# CHAPTER 22
# Artificial Tidal Pools: Habitat Enhancement of Built-up Shorelines of Singapore

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***Introduction***

Over the last eight decades, Singapore's coastal landscapes have gone through significant transformation. An island skirted by mangroves and mudflats, Singapore has become a modern-day coastal city state that is one of the most populated metropolises in the world. Seawalls, headlands, and breakwaters are built along the coast to protect valuable land and inland assets from coastal erosion and inundation. The majority of Singapore's contemporary coastline is thus reinforced by sea defences and other forms of coastal infrastructure.

Sea defences to shore up the coastlines are a fundamental need for small coastal city states like Singapore, especially in the context of land scarcity, expanding population and countering impacts from climate change. While sea defences and coastal infrastructure are largely permanent engineered structures, they are, however, not purpose-built for supporting biodiversity. One strategy is to enhance the capacity of these structures through purposeful engineered modifications to compensate for and replace lost biodiversity without compromising their intended functions. This requires a mindset change that challenges us to understand the functions of coastal infrastructure beyond engineering goals and to explore opportunities for supporting and restoring biodiversity. Ecologically informed engineering in the design and construction of coastal infrastructure can reduce the loss of intertidal and shallow water biodiversity on artificial shorelines.

The objectives of the project were to: (1) design and develop biophilic habitat enhancement structures for modified coastlines; and (2) create opportunities to engage researchers to study the establishment and succession of communities in the structures.

***Methodology***

*Study of conditions contributing to natural recruitment of organisms on artificial structures*

Seawalls support a relatively high diversity of intertidal organisms and share several metrics with rocky shores, such as the number of species present and dominant species. For example, the presence of hard substrates, such as granite armour rocks used for shoreline reinforcement, can support the recruitment of biodiverse corals and other reef organisms in areas where reefs either used to exist, or could exist if suitable substrate were present. We observed this phenomenon along seawalls at reclaimed sites such as Pulau Semakau, East Coast, and Marina East that continue to support rich assemblages of corals in less than a decade after the completion of reclamation works. Similar biodiversity revival within marinas were also seen in the submerged walls of the floating pontoons used for berthing boats that supported rich assemblages of marine organisms. In particular, the concrete coating used for the submerged walls provided suitable surfaces that encouraged the recruitment of marine organisms. However, the uniformity of seawall construction material, the inclination of their surfaces, and the lack of microhabitats such as holes, cracks, crevices and rock pools resulted in lower biodiversity assemblages compared to natural rocky shores.

Our observations of biodiversity occurring by chance along artificially engineered coastal structures presented us with the perfect opportunity for studying the factors that facilitated their successful development, such as surface material, rugosity, slope gradient and hydrodynamic regimes, among others. We adapted and then applied these factors to intentionally enhance the biodiversity of other existing and future coastal structures. Recent investigations suggested that larval supply of marine organisms was not limited in Singapore. However, the availability of suitable habitat is limited in many areas. We believe that by introducing appropriate substrates in the right environment, coupled with effective management of human activities, marine biodiversity can be revived or enhanced along otherwise barren areas. One way to do this is through the reverse engineering of structures – i.e., extracting design information from a manmade structure/object and using this information to enhance other structures/objects – to understand the design and engineering aspects and environmental factors that facilitated the recruitment of organisms in the examples described above. We looked at the nature of the built structure from the type of material used, the methods of construction, surface complexity, inclination, hydrodynamic conditions, exposure to varying tidal regimes and anthropogenic activities, and the historical condition of the sites that contributed to their ability to host and support biodiversity. Based on those metrics, we investigated different strategies for biodiversity enhancement and developed the following framework to assess coastal structures and their capacity to host biodiversity (Fig. 1).

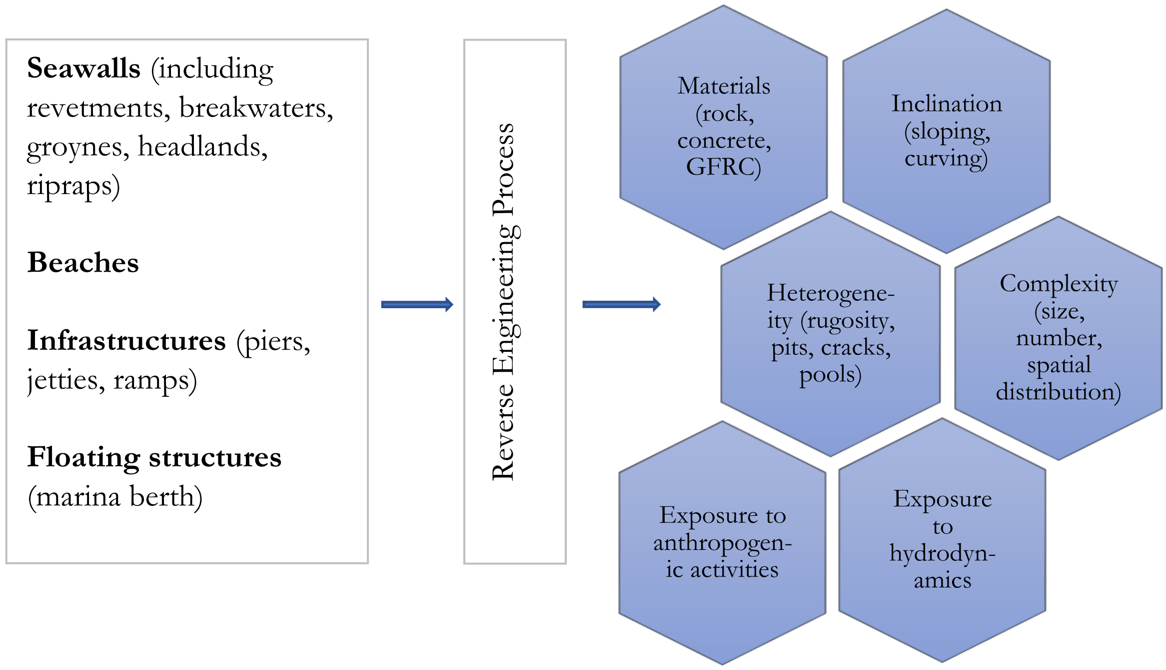



Fig. 1. A framework to assess coastal structures and their friendliness toward biodiversity.

*Design and development of enhancement structure*

We identified and investigated strategies for increasing the heterogeneity and complexity of built surfaces, introducing novel habitats such as tidal pools, enhancement units, and textured tiles, manipulating the substrate, planting coastal vegetation, and incorporating purpose-built elements to coastal structures.

We found that for enhancement on existing seawalls and coastal structures, surface complexity was the most important and also the most easily manipulated amongst all assessment criteria. Complexity could be manipulated at different spatial scales, ranging from millimetre to metre, and targeting different organismal behaviour. We worked with four complexity parameters that were developed in a separate research project by our research collaborators from the National University of Singapore, namely (1) the number of object types; (2) the relative abundance of object types;

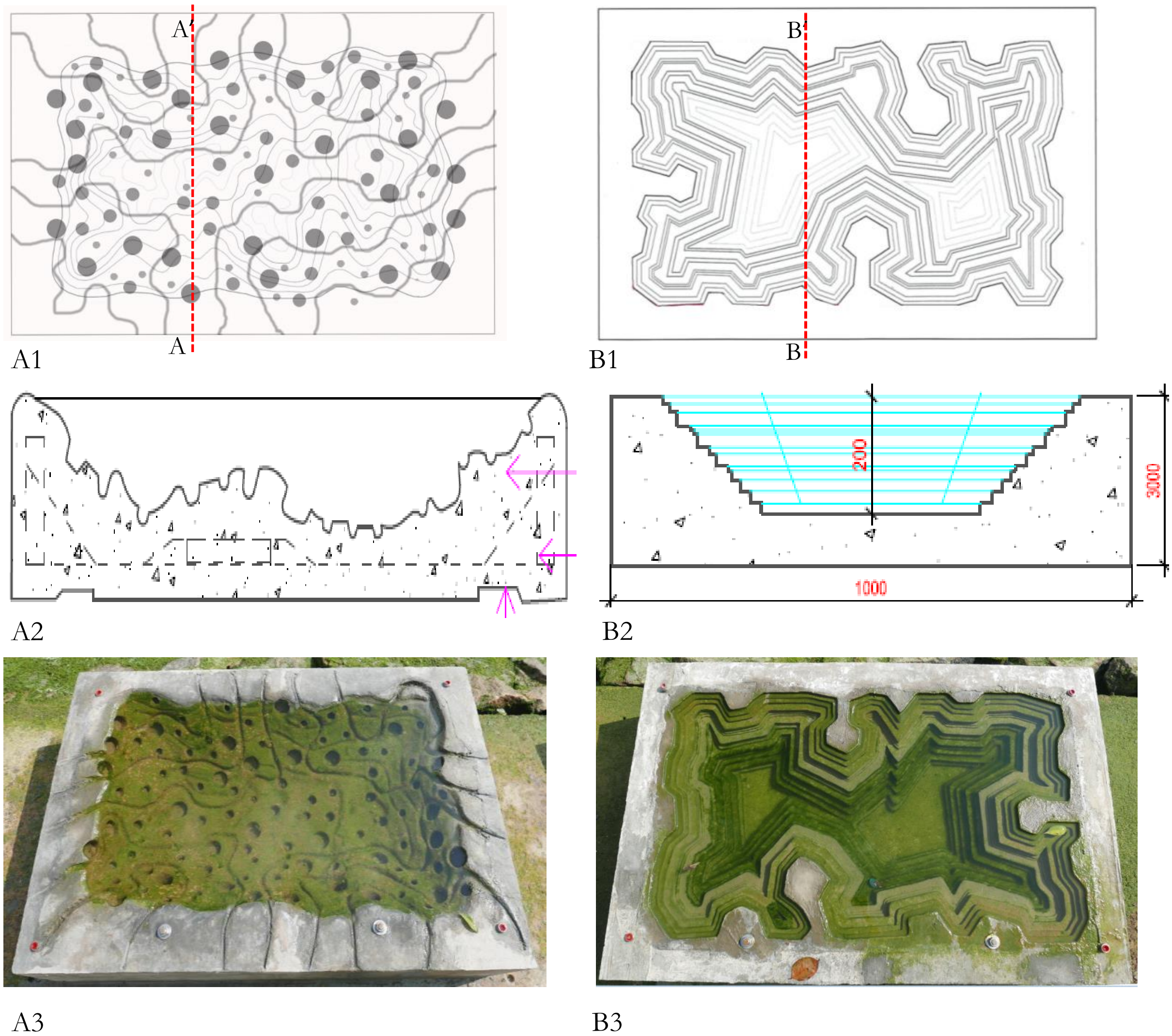
(3) the density of objects; and (4) the variability and range in the objects' dimensions, to design reverse-engineered tidal pool units to be introduced along an existing stretch of seawall with a barren horizontal surface.

These tidal pool units consisted of purpose-designed and fabricated concrete modules measuring 1.5 metres by 1.0 metre by 0.3 metre. They were fabricated with concrete suitable for the marine environment using negative fibreglass moulds, and were designed to collect seawater during high tide and to retain it during low tide to mimic a tidal pool environment. These tidal pool units were expected to create habitats that were similar to natural rock pools, to provide additional niches, and to encourage more diverse assemblages of marine organisms to thrive within the area.

To design the units, we first studied natural rock pool habitats to identify attributes that made them suitable for certain marine organisms to colonise and thrive, and found that a combination of crevices, grooves, and pits provided ideal niches and succession for a variety of marine organisms. These attributes were then incorporated in the design process, according to the four complexity parameters, to create conceptual designs that would most closely mimic natural tidal pool habitats. Multiple designs were created based on the different complexity combinations, and two designs were selected for testing.

The first design was a pool with a combination of evenly distributed grooves with pits of three sizes – 30 small pits (20-millimetre diameter), 30 medium pits (40-millimetre diameter) and 30 large pits (70-millimetre diameter) (Fig. 2A). The multiple sizes of the pits enabled us to increase the spatial scale of this feature. Pits and groves were cast on an inverted topographic surface. This surface plan mimicked a natural hilly landscape in Singapore (Central Catchment Nature Reserve), where the complex topography housed significant biodiversity.

The second design was a pool of the same rectilinear dimensions with a randomised arrangement of steps. The steps' thickness was calculated based on the aforementioned complexity parameters (Fig. 2B). The angular edges and offset create niches for marine organisms. We also embedded some pits (3-millimetre diameter) into some of the units of this design to test out the combination of pits and steps.




Figs. 2. (A) 1. Design of the pool with pits and grooves – Plan View; 2. Cross section A-A'; 3. Final cast of the pool with pits and grooves; (B) 1. Design of the pool with randomised steps – Plan View; 2. Cross section B-B'; 3. Final cast of the pool with randomised steps.

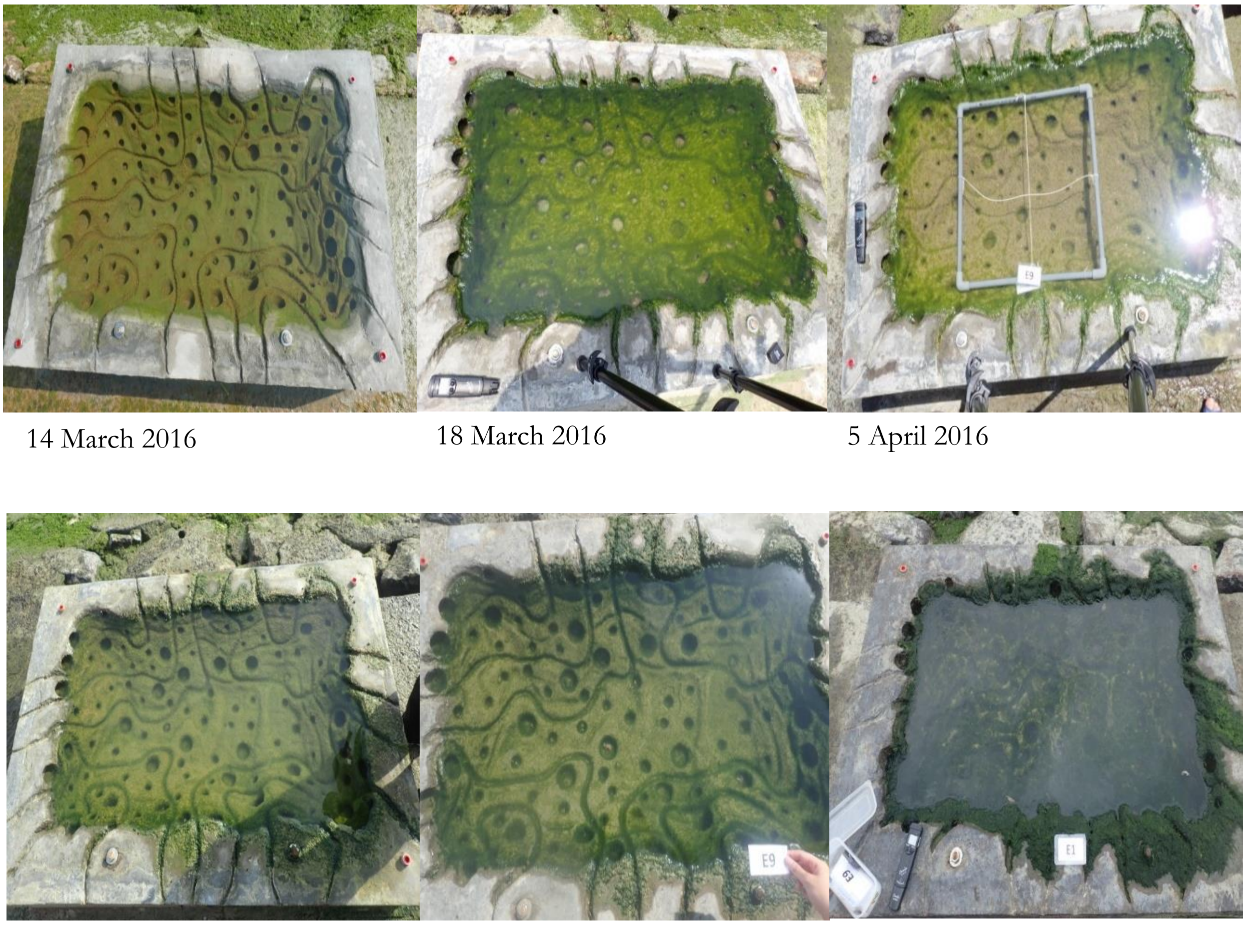
We studied the hydrodynamic conditions of the site that might affect the service life of the tidal-pool structures. Through hydrodynamic modelling, we calculated mean current speed and changes in bed thickness per year to identify whether the seawall was subjected to strong erosion or accretion. Mean current speed was also an indicator that helped determine if the coast was subjected to strong hydrodynamic forcing, that might result in lateral movement or even dislodgement of the fitted tidal pool structures. While there were studies suggesting that introduced artificial structures could have a positive impact on sandy shoreline stabilisation, the introduction of these structures should not compromise the ability of the engineered coastal infrastructure to perform its primary function. In the case of seawalls that were built for sea defence, the enhancement measures must preserve sea wall structural integrity, as well as connectivity of coastal processes.

We looked at the relationship between the tidal pool designs and community assemblage and succession by assessing their ability to provide shade and regulate temperature using drained and un-drained units. To reduce bias and account for treatment or site effect, we positioned the different design configurations randomly along a linear stretch of seawall and introduced control plots to assess the effectiveness of introduced structures versus no modifications. Control units in this context were empty plots on the seawall that were of the same size as the tidal pool units (Fig. 3). Data collected on these control plots would act as a baseline against which the treatments/modifications would be compared.


Fig. 3. The tidal pool units positioned in a randomised layout with control plots (empty slot without any tidal pool unit).

***Results***

The units were monitored fortnightly to gather data on the recruitment and succession of fauna and flora, as well as environmental parameters such as temperature, conductivity, and irradiance. We engaged a group of students from Nanyang Technological University to monitor and document the performance of the tidal pool units. Preliminary results indicated that the tidal pools were occupied by turf algae within the first week after installation and, shortly after, this single species was replaced by an assemblage of algae including *Bryopsis* spp., *Dictyota* sp., *Enteromorpha* spp., *Ceramiales* spp. and *Ceramium* spp. (Fig. 4). Fauna diversity and abundance increased over time and, after several weeks, we recorded periwinkle and nerite snails, crabs, tube and fire worms, feather stars, sponges, bead anemones, and even cuttlefish (Fig. 5). The performance of each tidal pool design and its complexity elements were also being monitored. The outcomes of this study were expected to provide a more comprehensive understanding of the combination of complexity treatments on species recruitment and biodiversity.



14 March 2016 | 18 March 2016 | 5 April 2016

26 April 2016 | 11 May 2016 | 31 May 2016

Figs. 4. Succession in unit E9 with contour designs.

Figs. 5. Marine organisms recorded in the tidal pool units.

**Conclusions**

Our results indicated that habitat enhancement of artificial coastal structures is one of the important strategies for biodiversity conservation in urbanised coasts. They also showed that by introducing appropriate substrates for the right environment, novel habitats could be created on shorelines with areas known to have low biodiversity. The performance of the habitat enhancement structures depended largely on the existing biophysical conditions as well as the structures to be enhanced. The conditions of the existing structures such as materials, inclinations, complexity, and exposure to human activities influenced the selection of suitable enhancement methods.

Projected sea level rise poses the most immediate threat to Singapore, and protecting our coastline has been identified as a priority in dealing with the effects of climate change. The current efforts to defend our coastal areas from erosion include the construction of walls and stone embankments. At the same time, ecologically informed engineering in the design and construction of coastal infrastructure would reduce loss of intertidal biodiversity on our artificial shoreline. Synergistically, the introduction of purpose-built coastal enhancement features would reduce the ecological impacts of future coastal protection and reclamation projects without compromising the functions of coastal defence structures.

Thus, the integration of engineering and ecological knowledge leading to the creation and modification of coastal structures that both protect the coast and better support biodiversity is an imperative win-win solution.