

# Harnessing urban coastal infrastructure for ecological enhancement

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Owing to a combination of increase in coastal population and processes related to global climate change, intense coastal development is inevitable. Shallow-water habitats are prone to be replaced by structures such as seawalls and breakwaters. While adding ample hard substrate to the seascape, these structures are not surrogates to natural habitats, and are often associated with nuisance and invasive species. These differences are attributed to design features including high inclination, low complexity and high homogeneity – all atypical of natural habitats. To date, coastal infrastructure has been designed with limited consideration to marine life developing on it. Consequently, its ability to provide ecosystem services similar to those offered by natural habitats has been severely compromised. This paper presents two case studies implementing ecological enhancement at the Brooklyn Bride Park waterfront. Both strategies are examples for restoring viable ecosystem services while also serving structural and societal goals. The first is an example of structural repairs of aging pier piles, by applying innovative technology of ecological concrete encasement which creates valuable habitat. The second is an example of boosting the ecological performance of a constructed riprap waterfront, by integrating precast tide-pools that add water-retaining habitat features lacking from standard coastal infrastructure.

## 1. Introduction

With two-thirds of the human population concentrated around coastlines (Creel, 2003), accelerated coastal development and changes to natural coastlines are inevitable. Throughout the years, natural coastlines undergo severe changes, and in many cases are completely overtaken by man-made infrastructure such as ports, coastal defence measures, power plants, industrial facilities and residential properties. The proliferation of hardened shorelines is also fuelled by processes related to global climate change, sea level rise and an ongoing increase in the frequency and magnitude of extreme weather events.

As most marine flora and fauna reside in coastal areas, anthropogenic changes to coastlines are one of the key reasons for loss of coastal habitats and for changes in species assemblage, richness and biodiversity (Dugan *et al.*, 2011). While coastal infrastructure such as seawalls or breakwaters add significant

amounts of hard substrate open to colonisation by marine organisms, these man-made structures do not support similar species assemblages to those of natural coastal and marine habitats, and are often associated with nuisance and invasive species (Firth *et al.*, 2014b). These differences are closely associated with design and material features related to high inclination, low structural complexity, high homogeneity and different artificial substrate properties, all of which are rarely found or do not exist in natural habitats (Perkol-Finkel and Sella, 2014).

Concrete is one of the main construction materials globally, and in the marine environment it commonly accounts for over 50% of coastal and marine infrastructure (Kampa and Laaser, 2009). This widely used material is known as a poor substrate for biological recruitment and is often considered toxic to marine organisms, mainly due to unique surface chemistry, which impairs the settlement of various marine larvae

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(Lukens and Selberg, 2004). The ecological enhancement measures presented here are based on the use of innovative ecologically active concrete technologies developed by EConcrete Tech Ltd, which harness biological processes for creating environmentally and structurally improved infrastructure. These technologies increase the ability of concrete-based coastal infrastructure such as seawalls or pier piles to supply enhanced ecosystem services, while improving their structural integrity and durability. This is achieved by slight modifications to the composition, surface texture and macro-design of concrete elements (Perkol-Finkel and Sella, 2014).

To date, coastal and marine infrastructure has been designed and built with little or no consideration of the marine life developing on it. As a result, the ability of these structures to provide ecosystem services similar to those offered by natural habitats is severely compromised. One of the key reasons that limits the ability of coastal infrastructure such as seawalls, riprap belts or breakwaters to serve as surrogates to natural coastal habitats is the absence of design and substrate features that create environmental heterogeneity and water-retaining features (Firth *et al.*, 2014a). Recent studies indicate that incorporating water-retaining elements that functionally mimic natural rock pools has the potential positively to affect biodiversity in built environments (Brown and Chapman, 2014; Firth *et al.*, 2013). The current authors propose innovative approach of designing and retrofitting coastal and marine infrastructure using environmentally sensitive design and construction technologies that enhance their ability to provide valuable ecosystem services, while also elevating their structural integrity and longevity.

The overall goal of the enhancement projects presented in this paper was to integrate ecological considerations into the design and construction works of an active waterfront infrastructure, thus decreasing its ecological footprint. The paper summarises two case studies implementing ecological enhancement at the Brooklyn Bride Park (BBP) waterfront (New York, NY, USA). The first is an example for structural repairs of aging infrastructure, that is, deteriorated pier piles, by applying environmentally sensitive technologies for concrete encasement, which provides required structural repair while generating valuable habitat and ecosystem services. The other is an example for increasing the ecological performance of a constructed riprap waterfront, by integrating precast tide-pools as a part of the riprap arrangement, thus adding water-retaining habitat features that are lacking from standard coastal infrastructure. Both strategies are examples for integration of principles of reconciliation ecology (Rosenzweig, 2003) in the design of coastal infrastructure that serve a structural/societal goal on one hand and an ecological function on the other. Results are discussed with respect to ecological and biological benefits, structural performance and associated regulatory perspectives.

## 2. Description of case studies

Brooklyn Bride Park located in Brooklyn, NY, USA, is an 85-acre (34.4 ha) post-industrial waterfront site stretching 2 km along Brooklyn's East River edge on a defunct cargo shipping and storage complex. The ambitious park design sought to transform a previously environmentally hostile site into a thriving civic landscape while preserving the experience of the industrial waterfront. At present, the park, composed of six renovated/retrofitted piers (piers 1–6) and surrounded areas, provides green space for active and passive uses including playing fields, sport courts, playgrounds, lawns, a roller rink and a greenway and boat launches for non-motorised vessels. Unlike other waterfront parks, where visitors remain perched above the water, BBP encourages close interaction with the water.

As a part of the holistic environmental approach of the park, two different enhancement projects have been incorporated into the park's renovation plan. The first is an example for structural repair of aging infrastructure, that is, deteriorated pier piles at pier 6 (Figure 1). This was done using an innovative technology of ecological concrete encasement, which creates valuable habitat and ecosystem services. The other is an example for increasing the ecological performance of a constructed riprap waterfront, at pier 4 (Figure 1), by integrating precast concrete tide-pools as a part of the riprap arrangement, thus adding water-retaining habitat features that are lacking from standard coastal infrastructure.

### 2.1 Ecological pile encasement: pier 6

Aging wooden pier piles, deteriorated by marine borers (mainly gribbles and shipworms like *Teredo* and *Limnoria*),

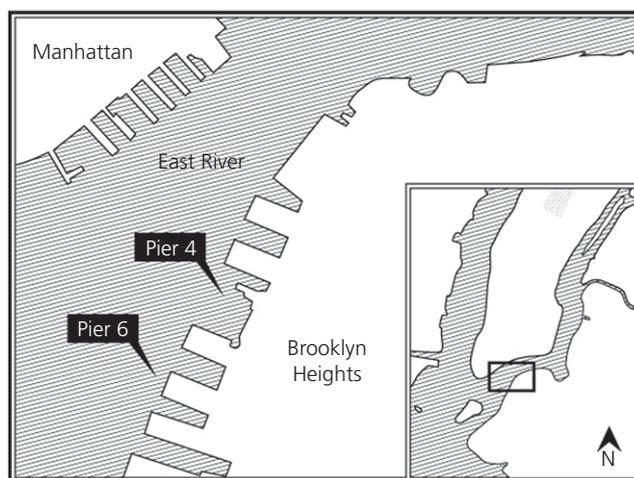


Figure 1. Location of the two enhancement projects at Brooklyn Bridge Park, NY, USA

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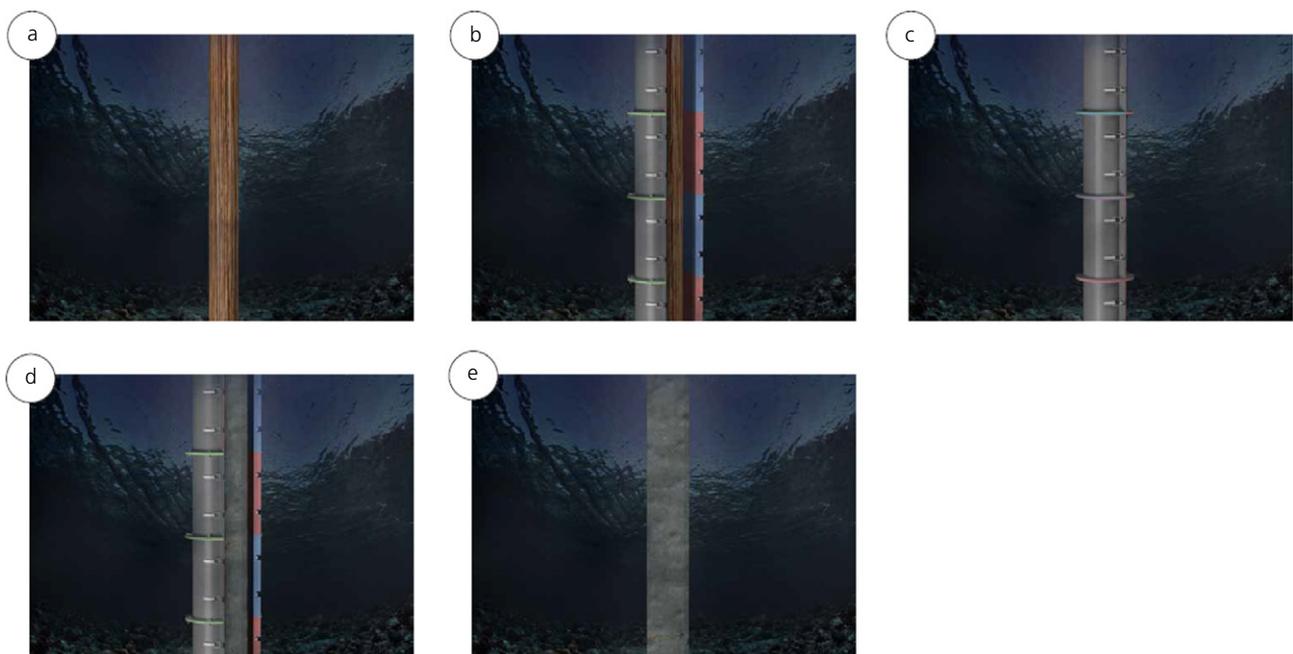
require a structural repair in the form of concrete encasement or a 'jacket', for maintaining the load-bearing structural properties of the pile. As opposed to standard pile encasement, using Portland cement and left-in-place fibreglass forms (susceptible to long-term deterioration), ecological pile encasement uses an innovative concrete mix that enhances the growth of marine flora and fauna (Perkol-Finkel and Sella, 2014). In addition, textured forms are applied and stripped after casting, imprinting a rough texture onto the surface of the concrete jacket, which induces rich marine growth.

In June 2013, a total of 18 piles underwent concrete encasement using ecological pile encasement technology in BBP's pier 6, nine piles at the south face of the pier and nine on the face (Figure 1). On-site, underwater casting was executed by D'Onofrio General Contractors Corp and Walker Diving Underwater Construction. The ecological jackets illustrated in Figure 2 provide all the functional and structural support required from a standard concrete encasement, yet with an added biological and ecological value.

All of the ecological jackets, as well as three standard control jackets (Portland-based concrete with fibreglass form) at each face of the pier, were monitored 3, 10 and 14 months post-deployment. Monitoring included underwater photography and a careful on-site survey for generating a comprehensive

species list (performed when water clarity was sufficient: 3 and 14 months post-deployment), as well as sampling for biomass (performed 10 and 14 months post-deployment). The latter was performed using small concrete tiles that were mounted on the jackets using a strap (1.5 m below the top of the jacket) allowing the tiles to be detached for laboratory analyses. The tiles were weighed prior to deployment and were reweighed after submersion (dry weight after 48 h in 60°C) so that the amount of accumulated organic and inorganic weight could be measured accurately. Similarly, detachable fibreglass tiles were mounted onto control jackets and all recruited cover was analysed for organic and inorganic weight.

Community data were analysed using Permanova tests (permutational analysis of variance – a non-parametric equivalent to univariate statistical tests) conducted on Bray Curtis similarity matrix applied on raw data, while biomass data were conducted on Euclidean distance similarity matrix applied on raw data. Tested factors in both cases included site (random factor: north against south), treatment (fixed factor: EConcrete against control), row (fixed factor: 1, 2, 3) and season (random factor: spring against summer). For community data, a non-parametric multidimensional scaling (MDS) was conducted in order to illustrate trends within the data. Each dot in the MDS represents a single sample, in which samples with similar



**Figure 2.** Schematic illustration of the ecological pile encasement system: (a) existing timber pile; (b) placing form; (c) injecting concrete into form; (d) form opening; (e) concrete jacket

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community assemblages cluster closely on the plot, while those with different communities are spread further apart. Vectors representing the relative contribution of taxa to the similarity between samples were superimposed on the plot. All analyses were performed using the Primer V6.1.13 and Permanova+ V1.0.3 programs (Anderson *et al.*, 2008; Clarke *et al.*, 2008).

## 2.2 Riprap enhancement: pier 4

Constructed beaches, revetments and breakwaters are often composed of boulders of quarry or dredged rock ('riprap') placed at the water line to protect the coastlines and/or prevent erosion. While composed of rock, a natural material, such coastal defence measures are not surrogates to natural rocky habitats and often provide limited ecological value to the surrounding (see Dugan *et al.* (2011) and references therein). In order to enhance the ecological value and increase the biological productivity of riprap zones, a precast tide-pool that integrates into coastal defence structures such as breakwaters or riprap beaches was developed and tested (Figure 3). The unit takes the place of standard armouring unit/rocks and fills up with water during high tide, thus creating a stable habitat that provides shallow water-retaining, moist niches that are absent from standard coastal infrastructure. Floating debris capturing is minimised due to an internal passive intake system.

Seven designed tide-pools were integrated during autumn–winter 2013–2014 into the newly constructed pier 4 beach at BBP within the mean higher high water zone. Each pool retains a volume of 13 gallons (59 litres) and creates a submerged habitat disconnected from the open water at low tide (Figure 3).

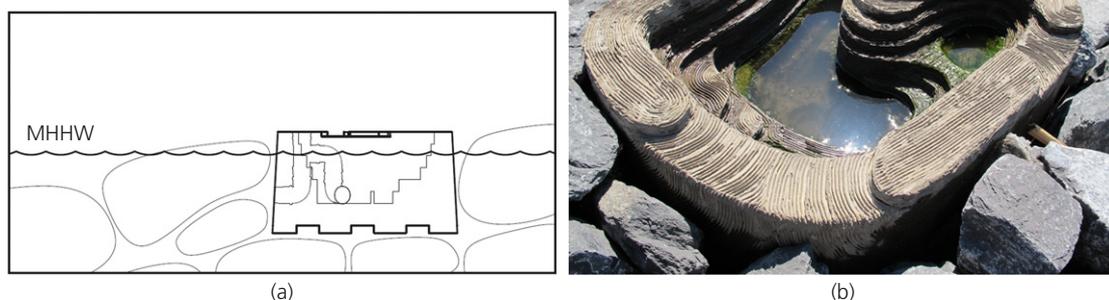
A biological survey of flora and fauna recruited onto the tide-pools was conducted during the spring and late summer of 2014. Results are discussed in comparison to marine life recruited onto the riprap adjacent to the pools.

## 3. Results

The applied enhancement measures at BBP contributed to the park's ecological value by increasing the availability of bio-enhanced substrate capable of sustaining rich benthic communities and by adding new ecological niches – that is, water-retaining elements that are not to be found in the park's infrastructure. Specific results of each of the case studies are detailed below.

### 3.1 Ecological pile encasement

Already at the 3 month post-deployment sampling the ecological jackets had live cover of 70–100% and a number of blue crabs (*Callinectes sapidus*) were observed mating on them. Control fibreglass jackets that present a smoother surface exhibited only scattered colonisation (20–50%). Similar results were obtained in the 10 month post-deployment survey, with a dominance of filter-feeding species (tunicates, barnacles, sessile polychaetes, sponges and bivalves), and habitat formers (barnacles and sessile polychaetes) that contribute to biogenic build-up on the substrate by calcium carbonate deposition. A shift in the community structure was noted on the final, 14 month post-deployment monitoring, when ecological jackets presented a more diverse community than prior samplings (Table 1). Assemblages included coralline algae, sponges, gastropods, barnacles, colonial and solitary tunicates, bryozoans and sessile polychaetes. Live cover on the jackets was 90–100%, with the lower cover at the upper tidal area



**Figure 3.** (a) Schematic cross-section of the tide-pool in place; MHHW, mean higher high water; and (b) photograph of the tide-pool on site

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Phylum	Class	Species	3 MPD visual census		10 MPD tile analysis		14 MPD visual & tile	
			ECONcrete	Control	ECONcrete	Control	ECONcrete	Control
Porifera	Desmospongiae	<i>Microciona prolifera</i>	+		+		+	
		<i>Halichondria bowerbanki</i>					+	
		<i>Haliclona loosanoffi</i>					+	
Cnidaria	Anthozoa	<i>Bunodactis stella</i>		+				
		<i>diadumene leucolena</i>					+	+
Bryozoa	Gymnolaemata	<i>Schizoporella unicornis</i>			+	+	+	
		<i>Membranipora membranacea</i>					+	
Mollusca	Bivalvia	<i>Mytilus edulis</i>	+	+			+	+
	Gastropoda	<i>Urosalpinx cinerea</i>					+	
Annelida	Polychaeta	<i>Spirorbis</i> spp.	+	+	+		+	
		<i>Hydroides dianthus</i>	+		+	+	+	+
		Family: Sabellidae	+	+	+	+	+	
Arthropoda	Decapoda	<i>Callinectes sapidus</i>	+					
	Maxillopoda	<i>Balanus improvisus</i>	+	+	+	+	+	+
	Infra: Cirripedia	<i>Balanus amphitrite?</i>	+	+	+		+	+
Chordata	Asciacea	<i>Botryllus schlosseri</i>	+	+	+	+	+	
		<i>Molgula</i> spp.			+		+	+
		<i>Molgula citrina</i>		+	+	+	+	+
		<i>Molgula manhattensis</i>	+	+	+	+	+	+
		<i>Didemnum</i> spp.	+	+			+	

MPD, months post-deployment

**Table 1.** Species list of taxa appearing on jackets 3, 10 and 14 months post-deployment. Note that different sampling efforts were conducted at the different time points (visual census

3 months post-deployment, on-shore tile analysis 10 months post-deployment and both visual and tile analysis 14 months post-deployment)

(Figure 4). Control jackets presented scattered colonisation with live cover of approximately 40–85%, with the lower cover at the upper tidal area (Figure 4).

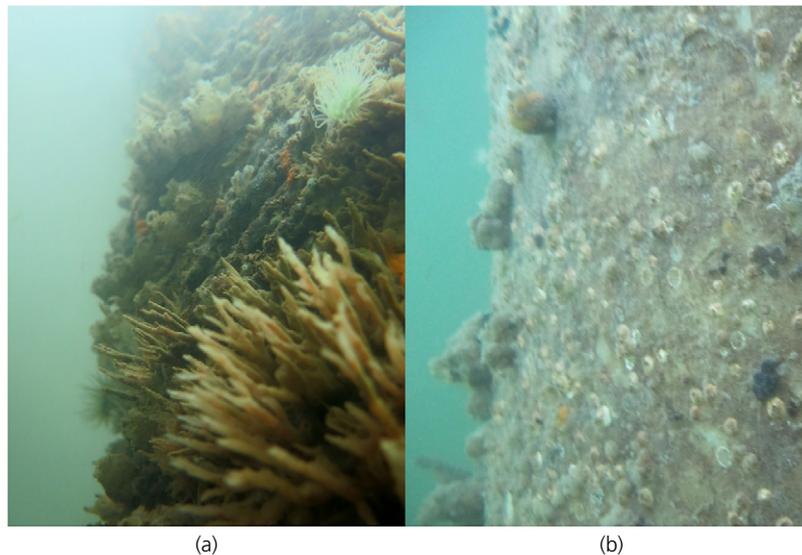
Communities on the control jackets consisted mainly of sessile polychaetes, barnacles, as well as colonial and solitary tunicates. A total of 19 species were noted in the final survey, of which 18 were found on the enhanced jackets and nine on the control jackets (Table 1). These findings point to a general trend of maturing community with a higher number of species with time, especially on the ecological jackets.

Statistical analyses of results from the tile sampling 14 months post-deployment indicated a significant difference between ecological concrete tiles and control fibreglass tiles (site × treatment interaction,  $P=0.001$ ). Differences were slightly stronger at the south site (post-hoc comparisons). These differences are illustrated by the MDS for the 14 month post-deployment

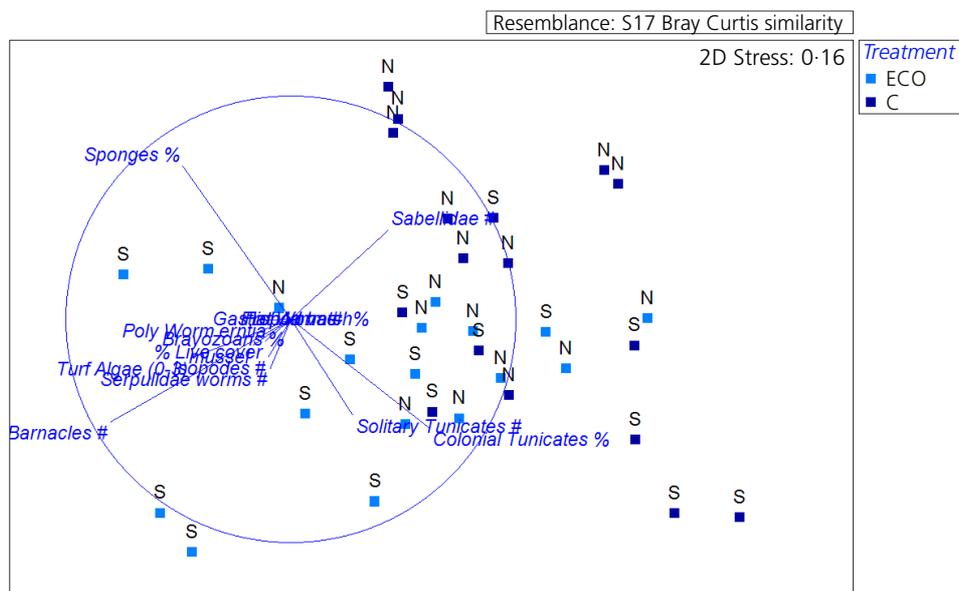
sampling, where tiles of ecological concrete are clustered on the right side of the plot, while most of the control fibreglass tiles are clustered on the left. North jackets are clustered on the upper side of the plot, and south jackets are clustered on the bottom (Figure 5). The superimposed vectors that represent the relative contribution of various taxa to the similarity between the samples illustrate that fibreglass control tiles had a more dominant appearance of soft-bodied colonial tunicates and tube worms (*Sabellidae polychaetes*), while ecological tiles had a more diverse community structure dominated by solitary tunicates, bryozoans, isopods, barnacles and hard-bodied tube worms (*Serpullidae polychaetes*).

Biomass of the sampled tiles significantly differed between ecological and control fibreglass tiles ( $P=0.001$  both 10 and 14 months post-deployment). After 10 months, ecological concrete tiles had an overall average biomass accumulation of  $0.083 \text{ g/cm}^2$ , more than tenfold compared to control fibreglass

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**Figure 4.** (a) Ecological jackets and (b) control – fibreglass jacket. Both are 14 months post-deployment



**Figure 5.** MDS of community data from tiles sampling conducted 14 months post-deployment. Vectors are indicative of the relative contribution of the taxon to the similarity between the samples

scattered in the plot. Ecological concrete tiles (ECO) are indicated with lighter squares; control (C – fibreglass) tiles are indicated with darker squares. N, north jackets; S, south jackets

tiles that had an average of  $0.007 \text{ g/cm}^2$ . This trend persisted at a slightly lesser magnitude in the 14 month post-deployment sampling, during which ecological concrete tiles had an overall average biomass accumulation of  $0.072 \text{ g/cm}^2$ , 3.5-fold greater than control fibreglass tiles that had an average of  $0.021 \text{ g/cm}^2$ .

### 3.2 Riprap enhancement

In August 2014, approximately 9 months post-installation, a monitoring event of the seven tide-pools was conducted. Tide-pools showed a live cover of 89–100% of the water-retaining portions of the pools. Both tide-pool clusters presented a

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Phylum	Class	Taxon (fam./genus/species)
Chlorophyta	Chlorophyceae	<i>Enteromorpha</i> spp.
Heterokontophyta	Fucales	<i>Fucus</i> spp.
Annelida	Polychaeta	<i>Spirorbis</i> spp. Sabellidae
Arthropoda	Malacostraca	<i>Rithropanopeus harrisii</i>
	Maxillopoda subclass: Copepoda	<i>Acartia</i> spp.
	Maxillopoda subclass: Amphipoda	<i>Ampelisca</i> spp.
Chordata		Unidentified juvenile fish

**Table 2.** Invertebrate species that colonised the tide-pools



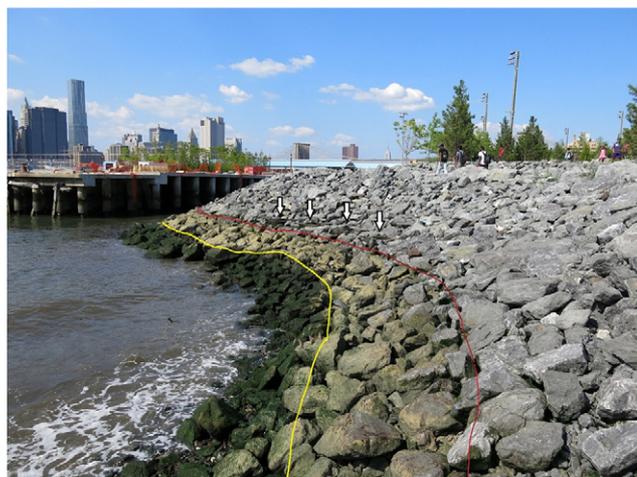
**Figure 6.** Pier 4 tide-pools, Brooklyn Pier Park, NY, USA, August 2014

community composed mostly of filamentous green algae, branching brown algae, copepods, amphipods, isopods, as well as Sabellidae and *Spirorbis* worms (Table 2, Figure 6). In addition, two individuals of the Harris mud crab (*Rithropanopeus harrisii*) and 17 individuals of an identified juvenile/post-larval fish were noted.

The control area surveyed included the rocky area surrounding the pools at a distance of 1–2 ft (0.3–0.6 m) from the edge of the pools. This area (at the mean higher high water) was very poor in biological findings, with only a few patches of algae, mostly at lower part of the rocks, where moist areas were noted (Figure 7).

#### 4. Discussion

Results support the notion that ecological enhancement of hard coastal infrastructure is feasible, even in a heavily urbanised setting. The two case studies demonstrate the ability to harness active infrastructure such as pier piles and coastal protection measures for biological and ecological purposes without compromising their functional purpose, showing an increase in ecosystem services provided by the structure.



**Figure 7.** Pier 4 tide-pools. The higher line marks the upper algae line. The lower line marks the upper frequently wet tidal area. Arrows mark tide-pools

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The enhanced jackets made of ecologically active concrete with a rough surface texture and complex design indeed enhanced the recruitment of marine organisms onto the jackets, creating a richer and more diverse habitat compared to control fibre-glass jackets that offer very limited habitat value. Species richness on the enhanced jackets was double that found on the control jackets (18:9, respectively). The majority of the species recruited onto the enhanced jackets were filter feeders like tunicates, sponges and bryozoans, capable of contributing to water quality and clarity in the area. In addition, many of the species dominating the enhanced jackets were habitat-forming species such as barnacles, bryozoans and sessile polychaetes that add to the complexity of the habitat with time, provide food and shelter to fish and motile invertebrates such as crabs, which used the ecological jackets as nursing grounds.

Habitat-forming species that deposit calcium carbonate skeletons onto the substrate like barnacles and serpulid worms are also considered ecosystem engineers (Jones *et al.*, 1994), contributing to the modification of the habitat by means of biogenic build-up. The latter also serves to protect the infrastructure by way of bioprotection, sheltering the structure from weathering and erosion (Coombs, 2011; Coombs *et al.*, 2013). It is important to note that the above-mentioned biological assemblages that developed on the enhanced jackets did not interfere with the concrete encasement performance, and a hands-on (level II) inspection of the encasements a year post-deployment found hard and sound concrete (Dinos, 2014).

Initial results from the designed tide-pools indicate that the designed precast units successfully mimic conditions offered by natural rock pools, and thus are capable of extending the upper line of biological activity in the riprap area. The pools widen the wet tidal habitat while also extending the distribution of water-dependent organisms in the area. It is expected that this trend will become even more significant with time, as community develops further and progresses into advanced successional stages.

## 5. Recommendations

- As the coastal population is expected to grow in the future, and with constant threats of sea level rise and an increase in the severity and frequency of extreme weather events, coastal development and application of coastal defence measures is bound to increase. In order to cope with global climate change and maintain healthy and productive coastal environments, it is crucial to integrate ecological considerations into the planning, design and implementation of future hard coastal infrastructure and management schemes.
- Ecological enhancement of coastal and marine infrastructure is a feasible, scalable and effective means for reducing the ecological footprint of hard coastal infrastructure, by

increasing its ecological value and biological performance. The case studies presented demonstrate the ability to implement principles of ecological engineering (Bergen *et al.*, 2001) for enhancing ecosystem services in urban marine environments.

- While 'green' building standards, such as the Leadership in Energy and Environmental Design system, are becoming increasingly common worldwide, similar guidelines for 'blue' coastal and marine infrastructure are only now emerging (see Envision, 2012; Metropolitan Waterfront Alliance, 2014) calling for further research and development of innovative environmentally sensitive technologies.

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