Living Breakwaters: A Review and Case Study for Raritan Bay, New York

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Contents

Executive Summary

In 2012 the U.S. witnessed 11 climate disasters, including Hurricane Sandy. These disasters led to ~400 deaths and over $110 billion in damages, making 2012 the second costliest year on record, only behind 2005 (NCDC, 2013). This recent increase in high-intensity storm events is requiring coastal managers to develop new strategies to cope with land subsidence, shoreline erosion, sea level rise and the increasing risk of storm-surge-induced floods. Traditional engineering approaches, such as concrete breakwaters, optimizing for risk reduction, are often suboptimal with respect to other functions. This has led to the creation of innovative concepts with regards shoreline protection. Specifically, through the combination of traditional breakwater design with natural ecosystems, called "living breakwaters". These structures are able to follow gradual changes in climate and other environmental conditions, while maintaining near-optimal shoreline protection, ecological values and socioeconomic functions. While still a relatively new concept, living breakwaters are beginning to gain traction. In 2013, and funded by the (Hurricane) Sandy Supplemental, an innovative competition called Rebuild by Design was launched calling for proposals to build sustainable coastal infrastructure. This competition led to the creation of the Staten Island Living Breakwater Project in New York, the largest and most complete living breakwater system ever designed.

This paper presents a high-level analysis of living breakwater design through a three-tiered approach: literature review of the current state of knowledge surrounding the potential advantages, case study of the Staten Island Living Breakwater Project, and numerical wave modelling of the wave attenuation capabilities of three example living breakwater designs.

Introduction

Throughout history humans have always been drawn to the water, especially the coast. Today's modern landscape is no different. Many of the largest cities around the world are located in coastal regions and by 2025 more than 75% of the world's population is expected to live within 100 km of a coast (EEA, 2006). Over 90% of coastal areas are already or expected to be developed to keep pace with this growth. However, a more developed coastline also means a greater risk from wave action and storm events. Historically, this has taken the form of "hard" engineered coastal protection structures whose sole purpose is shoreline protection. However, over the past decade there has been a growing global interest in coastal solutions that efficiently and effectively integrate natural and engineered systems to tackle the problem of shoreline protection. This has resulted in an increase in innovative designs of "hybrid" systems that combine and produce a diverse array of economic, environmental, and social benefits (Bridges et al., 2018). Recently, the U.S. Army Corps of Engineers (USACE), along with its partners and collaborators, have created the Engineering With Nature® (EWN®) initiative in the United States. This initiative is pursuing a vision for water infrastructure based on "the intentional alignment of natural and engineering processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration" (Bridges et al., 2018, pg ii).

If it would be possible to construct a structure that was capable of effective wave attenuation, while at the same time providing increased stability, ecological/environmental, and socio-economic benefits, why would we choose a more conventional structure over this one? In order to improve the design and implementation of such structures, it is critical to first improve our understanding of them. Until now, there are still many unknowns related to nature-based coastal protection structures, specifically in terms of breakwaters. Further lab based and empirical research of these structures can advance project design and encourage implementation, evaluation, and long-term use. Traditionally, worthwhile project opportunities far exceed available funding. Therefore, smart resource allocation requires an assessment of the various benefits and costs in order to maximize the target objectives of such nature-based coastal protection projects. However, until now this assessment has been incomplete for nature-based, hybrid solutions, due to a lack of data availability. Specifically, data regarding design & implementation best practices, as well as wave attenuation efficiency, is missing from the literature surrounding these structures.

The need for sustainable erosion protection, wave attenuation, and social resiliency were demonstrated during the severe storm events of 2012 (including “Superstorm Sandy”), specifically along the eastern coast of the United States. Area’s such as the Tottenville community of Staten Island, located within Raritan Bay, New York, experienced severe damage from storm waves. This damage, along with ongoing erosion that has been experienced over the last 35 years, prompted decision makers to call for an innovative and extraordinary competition in 2013. This competition, led by the Department of Housing and Urban Development (HUD) and funded by the Sandy Supplemental, became known as the Rebuild by Design competition. It called for proposals to build innovative and sustainable infrastructure projects in the Sandy-affected area. One of the winning projects was a series of “living breakwater” systems along the southernmost tip of Staten Island that aimed to successfully incorporate natural ecosystem components into an engineered breakwater design. This project, which is currently under construction, would constitute the largest and most complete “living breakwater” project ever undertaken, and was the primary motivating factor behind conducting this study. By studying this project, we will be able to gain valuable insights into how living breakwaters can be designed, implemented, and monitored, in a high-energy environment such as Raritan Bay.

With population growth expected to continue, as well as the development of our coasts, the need for reliable & sustainable shoreline protection systems is more important than ever. However, integrating natural ecosystems into engineered coastal defense structures raises several technical and socioeconomic questions, specifically regarding the wave attenuation capabilities, ecological/environmental benefits, design specifications, direct and indirect cost-benefit analyses, etc. The purpose of this analysis and findings is not to answer all of these questions proposed above. Instead, this research aims to examine the technical feasibility of a specific type of newly discussed hybrid coastal defense structure. While limited in its scope, this research can provide a unique baseline to further explore how to transition such structures from engineering specifications and pilot projects, to real “on-the-ground” projects.

The intention of this study is to provide the first global synthesis and meta-analysis of the contributions of hybrid breakwater structures to shoreline protection, ecological restoration, stabilization, and socio-economic related benefits. This will be done using a three-tiered approach. First, providing a comprehensive literature review of the current knowledge surrounding the recently studied benefits of nature-based, hybrid breakwater structures. Second, conducting a modern-day case study analysis of the Staten Island Living Breakwater Project, thus providing an up-to-date look as to how these living breakwater structures are currently being designed and implemented. Finally, by evaluating the wave attenuation performance of three example living breakwater designs using a 2-D numerical wave model.

1. Literature Review

The impact of wave energy at the land-water interface is a natural process that influences erosion, sediment transport, shoreline change, and more. These effects on nearshore processes and shoreline change are dependent on multiple factors, including: the offshore wave climate, wave propagation towards the shoreline, and sediment transport as a result of wave-induced currents *(Final Work Plan Currents and Sediment Dynamics Studies for The Raritan Bay Slag Superfund Site*, 2010). While these are natural processes, issues begin to arise when man-made structures and infrastructure are built near this interface.

Seeking the understanding how these natural processes interact with the man-made infrastructure has motivated the creation of coastal protection strategies, as a way to protect our coastlines, including the structures/habitats/communities that reside there. The concept of coastal protection strives to protect the nearshore and shoreline areas against flooding and erosion. The threats associated with erosion can be spatially and temporally limited, only affecting small reaches of the shoreline, or they can occur on large spatial and temporal scales, thus having profound impacts on entire coastlines (Wolters et al., 2005). There are three major questions that a coastal manager grapples with: whether one should implement coastal protection strategies, which strategies to choose, and what are the socio-economic impacts of each (French, 2002). Most commonly, the main objectives of coastal managers include minimizing shoreline erosion and maintaining the current integrity of the shoreline (Piazza, 2005). A large portion of the coastline in the United States is susceptible to erosion, which has led to the extensive “hardening” of our coasts in order to protect against damage to current infrastructure. In certain areas including California, Virginia, and Maryland, over 50% of the natural “soft” coastline has been replaced with artificial man-made structures (Bulleri and Chapman, 2010). As of 1995 in the EU, only 55% of the coastline (56,000km) was deemed “stable”, while 19% was considered to be suffering from erosion problems, and 8% from depositional problems (European Environment Agency, 1995).

Over the past century, high-intensity storm events have become more and more prevalent, further exacerbating the impacts of wave energy on both natural shorelines and the infrastructure located directly landward. In 2012 alone, there were 11 climate disasters in the United States, including Hurricane Sandy. In addition to the loss of almost 400 lives, these storms caused over $110 billion of damages, making 2012 the second costliest year on record, only behind 2005 (NCDC, 2013). This increase in natural disaster frequency, paired with the increasing risks of coastal flooding due to sea level rise, has led to the emergence of coastal protection and resiliency as a major socioeconomic and environmental concern for our government (Sutton-Grier et al., 2015). As a response to this increased need for protection, hard-substrate defense structures have become common staples in our coastal landscapes, specifically in intertidal and shallow subtidal environments (National Institute of Coastal and Marine Management of the Netherlands, 2004). Management objectives of these structures generally include: erosion and flooding prevention of high value coastlines, stabilization and retention of beaches and reclaimed land, and increasing the amenity value of the coast (Airoldi et al., 2005). The growing concern from natural disasters such as high-intensity storms, flooding and sea level rise, pose significant socioeconomic and environmental risks. Large investments are being made into coastal protection and resiliency techniques, but questions still exist on what method should be implemented and why.

1.1 Traditional Breakwater Design

Typically, detached breakwaters are shore-parallel structures that are implemented to either protect the shoreline, or intercept sediment that is moving along the shore (Wamsley, 2002). These structures typically provide shoreline protection via wave energy dissipation through the physical mechanisms of wave breaking and friction (Johnson, 2005).

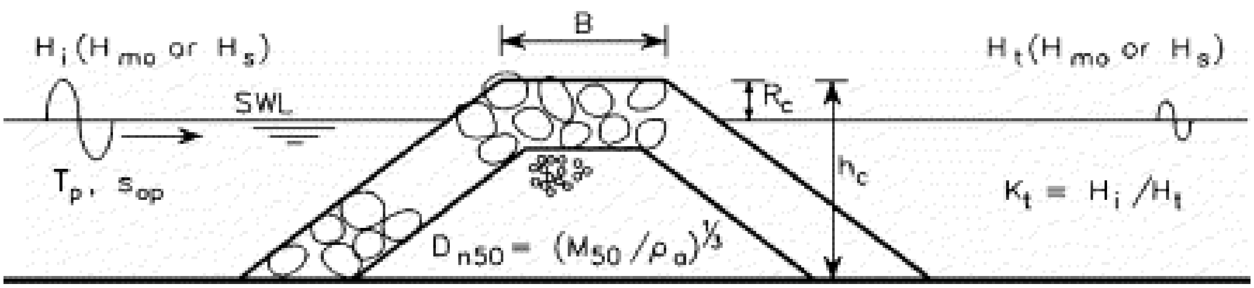

Figure 1. Wave transmission of detached breakwaters, along with notation. Image courtesy of [Van der Meer, 2005]

For decades, breakwaters have been used by the USACE to control erosion and flooding, and there are many advantages to the traditional breakwater as a method of shoreline protection. However, their effectiveness diminishes over time and they are unable to adapt with the changing coastal conditions of sea level rise and increased storm surge occurrence/intensity (O’Donnell, 2017). The vast majority of shoreline protection approaches still utilize a “traditional engineering” approach when considering mitigation efficiency. The issue is that an insufficient amount of concern has been given to the ecological, aesthetic, or socioeconomic impacts associated with these structures (Scyphers, 2011). One major setback with the traditional breakwater design is that erosive wave energies are reflected back into the water body, rather than being absorbed or lessoned by the structure (Douglas, 1999). This results in greater wave energy subjected on adjacent shorelines, as well as erosion on the barrier itself and loss of intertidal habitats.

Additionally, the traditional approach to breakwater design tends to perform well with regards to wave attenuation, however, sub optimally with regards to other functions as well as related to sustainability (Slobbe et al., 2013). This approach is limited in that it only provides high value during storm events (Sutton-Grier et al., 2015). A few additional disadvantages associated with traditional breakwaters include: modification of water flow, sediment transport, decrease in water quality, habitat destruction, and impacts on fish and mobile fauna (Airoldi et al., 2005). If certain environmental considerations, such as poor water quality in stagnant waters behind breakwaters, are highly valued, it often requires the crest of the structure to be designed to a lower level than is optimal for shoreline protection (Ferrario, Filipo, et al., 2014).

Another significant drawback of traditional breakwater design is the lack of, as well as destruction of ecological habitats. When compared to natural hard surfaces, these breakwaters lack the appropriate microhabitats, such as rock-pools and over-hangs, which serve as protective areas against predators and harsh environments (Bulleri and Chapman, 2010). Furthermore, traditional concrete breakwater structures are highly prone to invasive species (Glasby et al., 2007). Oftentimes breakwaters are situated near harbors and marinas, both of which are exposed to invasions via ballast water and ships' hulls (Ido and Shimrit, 2015). This, combined with the design of the breakwater itself, which is typically comprised of repetitive, smooth faced, concrete armor units, attracts opportunistic species that can withstand diverse environments.

There has been extensive research that has shown that at small (< 10 cm) and medium scales (1-10 m), specific surface features such as rock pools, pits, and crevices, provide valuable habitats for species (Coombes et al., 2011; Bracewell et al., 2012). The artificial surfaces of most coastal defenses lack many, or all, of these microhabitats that could be found on natural rocky shores (Firth et al., 2014).

1.2 An Emerging Field: Ecological Engineering

Over the past decade, a new field of engineering has been emerging into the design landscape. Ecological engineering is a relatively new concept that merges ecological, economic, and social needs, into the engineering design process of man-made ecosystems (Firth et al., 2014). The synthesis of these three fields lead to designs of sustainable ecosystems that integrate society with the natural environment, benefitting both simultaneously (Mitsch and Jørgensen, 2003). Examples of this can be seen in the increasingly popular "green infrastructure" techniques that have been gaining significant traction lately to solve land-based problems. However, less attention has been spent on the ecology of marine coastal landscapes, specifically those effected by man-made structures for coastal protection (Connell and Glasby, 1999). The need to balance protection, cost-effectiveness, and the societal value from coastal ecosystems has led to the inclusion of ecological issues into coastal engineering decision-making (Airoldi et al., 2005). Some examples include: restoration of salt marshes in Delaware, restoration of oyster reefs in the Gulf of Mexico and Chesapeake Bay, the DELOS Project in Europe, and much more. The World Association for Waterborne Transport Infrastructure (PIANC) describe their 'Working with Nature' approach as, "an integrated process which identifies and exploits win-win solutions with respect to nature, which are acceptable to both project proponents and environmental stakeholders" (PIANC 2011). The idea behind this concept is not to sacrifice shoreline protection, for ecological enhancement, but rather to find a way to accomplish both, while also generating additional benefits simultaneously.

Currently, innovative discussions are taking place on how to integrate coastal protection techniques with the use of natural and socioeconomic processes (van Slobbe et al., 2013). Both governments and businesses are interested in identifying where nature-based solutions can be used as a cost-effective alternative to investing solely in artificial defenses (Ferrario, Filippo, et al., 2014). Following the costly disasters in 2012, a key component of the President's Hurricane Sandy Rebuilding Task Force was building sustainable infrastructure. The guidelines called for "environmentally sustainable and innovative solutions that consider natural infrastructure options in all Federal Sandy infrastructure investments" (Sutton-Grier et al., 2015). Partly due to this increased attention from the federal government, there has been a growing interest among coastal planners on the state and local levels to seriously consider hybrid approaches in protecting the coastlines of the United States. One of the main drivers behind this has been the realization that there is significant potential for coastal ecosystems to mitigate storm and erosional impacts.

As previously mentioned, the EU-funded DELOS project (Environmental Design of Low Crested Coastal Defence Structures) was developed as interest grew for more nature-based solutions to coastal protection. The overarching goal of the project was to research the effective design of low-crested structures (LCS) to protect European coastlines, while simultaneously meeting goals related to the environment, natural resource management, and sustainability (Airoldi et al., 2005). The project blended the engineering and socioeconomic performance of LCS design with potential ecological benefits at various spatial and temporal scales.

The idea of "soft infrastructure" that has been discussed and developed in the past decade is now being incorporated by the USACE (Nordenson and Seavitt, 2015). This approach is very similar to other initiatives, such as the aforementioned "Working with Nature" approach. However, until now, "hard infrastructure" has dominated the coastal protection landscape. Based on increasing evidence that natural habitats, such as oyster reefs, can help protect from future disasters, a mix of these new natural systems and hard infrastructure have begun to be explored as a possible hybrid approach to coastal protection. Recent research has proven the effectiveness of such habitats at reducing wave energy, as well as providing socioeconomic and ecological benefits (Sutton-Grier et al., 2015). Additionally, there are many opportunities with regards to designing structures that incorporate the benefits of both natural and artificial structures, termed "hybrid infrastructure".

1.3 The Hybrid Approach

Oftentimes in a perfect world, natural infrastructure solutions would be the optimal choice. However, for highly urbanized coastal cities, due to a lack of space, as well as a need for protection against high-energy waves and storms, they are rarely the most feasible option for coastal managers. Innovative hybrid approaches to shoreline protection can provide a viable solution to this issue.

By integrating natural ecosystems into “hard” engineered defense structures, we can maintain viable levels of hazard mitigation, while achieving a multitude of additional benefits. These are known as hybrid structures. The hybrid approach may be more cost-effective in the long-run, as well as touch upon the three pillars of resilience (risk reduction, ecology, and socioeconomic). Added benefits of increased wildlife habitat, absorbing carbon pollution that is a driver behind climate change, and making our communities more aesthetically pleasing and livable, help to drive the motivation behind the development hybrid structures.

Many of these co-benefits described are precisely what make coastal areas so appealing for people to live and work near. Increased U.S. federal focus on hybrid approaches necessitates a review of the effectiveness of such strategies in providing storm and erosional benefits in order to understand what kind of protection can be expected (Sutton-Grier et al., 2015). In contrast to traditional rubble mound breakwaters, which often fail to offer diverse ecological habitats, inclusion of materials that offer varying complexities (surface roughness, grooves and pits) as well as design geometry (vertical/horizontal) can easily and cost-effectively be developed at different tidal levels (low, mid, high) to the designs used in breakwater construction (Firth et al., 2014). These “engineered reefs” can serve as hybrid breakwater structures when placed at emergent (high-crest) or near-emergent (low-crest) elevations, to reduce wave heights and reduce shoreline erosion and associated damages to property and infrastructure (Zhao et al., 2014). Simple adjustments can be made to these structures in order to enhance habitat complexity, thus mitigating the ecological impact of the construction (Borsje et al, 2011). These objectives can be met by incorporating the use of ecosystem engineering species that modify their environment to enhance coastal protection and ecosystem function. All of which are utilized in the design of living breakwaters.

1.4 Defining Living Breakwater: The Modern, Engineered Reef

The term “Living Breakwater” has occasionally been used to describe coral and oyster reefs, and their impact on shoreline protection. While there have been studies that have researched the efficacy of oyster reefs as breakwaters, none have considered large-scale, heavily armored oyster reefs, designed for high-wave energy environments. Until now, there have only been a couple of studies that have discussed concepts similar to the modern and complete definition of living breakwaters (Ido and Shimrit, 2015; Perkol-Finkel et al., 2014; Sutton-Grier et al., 2015; Zhao et al., 2014). However, this has been difficult given the very recent nature of the advancements in technology and information. To this end, there has yet to be a modernized definition for living breakwaters. Based on a literature review of recent research, as well as a comprehensive analysis of past/current pilot projects, it is now possible to provide at least a loose conceptual definition. While oyster and coral reefs may still be considered “Living

Breakwaters", for the purpose of this study, the following definition is a more complete, modern, and robust description of what constitutes the modern-day living breakwater.

In general terms, living breakwaters can be defined as hybrid breakwater structures, constructed from a combination of artificial and natural materials, that emulate natural coastal features, with the overarching goal of coastal protection.

These structures strive to provide the same shoreline protection benefits as traditional breakwaters (erosion reduction, storm surge mitigation, and wave attenuation/dissipation) while simultaneously providing additional environmental and societal benefits. In more specific terms, living breakwaters are low-crested, modified/artificially constructed reefs, that lie in shallow water. Typical attributes include but are not limited to: minimized crest elevations; multiple breakwater structures with small gap widths situated parallel to the shoreline; incorporating bio-enhancing, durable substrate material that provides shelter and habitat for various marine and aquatic species; constructed to accommodate shellfish, finfish, or hard corals; and dissipation of erosive wave energies. This "bio-enhancing substrate" can be made from a variety of eco-friendly materials such as ECOncrete, BIOBLOCK, Reef Ball's™, ReefBLK℠ or any other durable armoring material that will encourage shellfish settlement and/or habitat changes favorable to other aquatic species such as finfish.

A major advantage of living breakwaters is that they can be designed for a variety of goals, rather than being limited to providing a single benefit (such as shoreline protection). A few examples of pilot projects that have been recently undertaken to further understand this concept are: offshore placement of Reef Ball's™ in Stratford Connecticut, the oyster reef restoration project in Mobile Bay Alabama, the Virginia Artificial Reef Program, inclusion of artificial pits at the Plymouth breakwater in England, and the DELOS project. The next section provides an in-depth evaluation of the various benefits that living breakwaters can provide. They can be grouped into four main categories: ecological/environmental, social/recreational/economical, stability/longevity, and shoreline protection.

1.5 Living Breakwater Design: Advantages

Typically, traditional engineering structures such as breakwaters are designed to withstand certain high-intensity, low-probability events and accept failure under more severe conditions (Slobbe et al., 2013). However, infrastructure that is designed to be sustainable can adapt to variable and long-term changing conditions. With such uncertainty associated with our current climate and sea level conditions, it is important that we consider resiliency when making coastal protection decisions. Two major benefits that result from integrating ecosystems into coastal defense strategies is that they may be adaptive to changes in climate and sea level rise (Borsje et al., 2011), as well as provide many additional services. Some of these benefits include: water quality improvement, removal of carbon and nitrogen from coastal ecosystems, and production of fish and invertebrates of commercial, recreational, and ecological significance (Baggett et al., 2014).

Additionally, as living breakwaters become colonized with various marine species, they provide recreational opportunities such as fishing and snorkeling. Oftentimes, coastal protection measures are implemented in order to protect beaches, as well as other high-value public usage areas. A desirable feature of submerged and low-crested breakwaters is that they do not interrupt the view of the sea from the beach. The ability to increase the physical and visual access to the water's edge is an important feature to consider when attempting to maintain the tourist value of beaches, or any significant waterfront areas. Beyond this, by designing defense structures with appropriate crest heights and gap spacing between structures, allows for increased circulation, preventing the water shoreward of the structure from becoming stagnant (Zhao et al., 2014).

Properly designed living breakwaters can potentially provide the same protection benefits as traditional breakwater designs, but with lower net costs and a variety of additional benefits. There has been a significant amount of research done in the last decade that has independently studied various benefits associated with features that are included in living breakwater design (Kroeger, 2012; Perkol-Finkel and Sella, 2014; Ido and Shimrit, 2015; Ferrario et al., 2014; Scyphers et al., 2011; etc.). However, it is much more difficult to find a comprehensive overview of advantages in terms of hybrid breakwater design. A comprehensive overview of the current state of knowledge can be found below.

1.5.1 Ecological/Environmental Advantages

Typically, the primary goal of coastal protection structures is to modify hydrodynamic and sedimentary processes in order to protect valuable coastline or improve recreational conditions (Firth et al., 2014). Though, it cannot be ignored that any structure placed in the sea will inevitably become colonized by marine organisms. Given that, it is possible to modify a select number of design features in order to enhance species richness, while maintaining the engineering performance of the structure. Intertidal coastal ecosystems provide valuable services such as providing food and habitat for various species, as well as representing an important carbon sink (Bouma et al., 2014).

By modifying the texture and structure of the breakwater units, one can improve settlement and grow conditions, without decreasing the level of safety provided (Borsje et al., 2011). This ecological enhancement of the concrete based armoring units of the breakwater increases the ecological services provided, without hampering the structural performance, providing the building blocks required for living breakwater design. For example, a breakwater located in the North Sea Channel, off the coast of The Netherlands, several slabs were attached to the existing concrete blocks of the structure. These slabs were divided into six differently textured and geometrically structured sections and then tested for algal and macrofaunal colonization (Borsje et al., 2011). Slabs that incorporated cups and holes, as well as fine or coarse texture, displayed much more rapid colonization than smoother, traditional slabs.

Another example summarizes the results of a 24-month monitoring study of a breakwater section in Haifa, Isreal. The breakwater incorporated ECOncrete®, a bio-enhancing solution to traditional breakwater armoring units (Ido and Shimrit, 2015). The study compared the ecological performance of these bio-enhancing armor units, to an adjacent breakwater comprised of Portland based concrete (over 50% of coastal management structures are made from Portland cement (Sharma, 2009)). The results found that the ECOncrete® based breakwater displayed a greater richness and diversity of invertebrates and fish, as well as a lower ratio of invasive to local species, than the traditional breakwater. Additionally, engineering species, such as oysters, were more abundant on the ECOncrete® units. Simple adjustments, such as adding pits to armor units, can significantly increase the species richness and diversity (Firth et al., 2014). In a study of the Plymouth breakwater off the coast of England, 6 of the 10 functional groups were represented and unique to the drilled pits on the armor units.

One of the most promising features of living breakwater design is the inclusion of ecosystem engineering species, such as mussels and oysters, that can modify the local physical environment around them (Jones et al., 1994). These species, which are common to intertidal areas, possess a multitude of beneficial abilities. Most importantly, they can grow rapidly in brackish water, and they are able to trap and stabilize sediment, which in turn increases the soil elevation and wave attenuation efficiency, making their inclusion in breakwater design highly practical (Borsje et al., 2011). Unfortunately, when compared to historic levels, oyster reefs have experienced the largest global loss of any marine-based habitat type, estimated around 85 percent loss (Beck et al., 2011).

Oysters and mussels are filter-feeding organisms that can remove harmful pollutants from the water column. Typically, an adult oyster can filter 50 gallons of water per day, thus dramatically improving water quality (Zhao et al., 2014). Additionally, they are able to colonize and form reefs, which provide food and habitat, sequester carbon, remove nitrogen, and increase benthic productivity (Risinger, 2012). In 2012, NYC completed a study of five pilot oyster restoration projects called "The Oyster Restoration Research Project". The purpose of this study was to study the efficacy of oyster reef restoration, as well as develop criteria for determining the potential of such projects. In the past, oyster reef restoration was built upon the goal of improving harvests, however, in the last decade, there has been increased recognition on the various ecological, economical, and wave attenuation services provided by oysters (Baggett et al., 2014).

1.5.2 Economic Advantages

One of the most important considerations when determining a coastal protection strategy is the costs associated with the project. To date, coastal "green infrastructure" strategies have been unable to gain significant traction due to the lack of knowledge associated with the costs and benefits of such techniques. However, understanding the economic benefits and impacts associated with living breakwaters will allow for side-by-side return on investment comparisons with more traditional strategies. By adding in ecosystem benefits and maintenance costs into the benefit and cost analysis (BCA), the relative cost effectiveness of engineered reefs would likely increase (Ferrario et al., 2014).

Generating quantitative estimates of living breakwater projects has been scarce to date, however, research has been done with regards to oyster reef projects. Using information from two reef restoration projects with a total length of 3.6 miles in Mobile Bay, Alabama, the following figures were produced:

- Fisheries: 6,900 pounds/year of additional finfish and crab catch, with an economic value of $38,000-$46,000/year producing a total economic output of $39,000/year.
- Coastal erosion: 51-90% reduction in wave height and 76-99% reduction in wave energy at the shore.
- Nitrogen abatement: 280-4,160 pounds of nitrogen per year removed from Bay waters.
- Economic impacts from reef construction itself: $8.4 million in local output, $2.8 million in earnings and 88 jobs created." - (Kroeger, 2012)

During an analysis of the costs and benefits of an oyster reef restoration project in Chesapeake Bay, Hicks et al. (2004) determined that the economic value of the benefits exceeded the costs "several-fold". Specifically, Bockstael et al. (1989) estimated the valuation of regional services, such as water quality improvements in the Chesapeake, to be worth over $200 million. With Rothschild and colleagues (1994) suggesting that the average oyster harvest value of a reef in North Carolina and Virginia is $51,217 per hectare.

By studying existing data from the southeast Atlantic, as well as the Gulf of Mexico, Peterson and colleagues (2003) were able to quantify the value of fish production that stems from oyster reefs. They determined that 10 m^2 of oyster reef habitat creates 2.6 kg of fish and crustacean production per year. The net present value that they estimated for commercial fish per unit of oyster reef was $4.12 per 10 m^2.

In an additional study, 5.6 km of oyster reef produced more than 6900 pounds (39% commercial and 61% recreational) of additional catch per year and 1888 kg of nitrogen removal from local waters (Sutton-Grier et al., 2015). With the limited amount of research and data available to date, The Nature Conservancy calculates that the net present value, based solely on fishery enhancements, would lead to benefits exceeding costs in year 34 of the project.

While the economic benefits of reef restoration appear to be promising, the construction related costs seem to have a similar outlook. During a study of a coral reef restoration, it was found that traditional tropic breakwater construction typically ranges between $456-188,817 per meter, with the median cost being $19,791 per meter (Ferrario et al., 2014). However, the construction costs of coral reef restoration typically range from $20-155,000 per meter, with the median cost being $1,290 per meter. While nature-based, hybrid breakwater projects will undoubtedly prove more costly than reef restoration, due to both increased material & labor, the costs should remain relatively close to those associated with traditional breakwater design.

1.5.3 Stability/Longevity Advantages

Sea levels in New York City are expected to rise between 8-30 inches by 2050 and 15-75 inches by 2100, according to the NYC Panel on Climate Change. The ability of ecosystem engineering species to increase the soil and crest elevation of a breakwater, allows for the structure to keep up with sea level rise, which offers a sustainable and cost-effective solution to living breakwater longevity. This ability is associated to the biogenic buildup of species like oysters, which is a process that involves the deposition of calcium carbonate skeletons onto hard substrate, which can also add to the structure's strength, stability, and durability (Ido and Shimrit, 2015). Regardless of sea level rise, heavy structures comprised of concrete and limestone rock tend to sink over time, which requires additional effort and funds for maintenance (Piazza, 2005). This "reef accretion" is a result of inputs of oyster shell production and biodeposition, that combats against erosion due to hydrodynamic processes (Rodriguez et al., 2014).

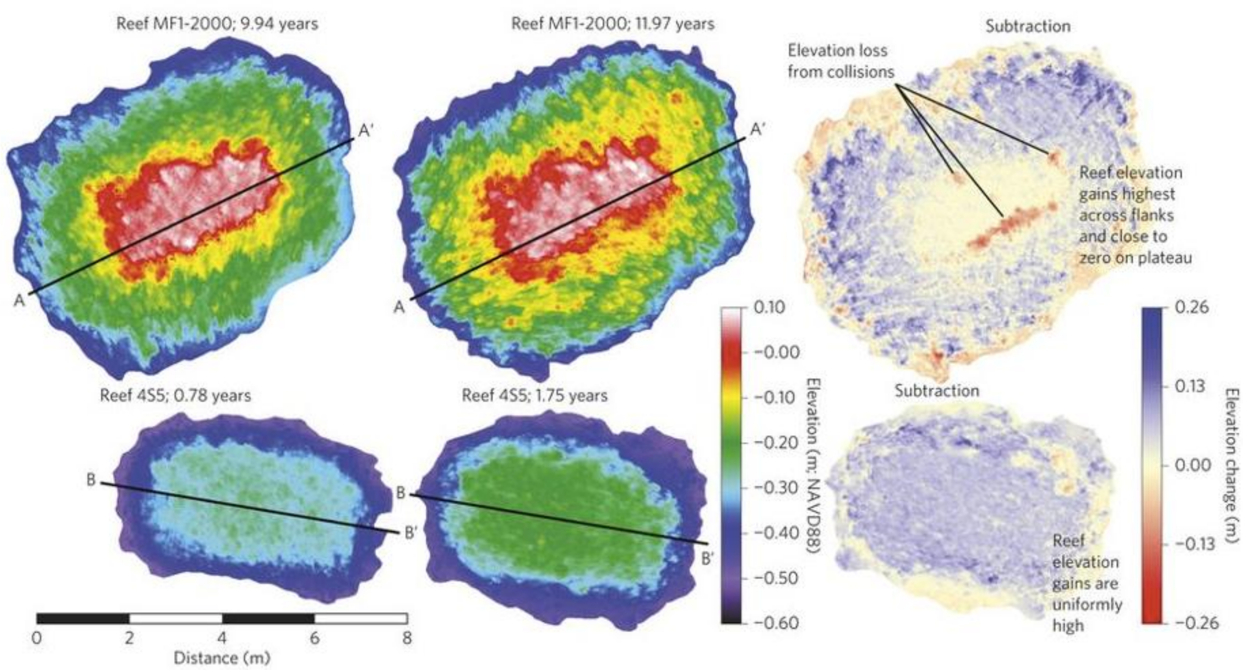

Figure 2. Reef accretion. Image courtesy of [Rodriguez et al., 2014].

In addition to the added longevity benefits of living breakwaters, they also possess added stability related benefits. As structures that include a "living" aspect, these breakwaters, much like oyster reefs, have the potential for self-repair. A large aspect of coastal resiliency is protection against high-intensity storm events, which are known to have negative impacts on our coastlines and structures located there. The self-repair resiliency posed by oysters provides a promising feature to help protect living breakwaters, as well as help them recover from storms. Furthermore, as previously mentioned, living breakwaters utilize a low-crest or submerged crest design, which is significantly more stable than an emerged crested structure (Kramer et al., 2003). Finally, the colonization of oyster shells on the breakwaters hard substrate provides surface complexity that adds protection from scouring, as well as increased wave attenuation and reduction of reflected energy.

1.5.4 Shoreline Protection Advantages

To date, our understanding of wave attenuation effectiveness over living breakwater type structures, with various unit designs, is limited. Both oyster and mussel beds have the ability to modify their local hydrodynamic and sedimentary surrounding, which serves to dissipate wave energy, reduce current velocity, and trap sediment (Borsje et al., 2011). However, from a shoreline protection standpoint, oyster beds are more effective in wave attenuation than mussel beds, which makes them the preferred species to include in living breakwater design (region specific). There has been limited research conducted regarding the wave attenuation abilities of oyster reefs, engineered reefs, and especially reefs that meet the definition of living breakwaters provided in this study. However, the research that has been conducted, while limited in scope and type, can still provide a strong foundation for performance expectations of this hybrid breakwater design. Below are the results from a study of the wave attenuation capabilities of the Barton Island & Swift Tract Oyster Reef Breakwaters, located in the Gulf of Mexico.

One of the most complete studies done regarding coral reef wave attenuation efficiency was conducted by Ferrario et al. in 2014. Ferrario and his colleagues reported that coral reefs significantly reduced wave energy, with the entire reef accounting for a wave energy reduction of 97%. Most of the wave energy (86%) was dissipated by the reef crest, which means that even narrow reef flats, or living breakwaters that do not possess wide flat regions, can still effectively contribute to wave attenuation.

When considering a breakwaters protection efficiency, an important value used to determine how well a structure performs, is the transmission coefficient, or K_t. This coefficient represents the ratio of the transmitted to the incident wave height H_t/H_i. Typical values for "low-crested" detached breakwaters range from 0.3 to 0.7, which means that 30-70% of the wave height is reduced (Ferrario et al., 2014). In comparison, the coral reefs studied by Ferrario et al. estimated an average wave height reduction of 64%, which lands in the upper range of values for traditional breakwater structures.

The overarching goal of living breakwater design, from an engineering standpoint, is to adjust breakwater alignment, crest height/width, and gap width, in order to reduce the overall breakwater footprint and volume, without compromising shoreline response and storm wave attenuation goals. The major draw of this concept is that you can reach optimal, or near-optimal values for wave attenuation, while simultaneously reaping a variety of additional benefits, that as we can see, have a strong foundation in recent research. However, a current limitation in living breakwater design, is the uncertainty associated with real-world application, which the following case study aims to explore.

2. Case Study

2.1 Background & Location

In addition to conducting an in-depth evaluation of the current state of knowledge, a modern living breakwater project that is currently underway was studied in order to verify the current state of practice. The project chosen is, to date, the largest scale nature-based, hybrid breakwater project undertaken and is located off the coast of Staten Island, NY. The following information regarding the Staten Island Living Breakwaters project was obtained from the final environmental impact statement released by the New York Governor's Office of Storm Recovery, as well as the consulting teams hired to manage the project.

During the 19th and 20th centuries, changes in land use and populations led to a decline in water quality, habitat extents (especially naturally occurring oyster reefs), and beach widths across Raritan Bay, located southeast of Staten Island, NY. These changes led to a decrease in the quality of the Bay ecosystem, as well as increased the coastal risk to communities and structures along the shoreline. The natural disasters witnessed in 2012 across the United States heralded the need for enhanced erosion protection, wave attenuation, and social resiliency from our coastal protection structures across the United States, especially highly urbanized regions like New York City. The shoreline along the southern coast of Staten Island has experienced ongoing erosion over the last 35 years and in many locations erosion rates have averaged 1-3 feet per year. In addition to higher erosion & storm surges, this area of Staten Island experienced significant wave action during Superstorm Sandy, the combination of which resulted in loss of life and significant damage to property.

In 2013, led by the U.S. Department of Housing and Urban Development (HUD) and funded by the (Hurricane) Sandy Supplemental, an innovative competition called Rebuild by Design (RBD) was launched calling for proposals to build sustainable infrastructure using both public and private resources. The goal was to promote a design-led approach to proactive planning for long-term resilience and climate change adaptation. The competition was a year-long process during which interdisciplinary design teams engaged with regional experts, government entities, elected officials, nongovernmental organizations, and local community groups to develop innovative resilience proposals for some of the most impacted communities in the region. This competition set a new standard for large-scale disaster response and infrastructure projects.

In the spring of 2014, ten teams comprised of designers, architects, landscape architects, water-experts, engineers, scientists, and academics from all over the world showcased their final designs. One of the seven projects selected to receive HUD funding was the Staten Island Living Breakwater Project, which received large funding through New York State's Community Development Block Grant-Disaster Recovery grant. This was mainly due to the project's ability to successfully incorporate risk reduction, ecological enhancement, and social resiliency, into its design. The project would be an innovative coastal green infrastructure project that would include a series of nature-based, hybrid breakwater structures set off the coast of Staten Island.

Specifically, the project is located off the southern coast, known as the Tottenville section of Staten Island. Land uses present within the project area are a mix of parkland and residential, with a few privately-owned vacant parcels. The largest of these land use areas is a 265-acre park, called Conference House Park, which includes extensive natural areas, forest, bluffs, wetland, and beaches that line the shore.

The integrated purpose of the Living Breakwaters Project is threefold:

1) **Risk Reduction**: Address both event-based and long-term shoreline erosion in order to preserve or increase beach width; attenuate storm waves to improve safety and prevent damage to buildings and infrastructure. The system of breakwaters is designed to attenuate damaging storm waves, reduce or reverse long-term coastal erosion, and diversify and enhance the bay ecosystem by creating structured marine habitat currently lacking in the Raritan Bay.
2) **Ecological Enhancement**: Increase the diversity of aquatic habitats in the Lower New York Harbor / Raritan Bay (e.g., oyster reefs and fish and shellfish habitat), particularly rocky / hard structured habitat that can function much like the oyster reefs that were historically found in this area. Reestablish habitat complexity and mimic the functionality of natural reefs that historically dominated the area, enhance the mosaic of shallow subtidal habitats for target functional groups, and increase the biodiversity of both fish and invertebrate species. Oyster restoration on and around the breakwaters will further enhance both the ecological performance and the educational benefits of the project. Oyster restoration on the breakwaters will be conducted by the Billion Oyster Project (BOP).
3) **Social Resiliency**: Provide programming that builds a community around education on coastal resiliency and ecosystem stewardship; foster and encourage community stewardship and citizen science, and increase physical and visual access to the water's edge and near-shore waters for recreation, education, research, and stewardship activities. The Water Hub component is a facility or set of facilities and associated programming designed to promote educational and stewardship activities related to the project and the educational programs associated with these facilities.

According to the construction management teams opinion of probable cost (OPC) estimate, the project is scheduled to be finished in December 2021. The bidding process is currently underway, and a monitoring program will be conducted for both the bioenhancement and the coastal performance. The detailed monitoring statement of work (SOW) for this program is currently in the drafting process.

Figure 3. "Tottenville Reach" phase of the Living Breakwaters project. Image courtesy of SCAPE Landscape Architecture.

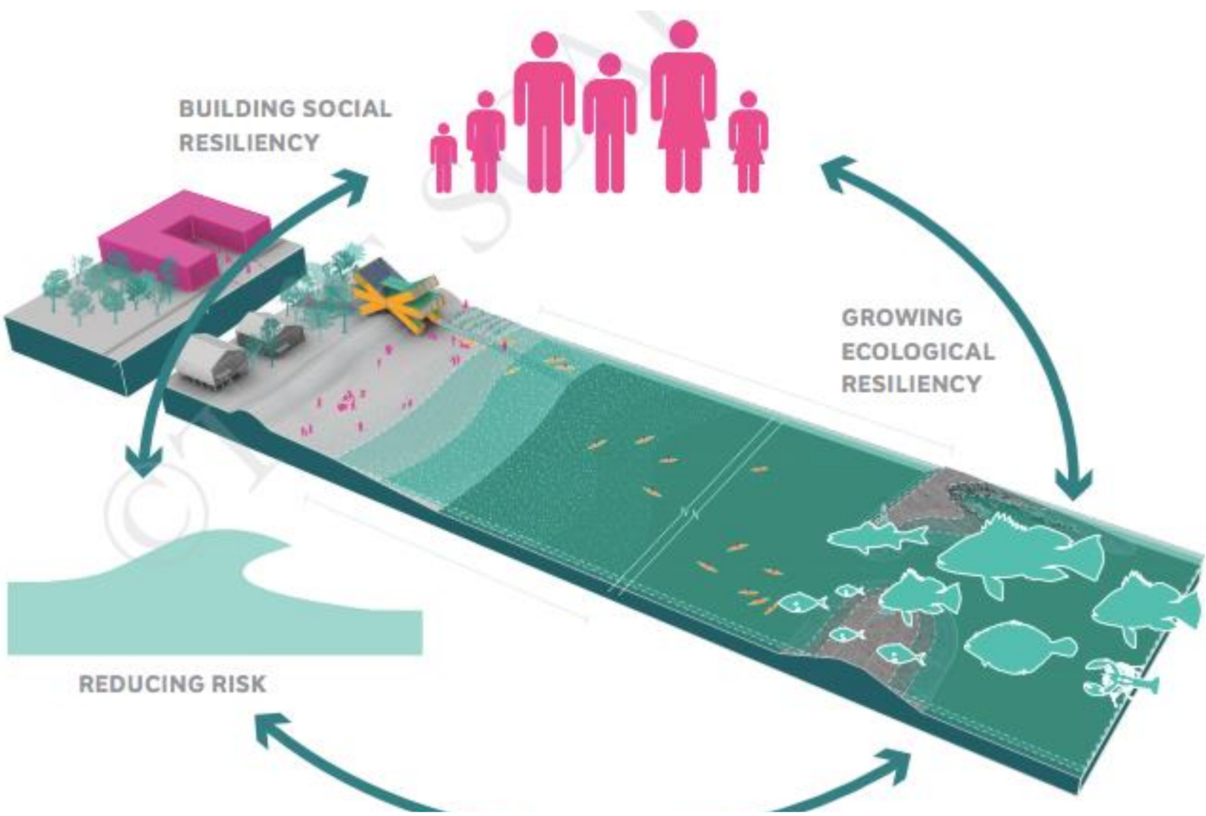

Figure 4. Three-headed approach to the project. Image courtesy of SCAPE Landcape Architecture.

2.2 Design Specifications

The initial phase of the project, coined "The Tottenville Reach", is to be comprised of a breakwater system that will span a total of 3,200 linear feet. The breakwaters will be spaced anywhere between 730-1,200 feet away from the shoreline and at varying crest heights. Early estimates project 151,780 cubic yards of rock and bio-enhanced concrete will occupy almost 500,000 square feet of space in Raritan Bay. However, approximately 115,990 cubic yards of the material will be below the mean high-water level of the bay, minimizing the visible footprint of the structures. The positioning and design of the breakwaters were optimized in order to meet three main goals: reduce risk of shoreline erosion via wave height reduction, improve the ecological resiliency of the region, and enhance social engagement and resiliency. Unlike typical rubble mound breakwaters, the living breakwaters incorporate a variety of integral habitat features to enhance their habitat performance without sacrificing their ability to attenuate waves or manage sediment. These features include "reef streets", "reef ridges," and "crenellated crests".

The Tottenville Reach incorporates three types of living breakwater design, each serving a specific goal and location (**figures can be found in the appendix**). First, the "Type A" or "Low Crested" breakwaters are designed as a means of shoreline erosion control, however, providing minimal impact on wave heights during high-intensity storm events. These structures are meant to protect locations where shoreline and land-based infrastructure is less vulnerable to storm wave action. Type A breakwaters will have a crest elevation of 5 ft and overall height of 11 ft. This crest elevation is designed to remain above the mean high-water height, accounting for 30 inches of sea level rise. Two segments of Type A breakwaters will be installed in the western portion of the project site and will together span roughly 900 feet in length. Roughly 95% of the volume of these breakwaters will be completely submerged. The "Type B" and "Type C" breakwater designs are meant to provide protection against severe storm wave action. Five Type B segments are to be installed, totaling almost 1,500 ft in length, featuring crest elevations of 14 ft, overall heights of 20 ft, and result in roughly 79,870 cubic yards of volume (72% submerged). Additionally, Two Type C breakwater segments will be installed in the eastern portion of the project site, totaling 800 ft in length, featuring crest elevations of 14 ft, overall heights of 24 ft, and result in roughly 51,970 cubic yards of volume (76% submerged). Modeling efforts undertaken by the design team project that the entire system of living breakwaters will be able to reduce wave heights to less than 3 ft in a 100-year storm event (considering 30 inches of sea level rise).

The material makeup of the breakwater designs will incorporate a stone core, marine mattress layer providing protection against scour, and outer layers that will consist of armor stones, bio-enhanced concrete armor units, and oyster restoration and nursery systems. All three types of breakwaters will be constructed from the same materials, however, as previously mentioned, will vary with respect to their dimensions and distribution of materials.

By designing numerous breakwater structures with small gap widths, instead of a few long, continuous breakwaters, minimal footprint sizes are accomplished, while also creating additional habitat variety between the ends of the breakwaters. This habitat variety is further enhanced by the incorporation of closely spaced rocky intertidal/subtidal protrusions that have been called “reef streets”. These reef streets, in combination with the bio-enhancing armor units, add a wide range of crevice and pit sizes that promote biogenic buildup, which will enhance the complexity and variety of the habitats created. As previously mentioned, the breakwaters will incorporate eastern oyster (Crassostrea virginica) restoration on and within the breakwaters. Nursery systems such as floats, anchors, oyster trays, and bottom placement of “spat” (juvenile oysters) attached to shells, will make up most of the restoration efforts. While the need for structural stability requires the use of a narrow armor stone gradation and placement on much of the breakwaters, the reef ridges present an area where smaller stones and a wider gradation in stone sizes can be used without reducing the stability of the breakwaters. This increases the variety in size of the interstitial spaces between the stone, further contributing to habitat complexity

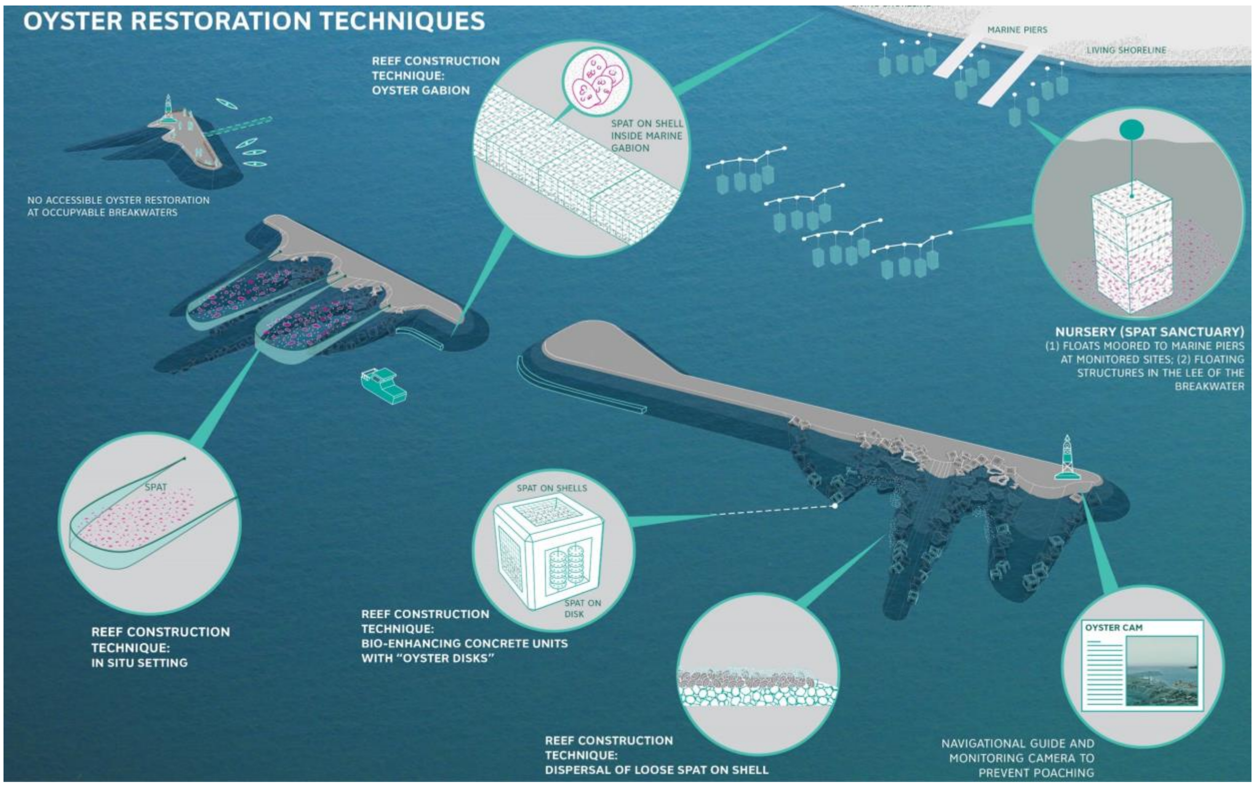

Figure 5. Oyster Restoration Techniques. Image courtesy of SCAPE Landscape Architecture.

The Staten Island Living Breakwaters have also been designed in order to promote public access, resulting in beneficial cumulative effects to recreation. Specifically, wider beaches and less intense wave action will allow for increased recreational opportunities along the shoreline, including fishing, boating, and general beach use. Furthermore, some of the breakwaters will allow for public access via boat or kayak, as well as educational programs offered through an on-shore “water hub” center. This will increase awareness for both ecological and coastal resiliency going forward, furthering the attention placed on hybrid coastal structures such as living breakwaters.

2.3 Project Costs, Benefits, and Timeline

Early estimates of the projects cumulative present value of net benefits (benefits minus costs) are projected at $13.7 million, with a Benefit Cost Ratio (BCR: Benefits divided by costs) of 1.22. The benefit to cost analysis is projected over a 50-year planning horizon and has been subjected to a sensitivity analysis. These early estimates demonstrate the economic viability and enormous amount of value that the project will provide to the local community, as well as throughout the New York City metropolitan region. The design specifications demonstrate both the ecological resiliency and coastal protection provided by the project, which provides both merit to the project, as well as a solid blueprint to coastal managers worldwide for planning of future living breakwater projects going forward.

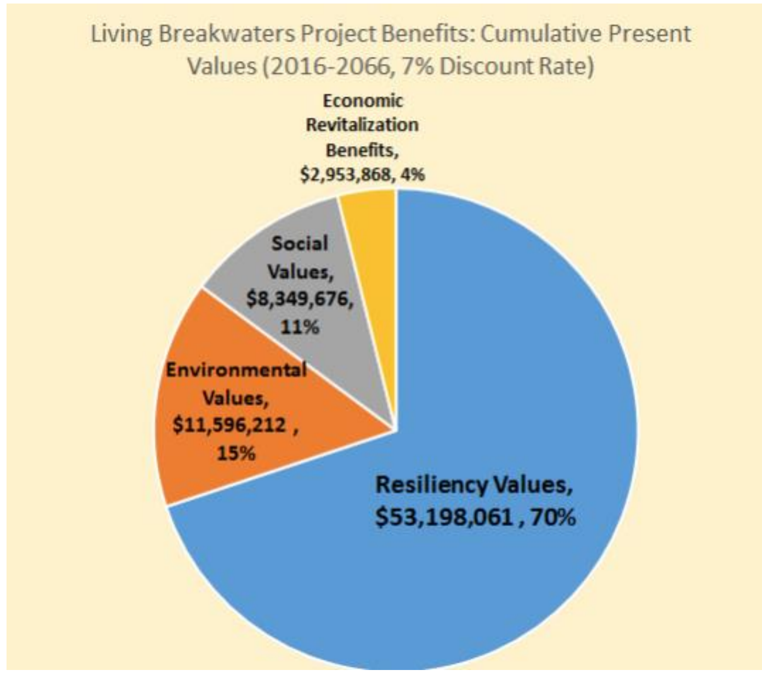

Figure 6. Cumulative Present Value of Net Benefits. Image courtesy of NY GOSR.

The state recently completed the design phase of the project, with construction set to begin mid-2019 and an anticipated completion by the end of 2020.

3. Wave Model Comparison

3.1 Background

One of the largest sources of uncertainty surrounding living breakwater structures relates to the quality of shoreline protection that they can provide. Up until this point, the purpose of this study was to provide an in-depth analysis of the recently researched potential benefits surrounding living breakwaters. To evaluate the hazard mitigation performance of living breakwater-type structures, the wave transmission coefficient, which indicates the portion of wave energy transmitted from the unprotected side to the protected side, is a common parameter. Although the relationship of this parameter with more traditional rubble-mound breakwater dimensions has been developed from model tests and field observations (e.g., the Coastal Engineering Manual [USACE 2002]), understanding of wave transmission effectiveness over hybrid & artificial reef structure designs is limited (Zhao et al., 2014).

In recent years, numerical modelling has been developed to be used as a complementary tool to assist in the different design processes of both traditional and innovative coastal structures.

Although there are several works on numerical modelling of traditional breakwater structures, there is a lack of information regarding hybrid structures such as Living Breakwaters. Numerical models may be used to simulate physical processes, such as wave transmission, by solving complex differential equations that describe that process. To further close the knowledge gap surrounding the shoreline protection capabilities of such structures, the final aspect of this study is the use of a numerical wave model to analyze the wave attenuation efficiency of 3 example living breakwater structures, building off the design specifications from the innovative Staten Island Living Breakwater project. The measured transmission coefficients for each structure were compared to values obtained from a physical model study of low-crested defense structures, performed by the DELOS project. This comparison served as a tool to provide validation for the numerical model test. The overarching goal of the wave model test is to provide expected transmission coefficient values for three types of Living Breakwater designs, as well as any other potential benefits that the structures' design specifications may have on shoreline protection.

The physical structures were created within a wave model that was designed to replicate local bathymetric & wave conditions of Raritan Bay, NY. Within this environment, 10-year and 100-year wave event conditions were simulated, to provide realistic wave characteristics of a high-energy, coastal environment. The wave attenuation efficiency of each breakwater variation was then tested within the model. Specifically, the first breakwater type that was tested, was modeled from the "Type B" breakwater dimensions of the Staten Island Living Breakwater project. The second breakwater type was a lower-crested variation of the "Type B" structure, that also incorporated partial oyster colonization. The final structure was based off a typical artificial reef design (submerged crest, no core component, appropriate drag coefficient).

3.2 Model Selection & Assumptions

Until now, the models based on two-dimensional RANS approximation are possibly the most adapted to the study of wave–structure interaction for engineering purposes, as the computational effort is reasonable and the number of simplifying assumptions is considerably reduced compared to other existing models (Garcia et al., 2004). Given this, a 2D Volume-Averaged Reynolds Averaged Navier–Stokes (VARANS) model, combined with a Volume of Fluid (VOF) method, named the IH-2VOF model, was used for this study. Within this model the flow is obtained using the VARANS equations, which are derived by integrating the RANS equations over a control volume (Lara et al., 2008).

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0$$

$$\frac{1 + c_A}{n}\frac{\partial \overline{u_i}}{\partial t} + \frac{u_j}{n^2}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{v}{n}\frac{\partial^2 \overline{u_i}}{\partial x_j \partial x_j} - \frac{1}{n}\frac{\partial \overline{u_i' u_j'}}{\partial x_j} - F_i$$

t = time; u= Reynolds-averaged velocity; P= pressure; n= porosity; ρ= density; v= kinematic viscosity; i, j= 1, 2 where 1 denote horizontal and 2 vertical directions;
F_i = Friction forces created by the porous media, in terms of the friction coefficient

To apply a VARANS model such as IH-2VOF, values for a linear and non-linear drag forces (α, β) are two empirical parameters that must be determined in order to apply a frictional coefficient onto the structure. The representation of the flow resistance forces inside the porous medium is generally based on the Darcy–Forchheimer equation. Most numerical models based on the VARANS equations incorporate the Darcy–Forchheimer equation. In this study, the coefficient values for this equation were based on laboratory data (Losada, 2008). The existing knowledge about the variation of the resistance coefficients originates from theoretical considerations, physical experiments and numerical calibrations. Based on comparisons with the experimental data relevant to this study (Di Lauro et al., 2017; Losada, 2008), the coefficient values were initially set to α = 200 and β = 1.1. Numerical results appeared to be more sensitive to the nonlinear drag coefficient β than the linear drag parameter α, because the flow is mainly turbulent. In the case when oyster colonization was assumed to be present on the structure, due to a lack of research regarding the β value of oyster reefs, this value was adjusted based off appropriate ranges for coral reefs (Nepf, 2012).

The added mass parameter C_A, which affects the inertia term in the momentum equation within the model, has been set to a constant value of 0.34, based on recommendations firstly suggested by van Gent (1995) and largely adopted in literature for the numerical analysis of wave structure interaction (Losada et al., 2008; Jensen et al, 2014).

As previously mentioned, 3 Living Breakwater designs were considered, the following configurations were simulated:

1. Staten Island project, “Type B” Living Breakwater
2. Low-crested, rubble mound breakwater with augmented friction coefficient representing 50% oyster colonization (Hybrid Living Breakwater)
3. Submerged crest height, wide crest width, rubble mound breakwater without the traditional multilayer cross section, with augmented friction coefficient representing coral growth (Artificial Coral Reef)

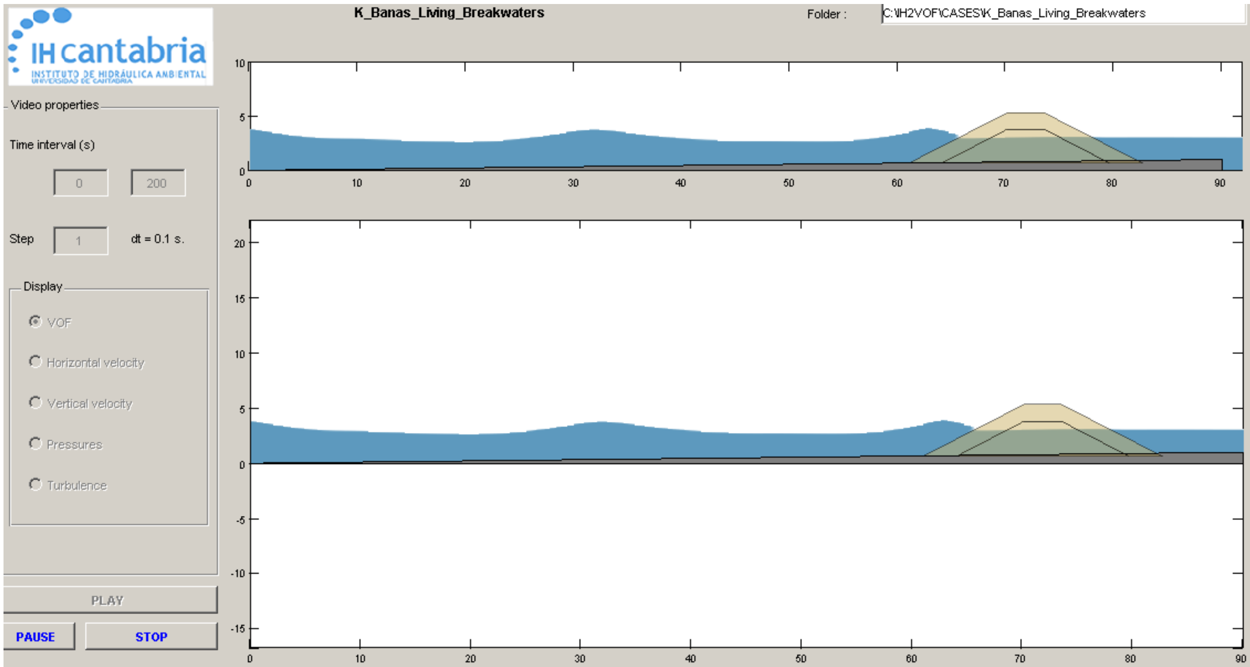

Figure 7. IH-2VOF model simulation of breakwater "Structure 1"

Based off the design specifications of the Staten Island Living Breakwater project, as well as recent experimental and numerical analysis of various rubble mound breakwater & artificial reef performance (Losada et al., 2008; Vílchez et al., 2016; Garcia et al., 2004; Nepf, 2012; Ahrens et al., 1987) the following design specifications & model parameters were determined for the 3 structures. The breakwaters are assumed to be constructed on a horizontal bed slope. The Forchheimer nonlinear drag coefficient β has been experimentally & numerically determined to be 0.24 for rigid canopies in water (Nepf, 2012). This value was used for the artificial reef structure, however, was computed as a mean average for Structure 2 (between structure 1 value of 1.1 and 0.24), to represent oyster growth colonization over half of the structure. The porosity values were determined from documentation from the Staten Island Living Breakwater project, as well as research conducted on artificial reef structures (Ahrens et al., 1987). Below is a tabular layout of the major design specifications & model parameters used for each structure, as well as depictions of the structures within the wave model. All 3 of the breakwater variations were designed with a 2:1 slope.

Name	Total Height (ft)	Crest Height (ft above MWL)	Crest Width (ft)	Armor Stone Diameter, D_{50} (in.)	Core Stone Diameter, D_{50} (in.)
Structure 1 ("Type B" Staten Island breakwater)	15	5	11	40	16
Structure 2 (Low-Crested, Hybrid Living Breakwater)	12	2	11	40	16
Structure 3 (Artificial Coral Reef)	9	-1	22	40	N/A

Table 1: Design specifications & model parameters for the 3 breakwater types

Name	Armor Layer Porosity (η)	Core Layer Porosity (η)	Armor Layer Forchheimer coefficient (α)	Armor Layer Forchheimer coefficient (β)	Core Layer Forchheimer coefficient (β)
Structure 1 ("Type B" Staten Island breakwater)	0.37	0.40	200	1.1	0.8
Structure 2 (Low-Crested, Hybrid Living Breakwater)	0.37	0.40	200	0.67	0.8
Structure 3 (Artificial Coral Reef)	0.45	N/A	200	0.24	N/A

Table 2: Design specifications & model parameters for the 3 breakwater types

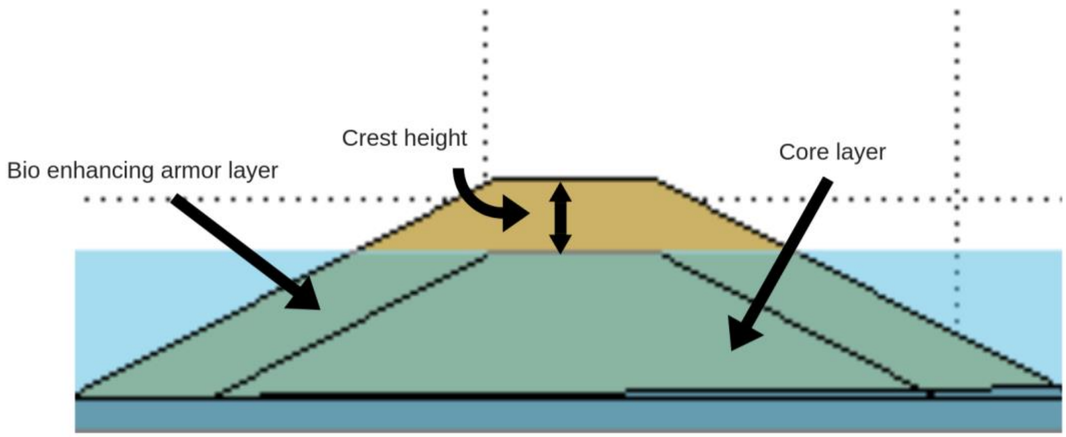

Figure 8. Structure 1, "Type B" design from Staten Island Living Breakwaters project

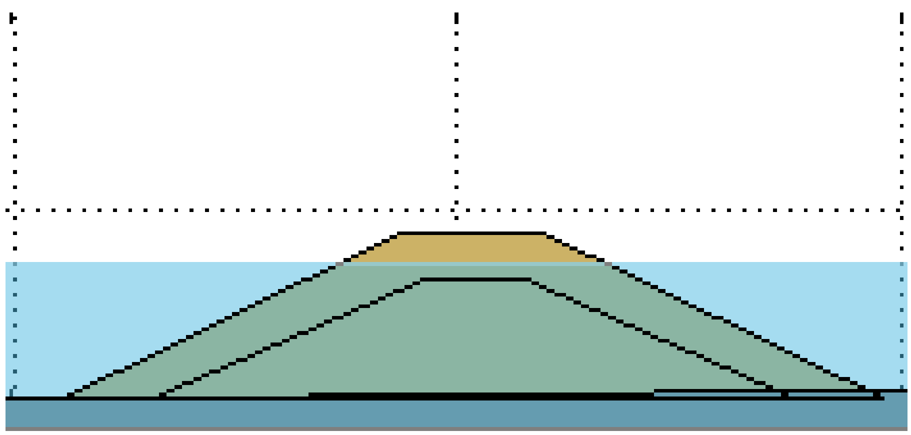

Figure 9. Structure 2, Low-Crested, Hybrid Living Breakwater, drag coefficient representing 50% oyster colonization, decreased crest height.

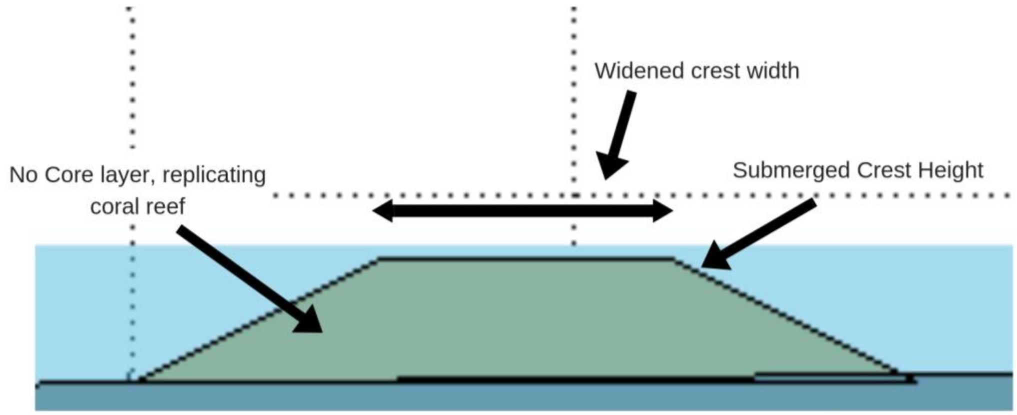

Figure 10. Structure 3, Artificial reef (submerged & wide reef crest). Drag coefficient representing 100% natural growth.

3.3 Model Set Up & Wave Characteristics

The mesh & geometry creation application, CORAL, was used to generate the orthogonal structured meshes, as well as the geometry of the corresponding bathymetry & breakwater structures. In order to ensure that the model was able to simulate the interaction of the regular wave train with the various breakwater structures, initial consideration was done regarding cell size & dimensions of the domain. Roughly two wavelengths were considered leading up to the structure, with roughly half a wavelength incorporated behind the structure. The total length of the domain was set to 300 feet, with a height of 30 feet, allowing clearance above the crest height in the case of potential overtopping. A variable mesh grid was chosen for this model, with 3 "Subzones" defined at specific X and Y coordinates. Constant values of Δx and Δy were calculated from the corresponding water level and wave characteristics. The 2nd subzone included the region containing the breakwater structure, while the 1st and 3rd were specified as regions that did not contain any structures. A total number of 82 cells were used in the y-direction, while in the x-direction 301 cells were used. A very fine mesh resolution was avoided due to the computational cost of the model.

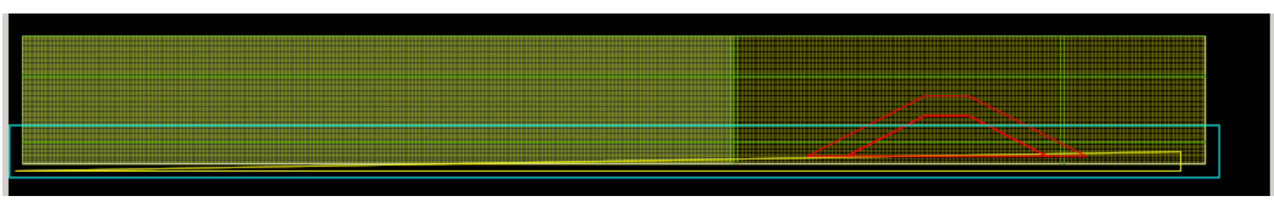

Figure 11. CORAL mesh, with 1V:100H bathymetric setup, 10 ft water level design.

A baseline wave climate of Raritan Bay was developed to determine historic wave conditions and as the input for the wave modeling within the application. The FEMA, Region II office, initiated a study in 2009 to update the coastal storm surge elevations within the states of New York and New Jersey including the Atlantic Ocean, the Barnegat Bay, the Raritan Bay, the

Jamaica Bay, the Long Island Sound and their tributaries (FEMA, 2015). The resulting model system includes the Advanced Circulation Model for Oceanic, Coastal and Estuarine Waters (ADCIRC) for simulation of 2-dimensional hydrodynamics, coupled with the unstructured numerical wave model Simulating Waves Nearshore (unSWAN) to calculate the contribution of waves to total storm surge. The model included a 30-year span (1982-2012), extracting peak storm tide and the coincident significant wave height (at peak storm tide) from 187 storm events (30 historical extratropical storms and 157 synthetic tropical storms) during this period. The wave data used for this model were extracted at a location in Raritan Bay, located close to the Living Breakwaters project site (see figure), in a water depth of -7.5 feet mean sea level.

Figure 12. Wave data extraction point, in relation to project site location.

The wave heights, and wave periods, for various return periods were then determined using the ADCIRC and unSWAN models using the data from the 30-year span. The 10-year and 100-year return periods were used as the basis for the wave conditions in the IH-2VOF model run for this study. Specifically, the significant wave height values were used as the incident wave heights for the model. The values can be seen below:

<u>10- year Return Period</u>
Significant Wave height (H_s) = 4.00 ft
Wave period (T_p) = 4.8 sec

<u>100-year Return Period</u>
Significant Wave height (H_s) = 5.65 ft
Wave period (T_p) = 6.31 sec

Bathymetry data in the area was based on two sources (FEMA, 2014a; Hill International, 2015; MFS, 2015). Water depth at the breakwater location was extracted from this data and set to a typical value of 10 ft. Additionally, active wave absorption was considered at both the generation & termination boundary in order to prevent the reflected waves to interfere with the incoming waves.

3.4 Analysis & Results

The results of the model were used to assess the wave attenuation performance of the 3 Living Breakwater layouts and geometries. The efficiency of each structure was determined by calculating the corresponding transmission coefficient. For a rubble mound breakwater, based on extensive experimental data, van der Meer and Daemen (1994) suggested the following expression to describe the transmission coefficient:

$$K_t = \frac{H_t}{H_i}$$

K_t = Transmission coefficient
H_t = Height of the transmitted wave behind the porous breakwater
H_i = Incident wave height

Two free surface gauges were established representing the two different hydrodynamic zones of the breakwater vicinity. The first gauge is located 10 feet seaward of the structure. The second gauge was placed 20 feet leeward of the breakwater, characterizing the transmission zone. The two gauges produced free surface time series plots for each simulation, which were then used to calculate values for H_i & H_t. The figure below displays the locations of the two free surface gauges, within the IH-2VOF model.

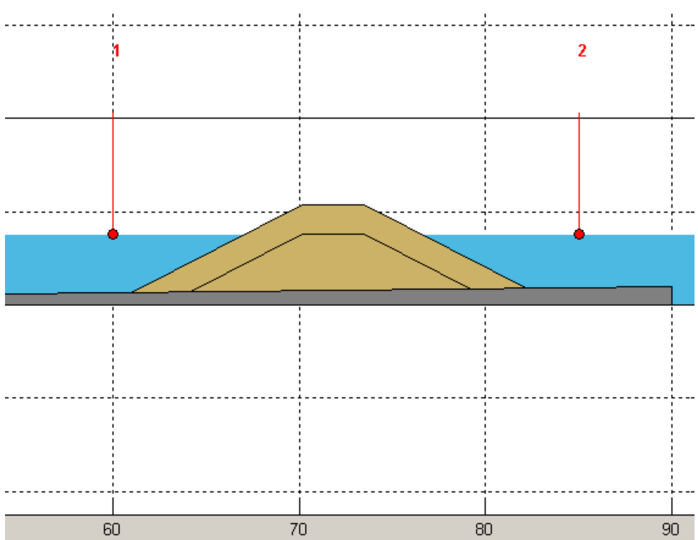

Figure 13. IH-2VOF wave model gauge locations.

All 3 of the breakwaters were modeled and run through simulations for each of the two wave scenarios (10-year and 100-year wave events). This led to a total of 6 separate simulations within the IH-2VOF model that yielded 2 transmission coefficients for each structure, corresponding to the two wave scenarios. The transmission coefficient values were calculated from singular wave frequencies taken from each simulation. The frequencies that represented average wave responses were specifically chosen. Approximately, 38 waves are represented in each panel corresponding to 10-year wave conditions, while 30 waves are represented when considering 100-year conditions. Time series of the free surface displacement for each gauge, representing all 6 simulation scenarios, can be found below.

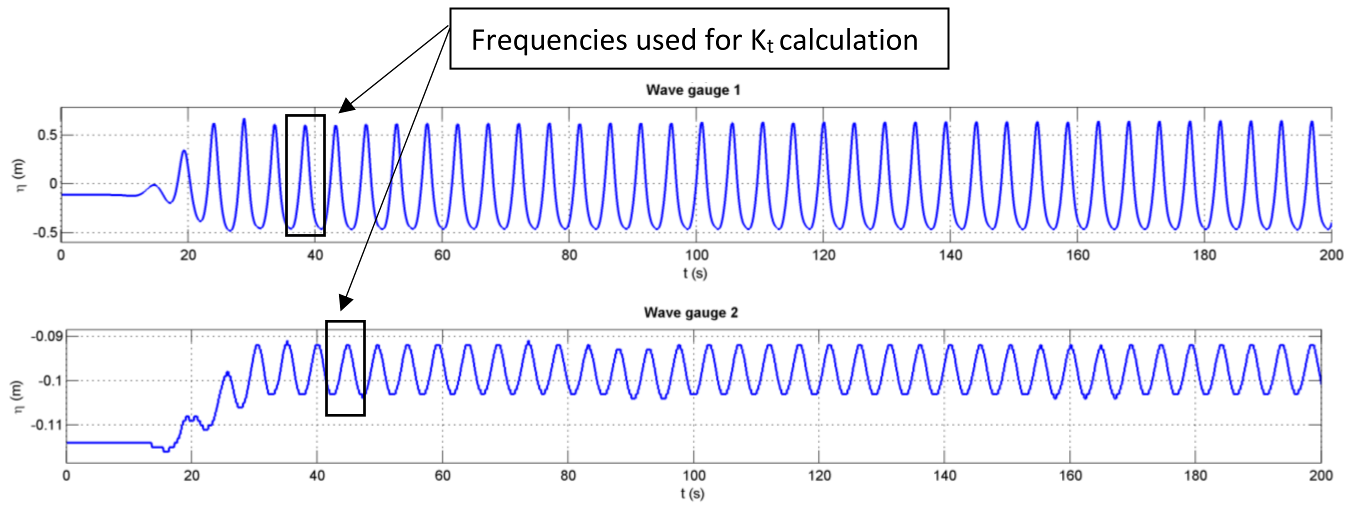

Figure 14. Free surface time series, gauges 1 & 2. Case 1: Structure 1, 10-year wave conditions

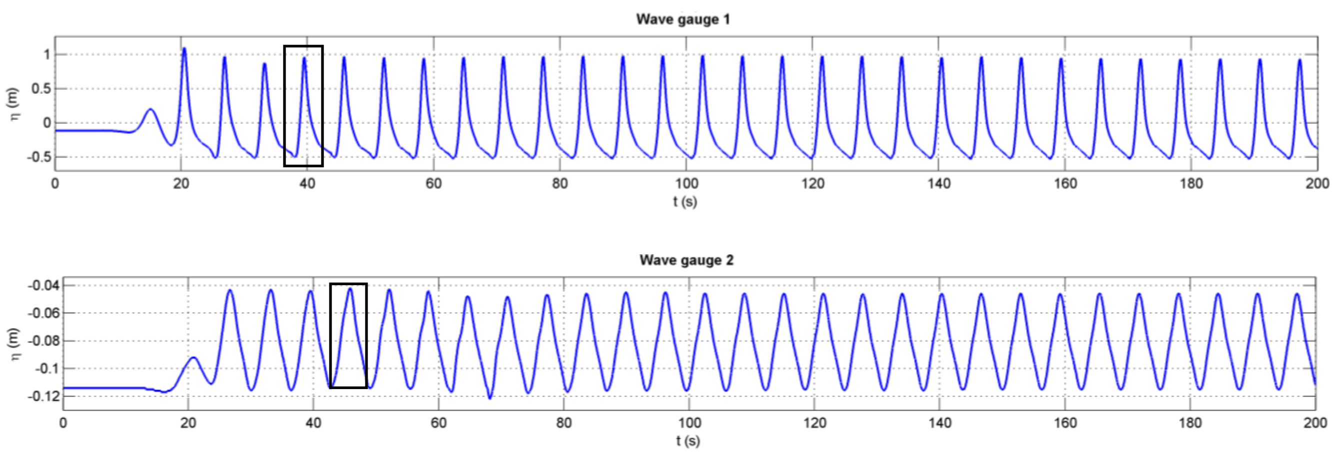

Figure 15. Case 2: Structure 1, 100-year wave conditions

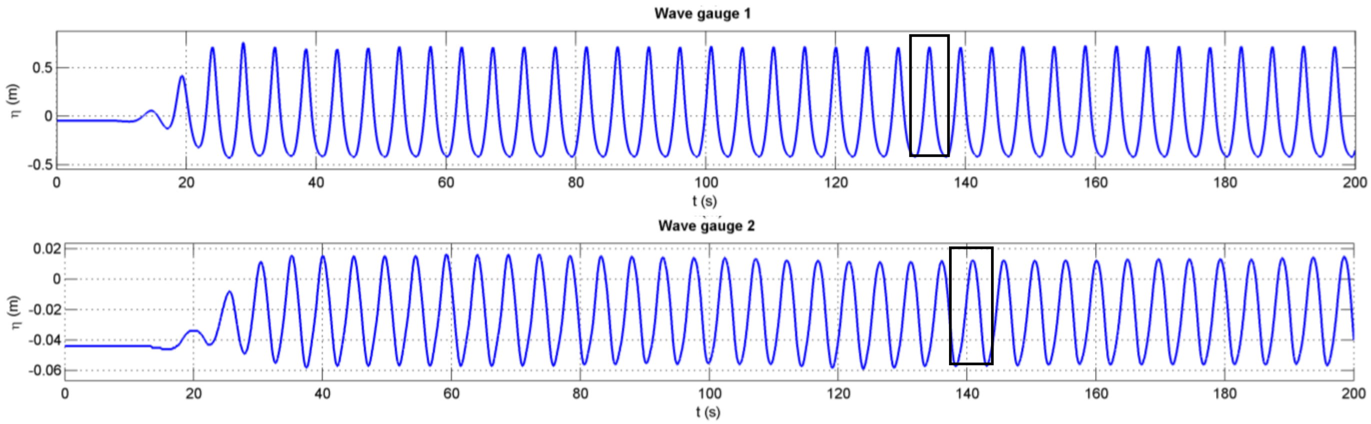

Figure 16. Case 3: Structure 2, 10-year wave conditions

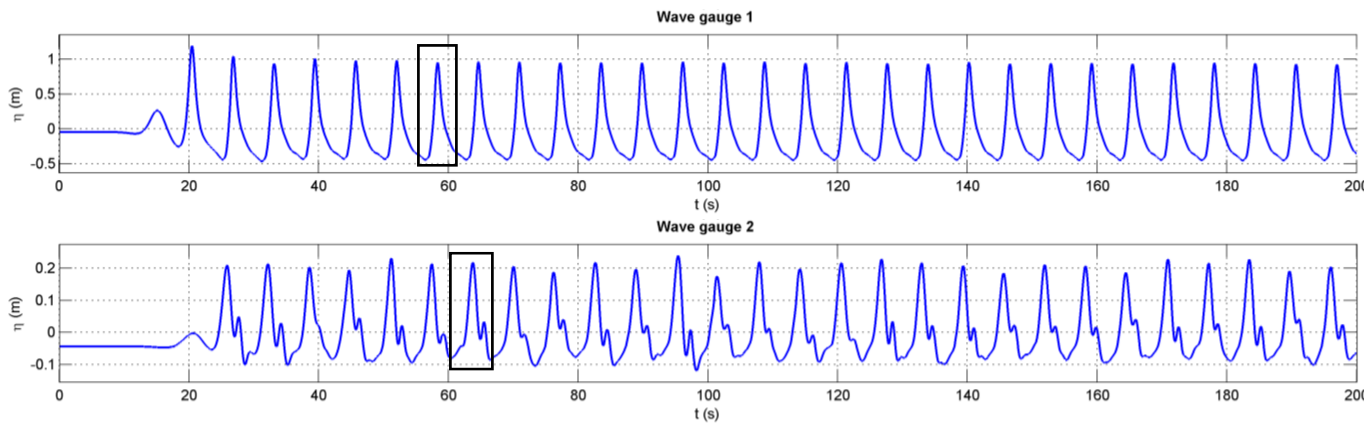

Figure 17. Case 4: Structure 2, 100-year wave conditions

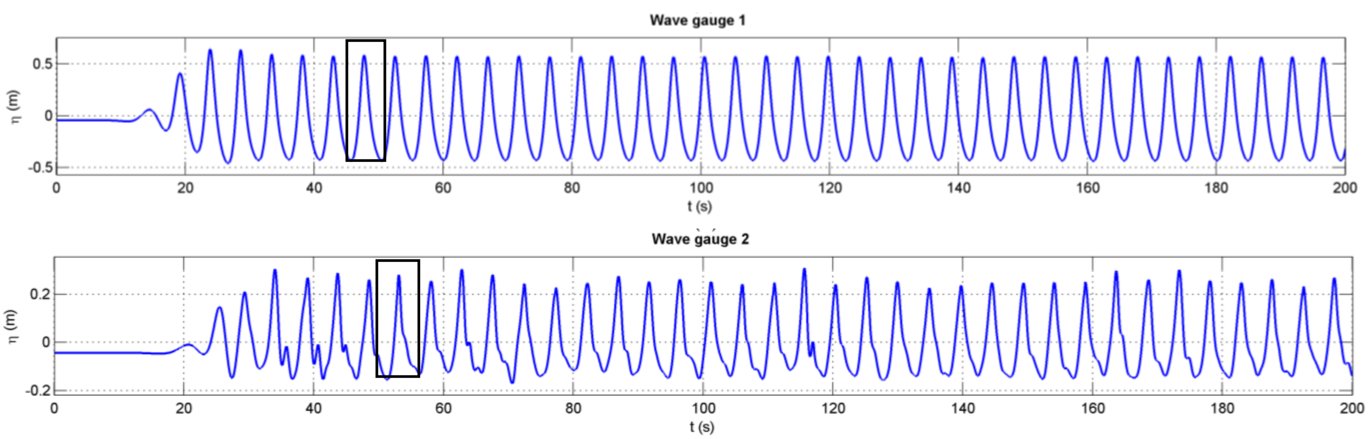

Figure 18. Case 5: Structure 3, 10-year wave conditions

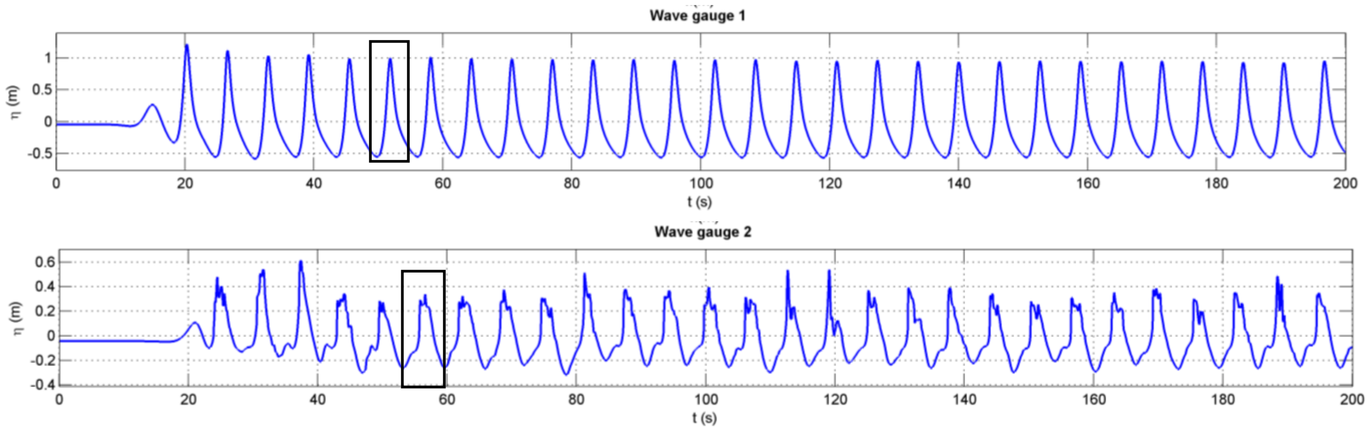

Figure 19. Case 6: Structure 3, 100-year wave conditions

The results of the numerical wave model analysis are below:

Name	Transmission Coefficient, K_t (10-year conditions)	Transmission Coefficient, K_t (100-year conditions)
Structure 1 ("Type B" Staten Island breakwater)	0.01	0.04
Structure 2 (Low-Crested, Hybrid Living Breakwater)	0.06	0.17
Structure 3 (Artificial Coral Reef)	0.32	0.35

Table 3. Modelled transmission coefficients for each Living Breakwater structure

3.5 Discussion

Results of the free surface time series were presented in Figures 14-19 for six different tests: three Living Breakwater types, under two separate wave conditions. As to be expected, the corresponding wave transmission coefficients (K_t) increased as the crest height of the structure decreased. However, in order to first validate the performance of the modelled results, transmission coefficients & geometric parameters were compared against previously published data released by the DELOS project.

As previously mentioned in this study, the European-scale project DELOS (Environmental Design of Low Crested Coastal Defense Structures) was developed to establish effective design of low-crested shoreline protection structures. One of the components of this project was laboratory experiments on low-crested breakwaters, which provided the transmission coefficient as a function of the relative submergence and the relative crest width of the structure (Kramer et al., 2005). In order to classify the three Living Breakwaters that were modeled in this study, the following values were calculated for each wave condition; which can be found below:

10-year Wave Conditions	Relative submergence, R/H_s	Relative Crest Width, B/L_o
Structure 1 ("Type B" Staten Island breakwater)	1.25	0.22
Structure 2 (Low-Crested, Hybrid Living Breakwater)	0.5	0.22
Structure 3 (Artificial Coral Reef)	-0.25	0.44

Table 4. Relative submergence & crest width under 10-year wave conditions

100-year Wave Conditions	Relative submergence, R/H_s	Relative Crest Width, B/L_o
Structure 1 ("Type B" Staten Island breakwater)	0.88	0.13
Structure 2 (Low-Crested, Hybrid Living Breakwater)	0.35	0.13
Structure 3 (Artificial Coral Reef)	-0.18	0.26

Table 5. Relative submergence & crest width under 10-year wave conditions

Based off the physical model results obtained from the DELOS project's laboratory study, expected K_t values for low & submerged-crest structures, with similar relative crest widths, range from 0.00-0.38. These values correspond well with the modelled K_t values for the three Living Breakwater designs that were tested. The highest transmission coefficient predicted within the model was for the artificial reef structure (Structure 3) under 100-year wave conditions. This value of $K_t = 0.35$ was still within the predicted limits of the DELOS test. As previously mentioned in this study, typical values for "low-crested" detached breakwaters obtained from a more general study, ranged from 0.30 to 0.70 (Ferrario et al., 2014).

When considering the frictional drag effect of the oyster/coral cover on wave transmission, no data was available because there was no sensitivity analysis conducted. However, an important result to note is the effect that relative crest width had on the transmission coefficient. While the artificial reef structure (Structure 3) provided a much higher K_t value than the emergent-crest structures, the difference in K_t between low & high intensity wave conditions was the lowest (relatively) out of the three structures. This resilience to high-intensity conditions can be mainly attributed to the relative width of the structure, however, it is also possible to partially attribute it to the surface roughness (drag coefficient) of the structure. This is because

Structure 2 also performed in a similar manner, which had a comparable surface roughness value. This is represented in the table below:

Name	Transmission Coefficient, K_t
	Relative % increase between 10-year & 100-year wave conditions
Structure 1 ("Type B" Staten Island breakwater)	400%
Structure 2 (Low-Crested, Hybrid Living Breakwater)	283%
Structure 3 (Artificial Coral Reef)	9.4%

Table 6. Relative % increase in Kt between low & high intensity wave conditions

Limitations/Challenges

One of the greatest limitations of working with hybrid approaches to coastal protection, such as living breakwaters, is that the few that have been constructed, have been built very recently. This means that in most cases, there is very little data on their effectiveness or cost to benefit ratio. As previously mentioned, there has been some research and data released regarding anticipated benefits of features included in Living Breakwater design, however, the extent of our knowledge is still rather limited. Due to the limited amount of knowledge available, there is a lack of expertise in the coastal protection and planning community, further hindering the development of such infrastructure. From a maintenance and safety standpoint, living breakwater structures and engineered reefs must be clearly marked to avoid navigational hazards, particularly in heavily trafficked areas. This is due to the low-crested nature of such structures. An additional, however minimal, safety concern is the introduction of contaminated oysters into food markets and the associated increases in public health risks. Regulatory requirements are very strict for oyster reefs to prevent illegal oyster harvest.

Another limitation to the implementation of Living Breakwater design is the increased construction time needed. Specifically, bio enhancing armor units such as ECOncrete require very precise manipulation during the construction/installation process, which can add unfavorable time to a project’s lifespan. Additionally, in the case of any restored ecosystem, it can take time for habitats and ecosystems to become established for the natural systems to provide the necessary level of coastal protection. However, the evidence surrounding the ecological and socioeconomic benefits of Living Breakwaters is much more developed than the effectiveness for shoreline protection. A clear assessment of the role and effectiveness of living breakwaters for hazard mitigation is important, as it will inform and encourage investments in coastal defense and resiliency.

The limited research conducted regarding wave attenuation capabilities, provided promising results for oyster and coral reefs. However, there are two main limitations surrounding this evidence. First, the experiments only tested reefs that were completely composed of either oyster shells or coral. Studies have shown problems related to the settlement of these structures, in addition to extensive restoration required after high-intensity storm events (O'Donnell, 2017). This is due to the rather fragile nature of such "natural" infrastructure, especially during the early stages of colonization. The second limitation is that these structures are an "ecology-first" approach, that may be very successful in creating valuable habitat, though not as dependable for shoreline protection as more traditionally engineered strategies. It should also be noted that, as is the case for many habitat types, the full range of services provided by oyster reefs is site dependent and thus varies across different geographic locations (Kroeger, 2012).

Since the Staten Island project is the first large-scale living breakwaters pilot project ever undertaken, there are several uncertainties surrounding the design and performance of the structures. While design-phase wave modeling was performed, including simulations that considered 100-year storm surge levels and 30" sea level rise, the effect of these high wave energies on the anticipated oyster colonization is unclear. Placement of the "reef streets" on the offshore side of the structures poses certain risks related to settlement and growth of the oyster colonies, mainly related to the occurrence of wave breaking and turbulent conditions. While the presence of oyster reefs was common in Raritan Bay up until the 20th century, the ability of these species to survive on an artificial structure, in a higher intensity wave climate, should be monitored. Both for project performance, as well as research purposes moving forward.

With regards to the numerical model study that was conducted, there are a few notable assumptions & limitations that should be noted. Even though the model performed well at determining appropriate K_t values for the breakwater structures, there is still room for further investigations and improvements. The first issue to be considered is a detailed analysis of the dependency of the empirical coefficients, α and β, associated with the linear and nonlinear drag force in the porous media flow. Specifically, targeted research regarding the effect of oyster & coral growth on these values is vital when designing a numerical model for living breakwaters. A much larger number of tests should be conducted, with less variable wave conditions, in order to more accurately determine the effect that this biological growth has on the wave attenuation efficiency of the structure.

These shortcomings have driven the innovation of hybrid approaches that are able to strike a balance between ecology and engineering. Approaches like living breakwaters, that incorporate environmentally friendly, yet durable, armoring units, ecological engineering species like oysters, and design modification related to crest height/width and gap spacing.

Conclusion

Until recently, traditional coastal defense structures have been used to protect our coastal shorelines and infrastructure from wave damage and coastal flooding. Thankfully the modern-day coastal engineer now understands the environmental costs in hardening the shoreline and near-shore area. Nature-based hybrid approaches, such as living breakwaters, offer protection against wave damage, while simultaneously creating or restoring coastal habitats. This study provided an in-depth evaluation of the current state of knowledge and practice surrounding such structures. The result was a wide range of potential: ecological, stabilization/longevity, socioeconomic, and shoreline protection benefits. By highlighting the current Staten Island Living Breakwaters project, we can get an idea of how this hybrid approach to coastal protection can be implemented as a solution to a real-world problem. Construction of a living breakwater system in such a highly populated, high-energy region, proves that such approaches to coastal protection carry considerable interest from both public and private entities, as well as provide a wide spectrum of advantages from both an environmental and engineering standpoint.

Given the state of our climate, sea levels, and ever-increasing development of coastal regions, now is the time to invest effort into the further design, testing, research, and development of hybrid infrastructure solutions for protecting our communities and strengthening our coastal resilience. Public interest in both shoreline protection, as well as habitat restoration, provides us with a strong motivation to further develop solutions that can incorporate both simultaneously. It is important to note that while there may be a strong desire to return our shorelines and near-shore ecosystems to their natural, original condition, this is unlikely to be achieved because coastal management strives to balance our environmental and social responsibilities. It is not possible to construct near-shore defense structures without there being some impacts on local habitats. However, it is possible to optimize the design of these structures in order to curb some of these unavoidable consequences. The inability to return to natural, pristine conditions, should not deter efforts to restore natural ecosystems and their vital functions. The implementation of nature-based hybrid structures offers decision makers the opportunity to consider physical, ecological, and socio-economic goals along with the associated trade-offs and compromises.

Research conducted over 20 years clearly indicates that among breakwater properties, structure transmissivity represents a vital variable for reliably foreseeing both circulation patterns around and behind breakwaters and long-term changes in local shoreline. Using the IH-2VOF wave model, numerical wave modeling was applied to determine the transmission coefficients of various Living Breakwater layouts, as well as attempt to assess the effect of oyster/coral growth on K_t. Wave conditions representing 10-year and 100-year scenarios in the project area in the lee of the breakwater were achieved for the model simulations. The model results demonstrate that living breakwater design can provide a comparable level of shoreline protection than simple low-crested rubble mound structures. A high-crest reef will be more effective in dissipating wave energy due to its bathymetric and topographic resistance;

however, low-crested and near-emergent reefs (closer to mean sea level) will be less exposed to intense forces and more likely to survive. As seen in the model, structures such as these can still provide considerable levels of protection in high-energy environments. However, during the modelling process, significant knowledge gaps were determined. Specifically, regarding appropriate Forchheimer coefficients (α, β) for oyster/coral growth, as well as porosity values associated with bio enhancing armor units (ECOncrete, BIOBLOCK, Reef Blocks…etc.). Further research into these issues, will provide much needed information to further develop decision-support tools and design criteria available to coastal managers.

While knowledge regarding the implementation of nature-based, hybrid breakwater structures is still rather limited, the literature review and case study that was conducted during this analysis led to the discovery of a few, general, best practices for decision-makers going forward. The foundation of which stems from the fact that spatial variability precludes standardized designs. Meaning that planning and design for living breakwater structures should be site-specific. Standardized designs imposed on the landscape without consideration for the ecology of a region will tend to take more energy to sustain (Bergen et al., 2001). The results of the DELOS project also point out that to inform sustainable shoreline protection measures, ecological knowledge is necessary regarding both local-scale and large-scale effects of such coastal structures.

As an example, oyster reefs are limited to low-medium energy environments with a small-moderate tidal range. Finfish and other species are additionally sensitive to these external factors. Meaning that while a structure may be designed to withstand the hydrodynamic forces of a high-energy environment, the ecological characteristics must be considered as well. It is important to note that further piloting and testing studies are required for high wave energy environments for a variety of reef types. Through the design of gap widths between structures, as well as the porosity of the structures themselves (reducing or eliminating the core), we can reduce water stagnation on the leeward side of the structure.

Finally, in addition to the physical & ecological context of a design, knowledge of the cultural context is important. Designs are more likely to succeed and to be accepted by the local community, when the people who live in a place are included in the design process. They can bring knowledge of the particularities of a region and are empowered through direct participation in effecting their local environment; which can increase the chances of a certain project being approved.

The traditional engineered breakwater has served to protect coastal communities for decades. However, due to our changing climate, sea levels, as well as increased public interest in environmental restoration, the design of such structures must change as well. Living breakwaters are unique in the way that they can continue to provide valuable shoreline protection, while simultaneously providing numerous ecological, stabilization, socio-economic, and recreational benefits. With a human population on Earth that continues to increase, so does our need to create innovative ways to decrease our respective footprint. While great effort has been made to accomplish this on land, the same effort must be extended to our shorelines and near-shore areas. With considerable work still to be done on this front, recent/ current projects, such as the Staten Island Living Breakwaters project, provide great examples for future decision-makers to build from.

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