Concrete Seawalls: Load Considerations, Ecological Performance, Durability, and Recent Innovations

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Abstract

Increasing frequency of extreme weather events, driven by climate change, has resulted in an increasing demand for coastal structures to protect and stabilize shorelines. Concrete seawalls are a common category of coastal protection structures, designed with the primary objectives of absorbing wave action, preventing coastline erosion, and alleviating flooding. Much research has been carried out on improving the seawall performance. This work is a review of the current state-of-the-art in concrete seawalls focusing on design aspects including wave loading and innovative seawall designs, ecological considerations, and durability aspects. Wave loads on seawalls have received significant attention; however, their quantification remains a challenging task especially for novel designs. Drawing inspiration from natural shorelines, modification of surface complexity at a multitude of scales can improve the otherwise poor ecological performance of seawalls. The corrosion of the steel is a major durability concern, and the use of non-corrosive reinforcement can increase seawall durability towards corrosion. Examples of innovative seawall designs and

systems which have the capability to outperform conventional seawalls are discussed. Advances in structural design, ecological engineering, and infrastructure materials science will drive the development of multi-functional seawalls which are sustainable, durable, and resilient.

Keywords: Seawall; coastal protection; design; ecology; sustainability; durability

1. Introduction

The management of coastal resources is a matter of utmost importance for the global economy, considering the high percentage of the global population that lives close to the coast [1-2]. Increasing populations in coastal urban communities has meant that coastal protection has become more widespread than in the past. Improper selection, design, and construction of coastal protection systems can result in damage to individual properties, loss of land, and environmental degradation, when structures are exposed to extreme weather events [3]. The damage that occurs is often not repaired due to high costs of repair, leaving the aging infrastructure vulnerable to further damage and potentially catastrophic failure. This alarming situation has been exacerbated by sea level rise and the increased frequency of severe storms and storm surges [4]. Therefore, adequate performance of coastal structures is key to the safety of our coasts and coastal communities. While 'adequate performance' is subjective, an ideal coastal structure would provide protection from extreme weather events, demonstrate ecosystem services, and last for its intended service life without the need for excessive repair.

Coastal structures are built on the coastline or at a small distance from the coastline and comprise a variety of structures such as seawalls, jetties, breakwaters, etc. They are generally divided into "soft" and "hard" coastal structures, with soft structures being erodible by the sea, while hard structures are generally not (substantially) erodible [3]. Coastal structures serve many purposes, including reducing coastline erosion, flooding, and wave impact. They can also protect boat traffic and stabilize navigation channels, in addition to serving aesthetic and limited ecological purposes [5]. General reviews of coastal protection structures can be found in [6-10]. This paper focuses on concrete seawalls, specifically, loading considerations, innovative systems, ecological performance, and material durability. Challenges that limit the performance of concrete seawalls and innovations that enhance performance are highlighted.

Concrete is the second most used material in the world (after water) as it is a cost-effective, highly versatile, moldable material, made with ingredients that are widely available [11]. Concrete is attractive for marine applications for these reasons and because of its inherent mechanical properties and durability, including in aggressive conditions [11]. Recent advances in material science, civil engineering, and construction technology have the potential to make concrete a sustainable, durable, and resilient material for seawall construction [12,13].

The primary purposes of a concrete seawall are reducing wave impacts, coastline erosion, and flooding [14,15]. Concrete seawalls are generally massive, long structures made of steel-reinforced concrete. While a very significant amount of research has been performed on seawall structures over the last century, there are still numerous concerns regarding seawalls. Three of the most important of these concerns are: a) the ecological performance of concrete seawalls is typically poor, b) the steel in the seawalls tends to corrode over time, leading to cracking and damage, and c) repair of damaged seawalls is not always carried out in a timely fashion.

Seawalls are subject to high magnitude forces due to wave action, especially during storm surges due to wave breaking and overtopping [16]. In addition, the waves reflected off the seawalls can cause significant amounts of sediments to move away from the seawall into the sea, which can result in undesirable scouring at the seawall toe [17]. Figure 1shows three common seawall designs are typically constructed to protect shorelines [18].

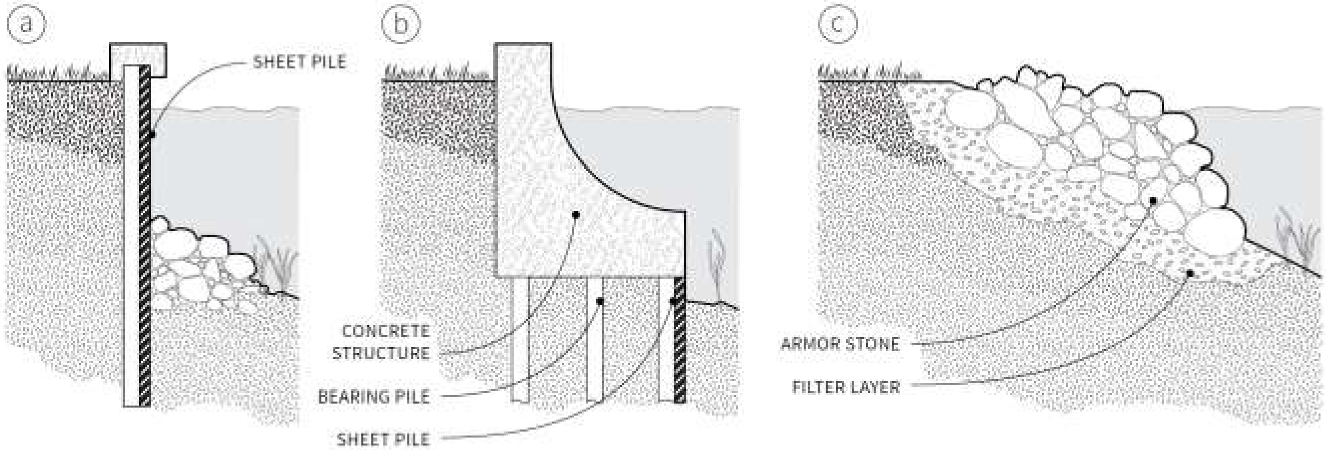

Figure 1: Typical concrete seawall designs for coastal protection: a) Vertical seawall, b) Curved seawall, c) Riprap (redrawn based on [18]).

Vertical seawalls (Figure 1a): Vertical seawalls are particularly attractive in locations where there is small footprint availability and/or harsh wave conditions and high surges. The stability of a vertical seawall against horizontal forces and sliding is provided by its weight and the friction with the underlying surface [19]. Such seawalls are subjected to high wave reflection in front of the structure with a reflection coefficient close to unity [20], which leads to greater forces and scouring at the toe.

Curved seawalls (Figure 1b): The curved design of these seawalls reduces wave overtopping and redirects wave energy due to waves breaking back in a seaward direction [21]. The curved-face of the structure attenuates wave energy resulting in lower stress magnitudes [22]. Failure analysis reveals that curved seawalls are more stable and perform better during dynamic loading when compared to vertical walls [23]. While they show better performance, curved seawalls are typically more complex to design and construct compared to vertical seawalls.

Riprap or mound seawalls (Figure 1c): These structures are simply mounds of various materials including concrete fill [24] and are relatively inexpensive when compared to vertical and curved walls. As riprap distributes weight over a wide surface, these structures can prevent foundation failure for locations with poor soil characteristics. One of the benefits of riprap is that the loss or failure of some of the armor stone will not result in total collapse and the system can continue to function [25]. Repair or restoration of riprap systems is also relatively easier. The porous geometry of riprap results in greater wave energy dissipation and reduced wave reflection. Therefore, riprap is also utilized in front of seawalls to prevent scouring. Special types of riprap configurations consisting of interlocking concrete blocks can also be employed to reduce wave run-up, overtopping, and scouring at the base of existing seawalls in cases of high tidal flows [26].

2. Scope, Overview, and Methodology

Three major aspects of concrete seawalls are covered in this article: design loads, ecological considerations, and material durability. Common seawall designs, such as those shown in Figure 1, often do not satisfy the expected level of shoreline protection, especially during extreme conditions [27-31]. The design wave forces borne by these structures represent a complex topic that has received significant attention by researchers as discussed in Section 3. In many cases, negative impacts on marine ecosystems due to concrete seawalls (including loss of biodiversity and the loss of seagrass near the seawall) are significantly high and unrecoverable in the long-term [32-34]. However, this loss of ecosystem services can be alleviated through the integration of ecological engineering considerations such as the use of multi-scale complexity [35-38] (Section 4). Seawalls often show cracking, degradation, and damage, commonly due to the corrosion of the steel reinforcement. Material degradation processes and means to mitigate damage are detailed in

Section 5. Finally, Section 6 discusses examples of innovative designs that have the capability to perform better than the traditional seawall structures.

The review was carried out in an objective manner, by searching several keywords: "*concrete seawall*", "*concrete seawall design*", "*concrete seawall design loads*", "*concrete seawall ecological performance*", "*concrete seawall durability*", "*concrete seawall non-corrosive reinforcement*", and "*concrete seawall design advances*". The first 30 results from each search were considered to be relevant publications and used as a starting point. There was overlap in some of the returned results; indeed only 155 out of the total 210 possible publications were distinct. The abstracts of these 155 publications were then reviewed; 60 of these publications were deemed not relevant or out of scope based on the abstract. The remaining 95 publications were reviewed in depth. Relevant publications that were cited in these papers and were not revealed in our search were also identified and reviewed. In total, more than 200 publications were reviewed. Sections 3 to 6 present a compilation of our findings for each topic of interest.

3. Load Considerations

Common design guidelines and standards for seawalls include Coastal Engineering Manual (CEM), Shore Protection Manual (SPH), ASCE standards, and FEMA publication manuals. The predominant forces for designing seawalls include hydrostatic, hydrodynamic, and wave loads [39,40]. These forces should be added to other loads such as dead, wind, and impact loads with a relevant combination factor depending on the coastal condition of the area [27,41]. However, accurate estimation of related design loads is not explicitly prescribed for different built environments. Hydrostatic loads occur as a result of static water pressure on the structure; however, they do not usually yield a governing loading condition for seawall design [42].

Hydrodynamic loads are caused by the dynamic effect of moving water on the surface of the structure and can be determined based on fluid mechanics. The impact loads result from debris, ice, and other objects striking the structure are typically modelled as concentrated loads [39]. The wave loads, which are usually critical for the design, represent the dynamic pressure induced by waves on structures [43]. The wave forces depend on both wave kinematics and dynamic characteristics of the structure and typically exhibit large variations [44]. Depending on the region, seawalls might be also subjected to lateral and vertical seismic forces as well as soil liquefaction [45,46], however, such loads are out of the scope of this paper.

Wave loads are challenging to analyze, as the wave-structure interaction is complex and depends on factors such as site conditions (i.e., water depth, wave characteristics) and the geometry/form of the structure [42,47-49]. A proper understanding of wave forces is critical for avoiding failure, i.e., structural collapse and overturning in seawalls, which can occur when seawalls are exposed to large wave breaking forces [50]. Although existing guidelines and standards propose practical methods to determine the design wave forces for vertical seawalls, to the best knowledge of the authors, there is no explicit method that can provide an accurate estimation of wave loads for all applications and conditions. As the other loads are relatively simple to quantify or do not govern loading conditions for design, the following section is dedicated to critically reviewing existing approaches for quantifying wave loads.

Generally, wave loads on coastal structures can be divided into slowly acting pulsating loads, and impulsive or wave breaking loads. Pulsating loads are non-breaking loads that can be determined with acceptable accuracy by existing empirical expressions, for example, as an approximately hydrostatic pressure produced by the highest water level reached by the design wave [51]. Sainflou [52] presented an analytical solution for non-breaking waves approaching at a right angle to the seawall that is still applicable to current designs [53,54]. On the other hand, impulsive wave loads due to wave breaking on structures are more complicated to calculate and have always been a challenge for designers [55]. There is not a unique universally accepted method accounting for the wave breaking force, also known as the impulsive horizontal force. A method was developed by Minikin (based on the Bagnold model [56]) [57], which takes into account wave impact force due to breaking waves onto a vertical coastal structure (Eq. 1). Although the Minikin formula gives a good approximation of wave breaking force for many cases, it is not dimensionally consistent [58].

$$F_{h,imp} = \frac{101}{3}\frac{\rho g H_d^2 h}{L_d D}(h + D) \tag{1}$$

where $F_{h,imp}$ $(\frac{N}{m})$ is the wave breaking force, ρ $(\frac{kg}{m^3})$ is the water density, g $(\frac{m}{s^2})$ is the gravitational acceleration, H_d (m) is the design breaker height, L_d (m) is the design wavelength, D (m) is the water depth at distance L_d in front of the structure, and h (m) is the water depth at the toe of the structure. Additional information regarding the Minikin method and the distribution of dynamic wave pressure can be found in [57,59,60].

Experimental work conducted by Goda [59] resulted in a new expression for predicting wave breaking force on seawalls which was later expanded to consider other parameters such as the effect of a berm, slopping top, and incident wave angle [61-63]. Further laboratory testing by Kortenhaus et al. [64] and Klammer et al. [65] led to a new prediction method for wave impact loads that is widely utilized in building and structural manuals such as the British Standards (BS6349-1, 2000) [66] (Eq. 2).

$$F_{h,imp} = 15\rho g d^2 \left(\frac{H_{si}}{d}\right)^{3.134} \tag{2}$$

where H_{si} (m) is the design significant wave height at the toe of the structure and d (m) the water depth.

Further developments were discussed in detail by Allsop et al. [67] and Oumeraci et al. [68] who presented a new formula for determining maximum impulsive horizontal force (N/m) given in Eq. 3.

$$F_{h,imp} = F_{h,imp}{}^{*}\rho g H_b^2 \tag{3}$$

where H_b (m) is the wave height at breaking and $F_{h,imp}{}^{*}(\frac{N}{m})$ is defined as relative maximum wave breaking force following a Generalized Extreme Value (GEV) distribution, expressed using Eq. 4.

$$F_{h,imp}{}^{*} = \frac{\theta}{\xi}(1 - \xi.\ln(p)\,\%) + \mu \tag{4}$$

where $(p)\%$ is the probability of zero breaking forces, θ is the scale parameter, ξ is the shape parameter, μ is the location parameters of the GEV probability density function as a function of the bed slopes [65].

More recently, Cuomo et al. [55] conducted a series of physical tests where they measured both pulsating (quasi-static) and impulsive wave forces at vertical structures. They showed that the impulsive forces recorded were larger than the values obtained using existing prediction methods. As a result, a new set of physically rational prediction formulae were proposed both for impulsive and pulsating forces (Eq. 5 and Eq. 6).

$$Impulsive\ horizontal\ force: F_{h,imp\left(\frac{1}{250}\right)} = C_r^{1.65}\rho g H_{m0} L_{h_s}\left(1 - \frac{|h_b - d|}{d}\right) \tag{5}$$

$$Pulsating\ horizontal\ force: F_{h,pul\left(\frac{1}{250}\right)} = 4.8\rho g H_{m0}{}^{2} \tag{6}$$

where L_{h_s}(m) is wavelength at the toe of the wall, C_r is the dimensionless reflection coefficient, H_{m0} (m) is significant wave height, h_b (m) is water depth at breaking, and d (m) is water depth in front of the wall. The term $(\frac{1}{250})$ refers to force at $\frac{1}{250}$ exceedance level.

Although wave loads on seawalls have received significant attention, their quantification remains challenging due to their dependence on a multitude of parameters and their stochastic nature [55,69]. For instance, current prediction formulas for impulsive wave forces are applicable to structures that behave as single degree of freedom systems. More detailed models are required for irregular structures with complex dynamic responses [70]. For innovative seawall designs (Section 6), including when seawalls have complex geometry and/or features such as perforations, the wave loads and the performance of the structure in terms of wave reflection has to be quantified through physical testing in wave tanks [10]. In wave tank testing, rigid scaled models of the structure are tested under different waves with loads with performance being defined based on water level, pressure and/or force measurements. It is important to note that physical testing has to maintain the similarity between the prototype structure and the model. The similarity is typically expressed through the Froude criterion, i.e., the Froude number in the prototype structure and the model have to be the same [71,72]. The design of the physical model depends thus on the prototype conditions as well as the wave tank capabilities. Exploring experimentally defined loads along with analytical and numerical models can lead to better seawall designs that use material in a more efficient way while promoting biocompatibility through multi-scale complexity.

4. Ecological Considerations

Marine diversity decreases with the loss of coastal wetlands and nearshore communities with seawall construction. The loss of horizontal extent of coastal communities occurs with seawalls, contributing to their poor ecological performance. A major reason for the poor ecological performance of seawalls is that seawalls truncate the intertidal zone and are less structurally complex than the natural communities replaced [73-75]. Reduced surface complexity results in overall decrease of microscale diversity of fouling organisms [76-83]. In addition to showing lower levels of benthic and ichthyofaunal diversity, as seawalls are limited in extent both vertically and horizontally compared to natural systems, they can cause habitat fragmentation and disturbance. Fragmentation of biotic communities and disturbance is exacerbated by scouring and repetitive maintenance along seawall structures [36,84,85]. Low structural complexity can lead to reduction of available habitat for recruitment and growth of common nearshore marine organisms [86,87]. Despite these shortcomings, if designed considering ecological features, seawalls have the potential to replicate natural marine habitats and support some species of marine life [39].

An effective solution for restoring the habitat of marine organisms and to potentially increase abundance and diversity populations is to design structures using natural materials or structures that emulate the physical properties of natural structures [88,89]. Fishes and benthic invertebrates populate and interact in greater numbers on materials with rugose and irregular surfaces rather than a smooth, flat wall [90]. In addition to rugose surfaces, the use of holes/crevices also helps increase benthic diversity [35,36,91-93]. Innovative seawall designs using precast concrete steps to introduce shallow water structures can attract fish and increase submerged aquatic vegetation [94]. Introducing multi-scale complexity/texture is critical for enhancing benthic biodiversity as it increases the availability of food [83,95] while providing shelter from predators for various nearshore marine species [92]. An effective example of such design would be to use precast concrete steps, accompanied by surface texture modifications (at smaller scales) using cobbled surfaces, grooves, hollow or cast ledges to further enhance microhabitats [35,41,96-98]. The importance of surface texture has also been confirmed in concrete breakwaters. Proprietary concrete mixtures with substantial texture showed greater abundance of fish, invertebrates, submerged aquatic vegetation, along with increases in diversity of marine organisms, when compared to mixtures with conventional concrete and no surface texture [99].

Whether the chemistry of the concrete itself has an effect on the benthic diversity is not clear. In one study, concrete mixture designs including alumina-rich cement blends and slag-based cement with different pozzolans were tested and monitored after 3, 6, 12 and 24 months for their biodiversity [99,100]. The tested matrices had about 10 – 20% higher marine fouling communities cover than standard Portland cement matrices [99]. The higher diversity in these alternative mixtures has tentatively been suggested to be caused by lower pH [88,99,101]. On the other hand, a recent study concluded that carbonated (lowered pH) concrete substrates did not support greater species richness and abundance, and/or alter community composition, in both temperate and tropical intertidal habitats [102]. It is possible that the use of 'natural' materials in the concrete mixture design could help increase biodiversity. Concrete mixtures using hemp fibers and recycled shell material supported significantly more live cover than control materials [103]. The direct effects of concrete composition on biodiversity do not appear to have been adequately investigated. In addition, it is unclear why exactly lower pH or the use of natural materials in the concrete mixture would increase biodiversity and how long such effects would persist.

Studies have also compared concrete with other materials. A case study in Australia compared sandstone and concrete used in construction of seawalls in terms of their effects on the marine life (specifically grazing gastropod molluscs) [104]. The two habitats supported a similar suite of benthic species, although in different numbers and frequencies of occurrence; tidal height also had an effect on the observed species. When comparing materials, the effects of ocean acidification also become important. The effects of ocean warming, acidification, and type of coastal infrastructure material on algal turfs has been investigated [105,106]. Seawater acidification resulted in greater covers of turf, though this effect was counteracted by elevated temperatures. Concrete supported a greater cover of turf than granite or high-density polyethylene (HDPE) under all temperature and pH treatments, with the greatest covers occurring under simulated ocean acidification [106].

Solutions to enhance the benthic diversity of fouling communities on already existing seawall structures have also been studied [107]. Four 1.5 m x 0.8 m seawall panels made of 'bio-enhancing' concrete with high structural complexity were deployed in an active marina. The panels were surveyed 2, 7, 12, 18, and 22 months post deployment using 0.3 × 0.3 m quadrats in both intertidal and sublittoral zones of each panel and compared to fixed control quadrats comprised of scraped sections of the original concrete marina seawall. Examined parameters included live cover, richness, biodiversity; all were significantly higher on bio-enhanced panels compared to control. Moreover, mobile invertebrates and resident fish species were clearly enhanced through design aspects (holes and crevices) of the bio-enhanced panels [107]. While modification of existing concrete should be done with caution, it stands to reason that careful modification of the concrete surface would result in increasing the benthic diversity of seawalls [100,107,108].

Multiple studies have focused on the combined effects of physical complexity and biotic complexity of the surface on the benthic diversity of seawalls [92,109]. To provide biotic complexity, the surface was manipulated by seeding with two common habitat-forming species and naturally recruited fouling. Physical complexity was compared for flat surfaces and surfaces with structured crevices [109]. Results showed that physical complexity, regardless of biotic complexity (through seeding or natural fouling), increases the amount of time that fishes interact with the substrate (2000 seconds on average for the structured and 1000 seconds on average for flat tiles). Biotic complexity also increased the interaction time – 1100 seconds for tiles seeded with algae, 1600 seconds for naturally fouled tiles, and 1800 seconds for tiles seeds with oysters. The average interaction time for unfouled flat tiles was close to 0 seconds while it was on average 2300 seconds for naturally fouled structured tiles, demonstrating the importance of both types of complexity [109,110].

It has been suggested that ecoengineering projects, which seek to maximize the biodiversity of multiple functional (taxa) groups on seawalls, should apply a variety of different microhabitats to alter the environmental conditions available to organisms [92]. Novel artificial structures such as rock pools or pits, planted vegetation, mangrove prop-roots, or reef blocks can be incorporated into new seawalls during construction to provide an alternate habitat for fish, invertebrates, reptiles and other marine organisms [12,111-113]. In addition to seawall design considerations which enhance their performance in regard to marine habitat, there are also proposed design concepts that provide nesting places for coastal wildlife by integrating hollow sections on areas of the seawall above the sea level [114].

Negative impacts on marine ecosystems due to concrete seawalls occur due to a variety of reasons: truncation of the intertidal zone, reduced surface complexity, reduced vertical and horizontal extent, increased turbidity, coastal eutrophication [115,116]. Limiting these negative issues can be challenging and a one size fits all approach is unlikely to work. However, as discussed in this Section, recent research has shown promising results when using approaches inspired from nature including increasing surface rugosity and biotic complexity.

5. Durability of Concrete Seawalls

A durable seawall structure will meet the desired level of performance while maintaining acceptable appearance throughout its service life [117]. Since concrete is weak in tension, steel reinforcement is often used to provide the needed tensile strength. However, since steel is vulnerable to corrosion from chlorides in the seawater, in practice, it is challenging to design concrete seawalls that have a long service life with minimal maintenance in the harsh marine environment. Durability concerns for concrete seawalls are discussed in this Section.

5.1. Steel Rebar Corrosion

Deterioration of the reinforcement in any concrete structure, including in concrete seawalls, affects structural safety and serviceability in an adverse manner [118]. When steel is embedded in concrete without sufficient protection (cover) or when the covering concrete is cracked, chloride ingress initiates. Over time, the chloride ingress leads to the onset of pitting corrosion when the chloride concentration near the steel surface exceeds a critical threshold [119-121]. This threshold is not easy to calculate or predict, since it is affected by several factors related to the steel, the concrete, and the exposure environment [122,123]. Much research has been done on chloride ingress and corrosion in marine conditions, including the development of a theoretical model to predict the service life of reinforced concrete seawalls which shows that the service life increases with cover thickness, concrete tensile strength, threshold chloride concentration, burial depth and surface load, but decreases with an increase in rebar diameter and water-cement ratio [124].

Performance of seawalls predicted in theory and practice is often different. This is partly due to concrete cracking, which is challenging to model and can greatly modify the rate of chloride ingress. In seawalls, where the concrete cover is often cracked due to abrasion, storm effects, and poor maintenance, it is rather probable that chloride-induced corrosion will occur at some point

[125]. Premature corrosion reduces the performance of the structure under normal conditions. Under hurricane loading, such seawalls may fail in a catastrophic manner, causing substantial loss of life and economic damage. Therefore, it is critical to minimize chloride-induced corrosion in seawalls. Figure 2 shows examples of damaged seawalls with evident corrosion.

Corrosion requires the presence of both oxygen and moisture [126-128]. Therefore, corrosion does not typically initiate in reinforced concrete that is permanently immersed in seawater. Even if corrosion does initiate, the corrosion rate is negligible because of the small amount of oxygen that reaches the steel surface [129].

Figure 2: Seawalls showing evident corrosion damage.

Considering the long service life of seawalls (sometimes up to 100 years), eliminating steel corrosion is challenging. Numerous measures can be considered to mitigate steel corrosion:

Concrete mixture design: Concrete mixture design can be modified to increase the time before corrosion initiates. Such modifications include the use of supplementary cementitious materials (SCMs), reducing the water-cement ratio, and decreasing the porosity and permeability of the concrete [130]. Such changes slow down the ingress of chloride into the concrete, though they may be less effective once the chloride reaches a critical concentration near the steel surface. The use of SCMs often improves concrete sustainability and durability, and most current marine concretes include such materials in their mixture designs. Increases in service life that result with the use of SCMs have been demonstrated, including in a recent laboratory and case study of concrete exposed to chloride environments at the University of Toronto [131]. Chloride transport models have shown that incorporation of fly ash and slag in concrete slowed chloride ingress to a much-decreased rate over the long-term, leading to corrosion delay/prevention and dramatic increases in the predicted service life [131,132].

Coatings and anti-corrosion admixtures: Implementing waterproofing coatings and anti-corrosion admixtures in concrete, either as topical applications or throughout the material can lead into excellent anti-corrosion performance of the structure [133]. Topical applications need to be re-applied periodically. However, neither solution may be effective if the concrete cover is cracked. The use of such admixtures can also increase initial costs, although they can reduce costs over the life-cycle in addition to providing environmental benefits.

Allowable crack width: Reducing the maximum allowable crack widths to smaller values increases the time needed for chloride ions to reach the steel reinforcement and cause corrosion; however, such changes might also result in over-design [14].

Steel reinforcement alternatives: As long as conventional steel reinforcement is used in seawalls, there is always a probability of corrosion initiation, even when appropriate corrosion mitigation measures are taken. Therefore, the use of non-corrosive reinforcement, such as stainless steel or fiber-reinforced polymer (FRP) is an attractive alternative to the use of conventional steel rebar. Such reinforcements do not corrode and are starting to be used more commonly in marine applications [134]. While their use will increase initial costs, significant cost-savings have been demonstrated through the service life [135].

Quality assurance and maintenance: Implementing appropriate quality assurance protocols and conducting appropriate tests during the construction process can reduce the risk of corrosion. These tests include rapid chloride permeability, bulk resistivity, or compressive strength testing of cubes and in-situ cores, water absorption tests, water permeability tests, and reinforcement cover surveys using cover meter [136]. Similarly, regular maintenance of seawalls can identify issues before significant repair or reconstruction is required.

5.2. Alkali–Silica Reaction

Alkali-silica reaction (ASR) is a reaction between reactive silica in concrete aggregates and the alkaline pore solution leading to a gel product, which expands on imbibing moisture and leads to cracking and spalling. Deterioration of coastal structures due to ASR has been reported in multiple studies in different regions around the world [137,138]. Among these cases, there was a 1.4 km long precast concrete armor unit in the United States which was designed for a service life of 50 years, but had to be entirely replaced after 22 years due to excessive damage [137,138]. Multiple cases of damage in coastal structures attributed to ASR, have been reported in Japan [139]. In addition to seawalls, affected structures included T-type piers, partial shelters at the seaside, and precast concrete armor units. Reported crack widths ranged from 0.2 to 15 mm [139].

Prevention measures to limit ASR damage have been discussed in detail in literature [140]. The most obvious strategy is to use non-reactive aggregates, but this is sometimes not possible due to cost restrictions. If reactive aggregates are used, then ASR can be mitigated as follows:

- Use of SCMs, especially fly ash, in sufficient quantities; these reduce the pore solution alkalinity and the resulting expansion [141].

- Use of adequate dosages of lithium admixtures to suppress the swelling. These materials do not reduce the formation of gel, but reduce its expansive nature [142].
- Reducing the alkali contribution from the Portland cement component of the concrete, either by reducing the amount of cement or by reducing the amount of alkali in the cement reduces the pore solution alkalinity and the resulting expansion [143].

5.3. Sulfate Attack

Sulfate attack is caused by external/internal sources of sulfate reacting with aluminate phases in the concrete. These reactions lead to the formation of expansive phases such as ettringite, which cause damage. Alternatively, sulfate attack could be a physical damage mechanism, where damage is caused by crystallization pressure exerted by certain sulfate phases in the presence of water. Sulfate attack in marine environments occurs when seawater containing sulfate ingresses into the concrete. Sulfate attack in concrete seawall structures can cause deterioration in the form of expansion, cracking, loss of strength and stiffness, and disintegration. Sulfate attack, and other damage mechanisms which cause cracking, can eventually lead to greater chloride ingress and steel reinforcement corrosion, compounding deterioration [144,145].

Evidence of external sulfate attack was found in a polished section of a damaged concrete seawall in Wood Island (Kittery, ME) [146]. This attack occurred on the seawall surface exposed to the seawater. Other cases have also been reported; however, it is noted that sulfate attack may be suppressed in the presence of chloride, which is found in higher concentrations in seawater. There are multiple measures that can be implemented to limit the deterioration by sulfate attack in concrete seawall structures, including replacing a portion of the cement with SCMs such as fly ash, slag, silica fume, and the use of high-quality concrete with low water-cement ratio, porosity and permeability [147-149].

6. Innovative Seawall Designs

In the following section, recently developed innovative seawall structures for protecting shorelines are discussed.

6.1. Use of FRP as Reinforcement

Considering the pervasive issue of corrosion, the use of FRP and stainless-steel reinforcement can be valuable in eliminating corrosion. Much research has been done on these materials, as they are corrosion resistant and provide sufficient mechanical performance [150,151]. FRP is especially attractive, as these materials have higher specific strength, higher specific stiffness, and lower specific weight relative to conventional steel rebars. FRP has already been used in construction of real-life seawalls in South Florida [150].

In 2019, quality assurance and code compliance evaluation of glass FRP (GFRP) rebars for use in seawalls were carried out for a project at the seaside community of Flagler Beach, FL which was severely impacted by Hurricane Matthew in 2016. The protection system was a GFRP-reinforced concrete secant-pile seawall/bulkhead designed to provide support for the highway in the event the adjacent sand dunes were lost during a major storm [152]. The use of GFRP should eliminate the possibility of corrosion, resulting in minimal repair and maintenance costs of the structure over its life cycle [152,153].

The feasibility of using basalt FRP (BFRP) as reinforcement has been investigated in the lab [154]. An alternative design of a seawall system using BFRP bars was tested and the results of the seawall slab specimens demonstrated that the system design achieved the required performance [154]. Overall, there is a growing awareness of the properties of FRP as a structural material within the construction industry and there is ongoing research to further investigate where and how it can be used in concrete structures in pursuit of improved durability, performance, and resilience [155].

6.2. Permeable and Perforated Structures

The use of pervious and perforated concrete seawall structures can mitigate the wave load on the structure and reduce wave reflection in front of the structure [156-161]. Such structures will also result in improved water quality and have lesser negative effects on coastal ecosystems due to exchange of flow between open sea and the enclosed regions [8,162-165].

Jarlan [166] proposed a perforated vertical seawall structure to reduce wave reflection, and thus, wave loading (Figure 3**Error! Reference source not found.**). The system consists of two vertical walls with a chamber between them. The wall that is positioned toward the sea is perforated while the wall behind it is solid. As incident waves pass through the perforated wall, they are partly reflected dissipating a large portion of their energy through vortices and friction. The hydraulic performance of the system is highly dependent on the porosity of the front wall and the ratio of the chamber width (B) over the wavelength (L) of the incident waves ($^{B}/_{L}$) [167]. Experiments conducted over a full range of incident wave periods showed that the traditional Jarlan-type system has its optimal performance when $^{B}/_{L}$ is ~2 [168]. A more complex Multi-Chamber System (MCS) has also been designed and experimentally investigated in the Large Wave Flume of Hannover [169]. The MCS seawall design decreases wave reflection, wave run-up, and overtopping. Therefore, it also significantly reduces the resulting horizontal wave forces applied to a seawall. This design can be an ideal alternative for new concrete seawalls over a wide range of practical $^{B}/_{L}$ ratios ($^{B}/_{L} > 0.25$).

A new type of permeable vertical seawall consisting of prefabricated rectangular cells with two perforated walls supported on four circular piles (Figure 4) was investigated by Somervell et al. [170]. The number of cells can be adjusted to reach optimum hydrodynamic performance based on the existing water and wave conditions. This flexible structural system can be modified even after construction to meet changing conditions. The upper part of the vertical walls performs like a wave energy attenuator and the space between the piles provides the required sediment transportation through the structure and acceptable water circulation [170]. The proposed system has enhanced wave energy dissipation and reduced wave reflection coefficient especially in shallow water (h/L < 0.4) and to a lesser extent for deeper water (h/L < 0.5). Both the wave energy attenuation and the wave reflection effects varied depending on the porosity of the upper-portion, with the changes being more dependent on the seaward-side wall porosity rather than shoreward-side. Minimal effects on shoreline morphology and marine habitats are expected with such structures as the space between the piles provides passage for sediment transportation [70].

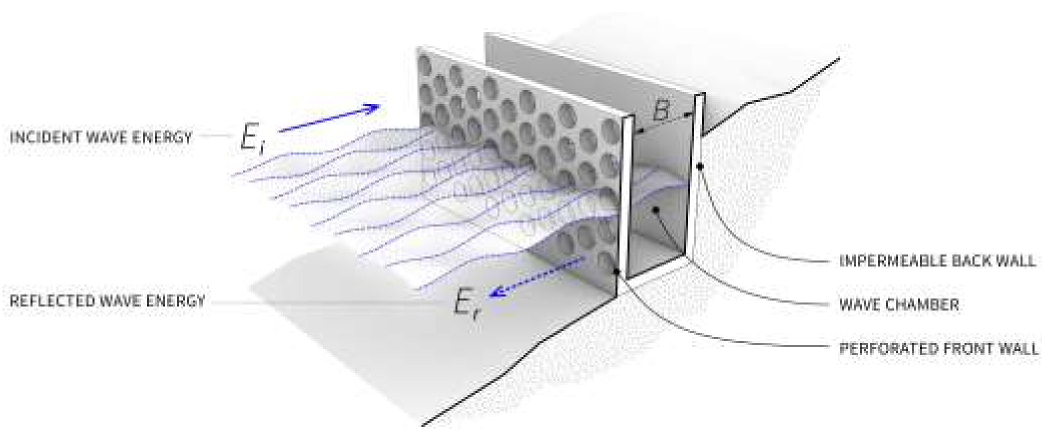

Figure 3: Illustration of a perforated vertical breakwater (redrawn based on [166]).

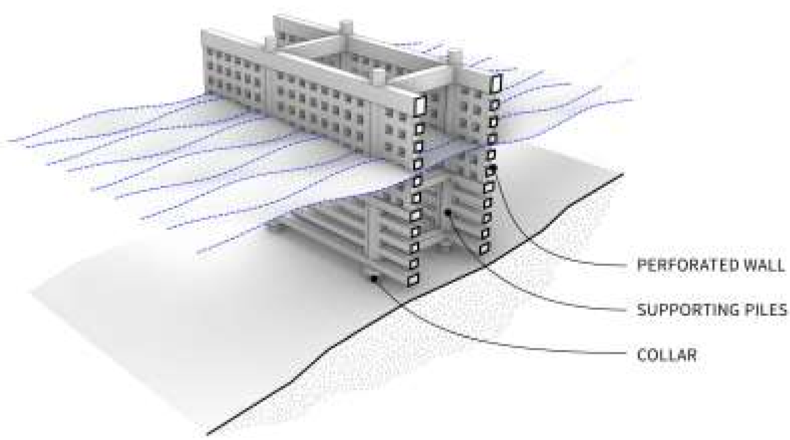

Figure 4: Schematic view of vertical cellular walls (redrawn from [170]).

6.3. Prefabricated Thin-Walled Hollow Seawall

The massive weight of seawalls can be a disadvantage due to high construction costs and large deformation of soil layers underneath resulting in high ground pressure and settlement failures [172]. To reduce the weight and the associated cost, an innovative seawall system consisting of thin-walled concrete blocks (Figure 5**Error! Reference source not found.**) has been developed by BUSADCO [172,173]. The structure is composed of two thin-walled hollow concrete blocks (HCB) at the lower levels, a solid concrete curved wall (SCCW) at the top level for reflecting incident waves, concrete tie beams (CTB) for connecting the HCBs, and concrete berm blocks (CBB) for preventing erosion at the toe of the seawall (Figure 6) [172]. This novel design reduces the amount of concrete used compared to regular seawalls and is consequently suggested to lead to more cost-effective design. The results from a numerical study showed that this lightweight concrete seawall can successfully withstand destructive wave-induced forces without soil failures beneath the structure and the entire displacement of the structure can be significantly reduced (up to 54% in lateral displacement and 64% in vertical displacement) [172-174].

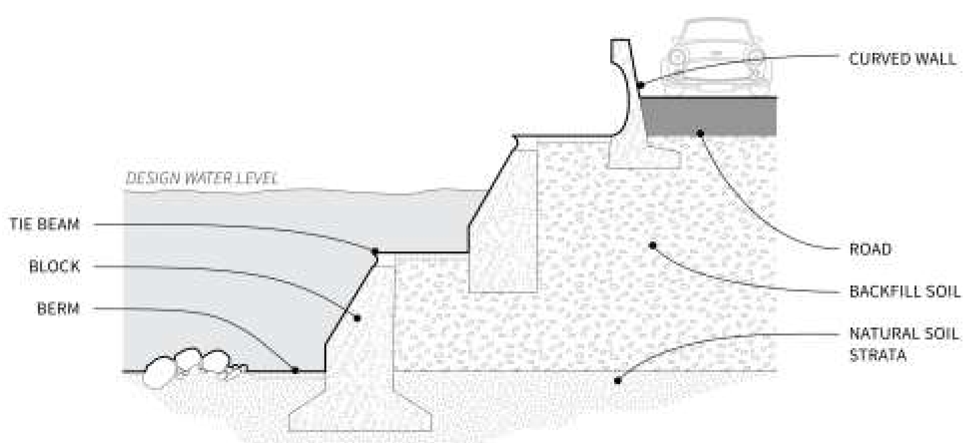

Figure 5: Illustration of a thin-walled hollow seawall (redrawn from [172]).

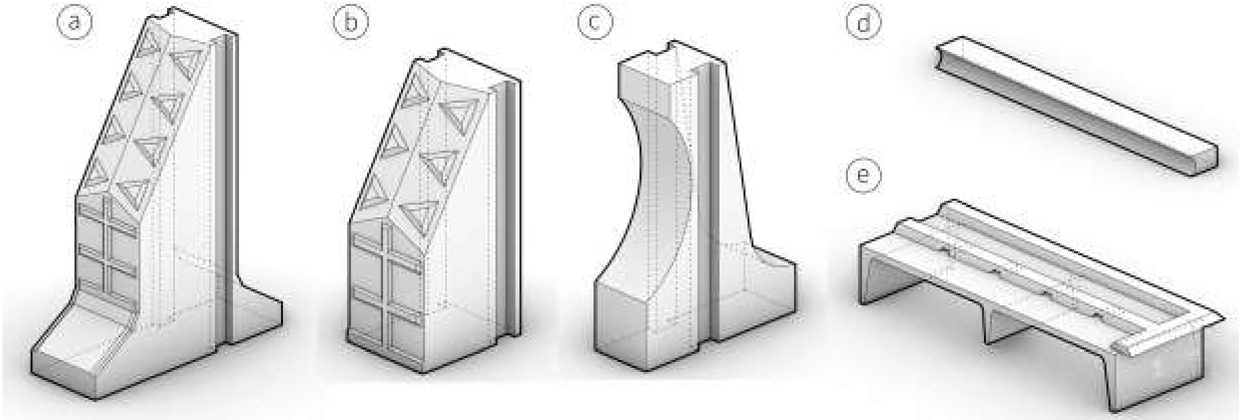

Figure 6: Different concrete components of the seawall: a) HCB-1, b) HCB-2, c) SCCW, d) CBB, and e) CTB (redrawn from [172]).

6.4. New Methods for Seawall Construction and Production

Existing seawalls typically suffer from sliding due to soil erosion at the toe and strong hydraulic pressures caused by storm surges and wave impacts [175]. Recently, a method was developed to protect seawalls against sliding through constructing a seawall reinforcement structure [176]. In this novel method, one bottom layer of concrete blocks is laid horizontally over the sediment covering fabric and abutting the seawall base and multiple vertical blocks are applied over the first layer (Figure 7a). Each block has a four-prong star-like geometry in an integral paired relationship (Figure 7b). Concrete piles are drilled or cast in place through the bores to the bottom sediment to hold the structure in place in case of severe storm surges to withstand outward movement of the seawall (Figure 7c). This new method and resulting structure can dissipate the incident wave forces and prevent erosion along shorelines and consequently enhance the sliding stability of seawalls. In addition, a variation of this method can be employed to construct a jetty by interconnecting vertical and horizontal interior spacers within the blocks (Figure 7d).

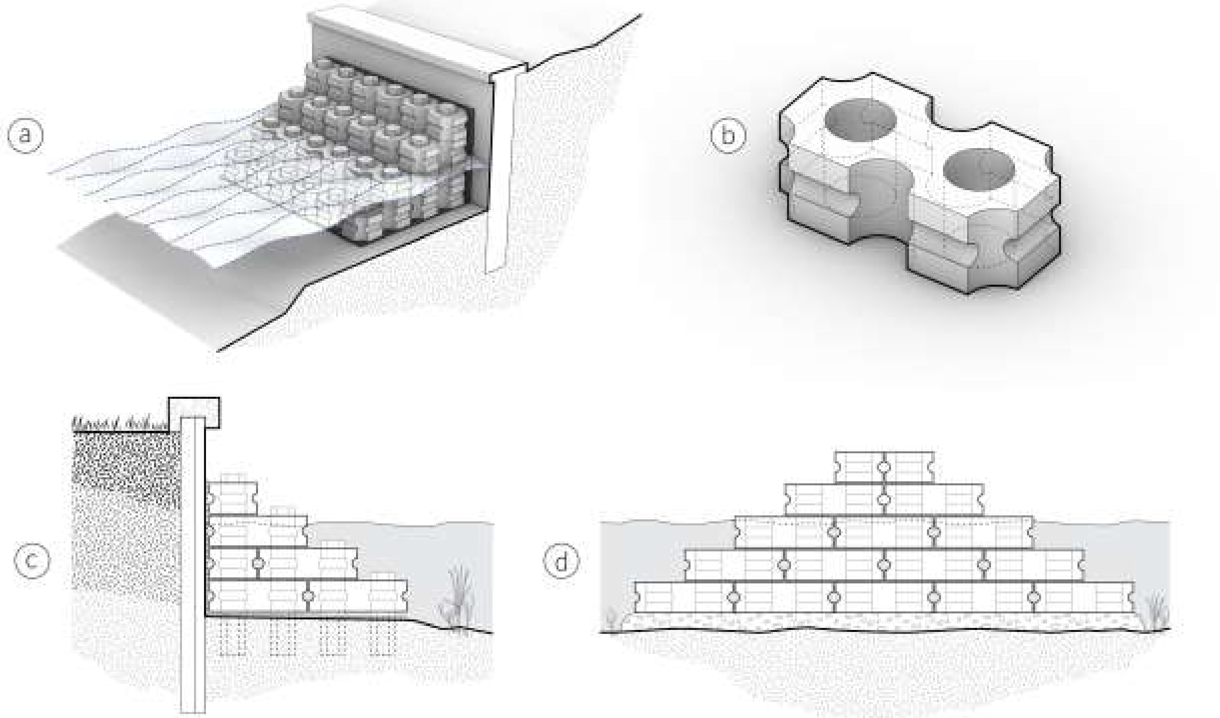

Figure 7: Illustration of permeable fabric blocks for seawall reinforcement: a) An existing seawall reinforced with this method, b) A perspective view of the concrete block, c) A side elevation of reinforced seawall, d) A section view of a jetty configuration (redrawn from [176]).

Material composition and structural complexity effects have been investigated in the development of an innovative seawall system called "SEAHIVE^{TM}", which is a modular marine and estuarine protection system [177] (Figure 8)**Error! Reference source not found.**. The SEAHIVE^{TM} system is comprised of a series of perforated hollow prismatic elements. Perforations on the side faces of the elements provide passage for water flow under surging or breaking waves dissipating the wave energy within the elements adding also structural complexity to the structure and thus improving their potential for biocompatibility. Biocompatibility can be further enhanced through the use of textured surfaces at multiple scales. The modularity of the SEAHIVE^{TM} system has adaptive features allowing elements to be oriented vertically or horizontally paving the way for various applications and topographies. The proposed system can be employed as an independent shoreline protection system or an auxiliary system enhancing existing shoreline protection structures. The design of the SEAHIVE^{TM} system is being developed through a series of experimental tests under the direct effect of wind and wave actions in a wave tank facility. Preliminary results show that the presence of perforations along the elements affects the pressure profile both in distribution and in magnitude with the pressure decreasing for elements with more perforations however this decrease varies for elements with different cross-sectional profiles.

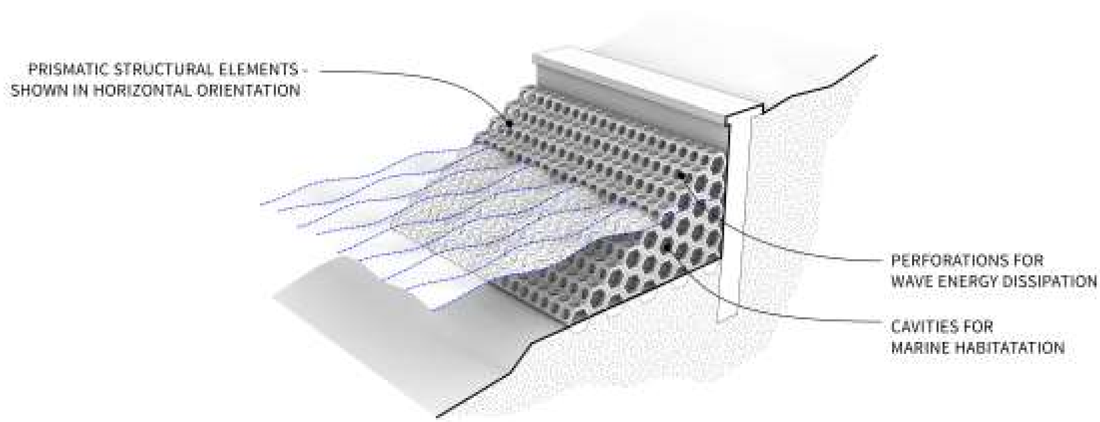

Figure 8: Illustration of a SEAHIVE^{TM} system configuration (redrawn from [177]).

Modular seawalls can also be constructed by simply pilling concrete blocks. Concrete block seawalls produced by natural casting methods are typically accompanied by critical disadvantages such as their high production costs, time-consuming production due to the use of multiple molds, and difficulties in casting process because of intensive material, and low durability in usage conditions. An innovative production method was proposed by Tran in which seawall concrete blocks can be produced with high efficiency, short production cycle, and lower cost [178]. The method uses semi-dry pressing with high pressure and can use high amounts of waste SCMs

[178]. Common shapes of concrete blocks and armors can be produced using this method are shown in Figure 9 [178].

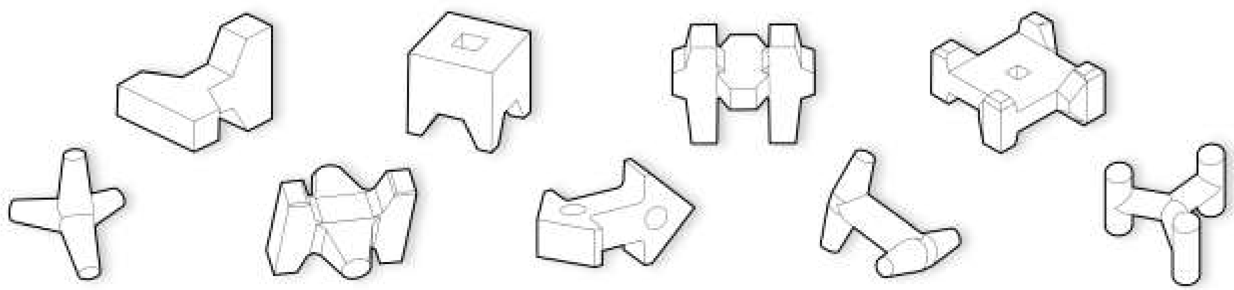

Figure 9: Common shapes of seawall concrete blocks used for shoreline protection [178].

It is not clear if land-based sources of pollution increase or decrease with several of these novel designs and further study is needed. Incorporating microbial components that can absorb Nitrogen and reduce nutrient loading/sediments adjacent to the seawalls could provide further ecological advantages for these designs. In order to truly take advantage of these innovative designs, they must be constructed using durable concrete (which avoids the issues discussed in Section 5). Using sustainable concrete will also reduce the overall environmental impact of construction, and recent advances in concrete technology, including the use of ultra-high performance concrete, seawater-mixed concrete, and concrete 3D printing [179-181] can be leveraged to make seawalls (more) sustainable and durable. Additional material and structural optimization can be performed through careful study and analysis of design loads (Section 3), which may need testing in a wave tank. Finally, following the principles identified in Section 4, the designs can provide promising ecological performance, leading to next-generation multi-functional seawalls. Only a few studies have addressed the need for multi-functionality of seawalls and coastal structures [182,183] and it is hoped that further interdisciplinary research will lead to advances in this challenging topic.

7. Conclusions

Coastal protection including through the use of concrete seawalls is becoming increasingly important in light of increasing coastal population, sea level rise, and the increased frequency of extreme weather events. Properly constructed and maintained concrete seawalls are crucial for the resilience of coastal communities, and will protect these communities from erosion, coastal pollution, and flooding. This paper provided an interdisciplinary overview of important challenges facing concrete seawalls to pave the way for more durable and ecologically engineered coastal infrastructure. The following are the major conclusions of this work:

- The absence of a universally accepted methodology for calculating wave forces in different hydrodynamic conditions complicates the research, development, and performance optimization of novel seawall systems. Laboratory testing and pilot installations are thus critical for the deployment of new technologies.
- Traditional seawalls can cause fragmentation and loss of natural habitats, and generally show poor ecological performance, often as they are less structurally complex than their natural counterparts. Seawalls can be ecologically engineered by incorporating natural materials or using structures that emulate the physical properties of natural nearshore communities. Multi-scale complexity, through the use of rough surfaces, holes/crevices, and texture helps increase biodiversity of concrete seawalls.
- Using non-corrosive reinforcement including GFRP and BFRP can significantly increase the durability of the seawalls and reduce life-cycle costs because of the elimination of the

possibility of corrosion. Seawall concrete durability can also be enhanced through the use of SCMs, low permeable/porosity concrete, and good quality control.

- The use of pervious, perforated, or hollow concrete seawall structures can mitigate the wave load, reduce wave reflection, reduce overall mass, improve water quality, and improve nearshore marine diversity.

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