, no corrosion was observed in most places even when the concrete cover was 23 or 25mm. In summary, the reinforced concrete reefs have sound chemical properties except for chloride concentration and its associated factors. However, chloride alone cannot cause corrosion of reinforcing steel bars; it needs the other factors such as oxygen and a continuous supply to invoke corrosion. The oxygen dissolved in the target seawater ranges from 6.54 to 8.18mg L^{-1}, which is much lower than the 300mg L^{-1} in air. Thus, the originally designed service life will be achieved and the concrete reefs will have a longer service life than expected.

3. DISCUSSIONS AND CONCLUSIONS

Two AR decommissions are introduced. The first decommissioning is due to an inappropriate use of scrap tires, which have resulted in negative environmental impact on the benthic habitats in Florida, USA. The decommissioning procedure has a long way to go because of significant budget required to remove the entire underwater crews. The other countries also having scrap tire ARs in their own waters may have similar problems; however, there is few literatures describing a detail of the environmental issues associated and discussing any decommissioning plans established. It is believed that the wires and concrete substrates binding the tire units are not robust enough and accordingly their horizontal and vertical movements have been observed. However, it should be noted here that other ARs also experience a horizontal and vertical movement. For example, recently, a cylindrically-shaped AR was found in the coastal water near Busan, at the southeast corner of Korea. This AR was originally installed in the coastal water near Nagasaki, a coastal city in Kyushu, Japan, released due to an unknown factor, traveled through the strait, and arrived at Busan. This illustrates that loss of ARs is not desirable but it happens all the time. Then, the concern should be the-after-release-action. In the case of the tire ARs in Florida, the issue remains because these ARs have disturbed the benthic flora and fauna in a severe manner and resulted in negative environmental impact.

In contrast, the second decommissioning introduced here is owing to a scientific investigation on the service life of the cube-type reinforced concrete ARs. From the four target AR sites, total sixteen ARs were decommissioned and tested by destructive and non-destructive testing tools. From the test results, it was found that the physical and chemical properties of the ARs are sound except for chloride concentration and its associated factors. However, chloride alone cannot cause corrosion of the reinforcing steel bars; it needs other necessary elements such as oxygen and its continuous supply to invoke corrosion. The study claims that the originally designed service life will be achieved, and the concrete reefs will have a longer service life than expected. Consequently, the minimum concrete cover depth of 40mm is proposed in practice.

The two cases above seem to describe two distinct purposes, procedures, and contributions to artificial reef communities. In reality, these two are all about decommissioning of ARs, which should be considered as part of any proposal and project. At this stage, based on Willard W. Waller (1970) on the Family, Education, and War, we may note the following. “Every institution, every society has its rationalizers to defend it and its code to justify it. When the society is changed, there is always a violation of the existing moral consensus, but a new moral consensus at once arises to justify the change.” The statement can be continued as follows. “Every artificial reef, AR society has its rationalizers to defend it and its code to justify it. When the society is changed, there is always a violation of the existing artificial reefs, but a new artificial reef at once arises to justify the change.” By referring to the existing artificial reefs, preparing any decommissioning procedures, protecting our marine environment from unexpected events, trying to understand the unknowns (more than 99% of marine benthic species and 95% ocean), and any present continuous activities, we continue to explore the man-made structures.

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