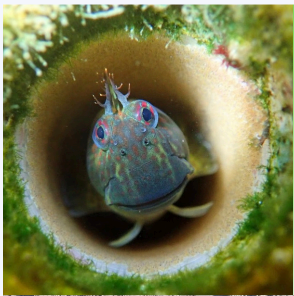

November 2023 Edition

GUIDELINES OF DESIGN, INSTALLATION & MAINTENANCE OF

Eco-engineered Features on Artificial Shorelines

Civil Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong Special Administrative Region

CEDD

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1 Overarching considerations

1.1 Artificial shorelines are characterised herein as hard anthropogenic coastal armouring or defence structures. Hard eco-engineering refers to enhancement of ecological services through the alteration of artificial structure, it is either retrofitted or constructed (Sawyer et al., 2020). Soft eco-engineering refers to reintroduction of natural biological shoreline features such as replacing artificial structure with sediment, vegetation and/or other habitat forming organisms (e.g., mangroves and oysters) to increase biodiversity and ecosystem functions (Morris et al., 2019).

1.2 It is a well-established theory that an increase of habitat heterogeneity can often promote species diversity in the ecosystem (Ricklefs and Schluter, 1993). Therefore, selecting a variety of both hard and soft eco-engineered features with different microhabitats (instead of installing one type of feature) can aid in driving higher regional biodiversity (i.e., β diversity) by considering the various habitats needed by different species.

1.3 Habitat heterogeneity through the incorporation of hard and soft-engineered features can allow a diverse community of native species to fill ecological niches and increase the biological resistance to invasive species (i.e., having less resources available for non-native species, and having native predators to prey on and control the invasive species). The ability of native communities in Hong Kong to bio-resist invasive species is dependent on temporal environmental conditions and seasonality (Astudillo et al., 2016).

1.4 The primary recommendation is to tailor the expectations of the eco-shoreline design to the project’s goals (O’Shaugnessy et al., 2020). Eco-engineering implementation needs to have a targeted objective and stakeholder engagement. The targets may include biodiversity enhancement, increased specific ecosystem services, increasing populations of a target organism(s), and/or community utilisation of the waterfront (O’Shaugnessy et al., 2020).

1.4.1 The targets may also involve aesthetic elements that enhance such sites' amenity and recreational value (fishing, nature appreciation, boating, etc.).

1.4.2 Key habitat forming and functionally important species should also be targeted.

1.4.3 Other options to improve the implementation of the feature(s) should be explored with local stakeholders, as solutions are often context dependent.

1.5 The cost-benefit, life span (i.e., durability) and sustainability of the eco-engineered features should also be considered during site selection, design, and implementation.

2 Site selection

2.1 When choosing implementation sites of eco-shoreline, environmental and biotic factors should be taken into consideration for minimal maintenance in the future (**Appendix 1**). For example, areas with busy marine traffic should be avoided. Furthermore, sites that are more exposed with stronger wave action may need extra effort in securing eco-features on the seawalls. For biotic factors, the presence of bio-eroding species may hinder the success of the projects. In particular, the oyster basket experiment in Lung Kwu Tan was affected by the boring bivalves *Aspidopholas tubigera*, leading to fragmentation of the oyster shells. In addition, nearby pollutant sources such as sewage outflow and storm drainage discharge points should be avoided. Therefore, replenishment might be needed to maintain the functions of oyster baskets. Correct site selection and preparation should lead to minimal maintenance.

3 Hard eco-engineering considerations

- Hard eco-engineered feature design specifications

3.1 The recommended specifications of hard eco-engineering features that can be considered into the design of future eco-shorelines are provided in **Tables 3.1** and **3.2** for reference. The recommended dimensions are based on on-site observations and for reference from the eco-engineered features tested in Hong Kong (**Figure 3.1**).

Table 3.1. Description of hard eco-engineered features tested on vertical seawalls and recommended dimensions (range) for eco-panels and eco-tiles suitable for implementation in Hong Kong intertidal seawalls.

Vertical Seawall	**Tested features**		**Recommended for Hong Kong**	
Dimensions	**Eco-panels**	**Eco-tiles**	**Eco-panel**	**Eco-tiles**
Size (cm)	Length: 180 Width: 90 Height: 15	Length: 25 Width: 25 Height: 8	Length: 100-200 Width: 90-150 Height: 15-25	Length: 25-50 Width: 25-50 Height: 7-10
Ledge/extrusion (cm)	Length: 4-9 Width: 1.5-6 Height: 1-3	Length: 5-25 Width: 1-5 Height: 1-3	Length: 5-25 Width: 2-6 Height: 3-10	Length: 5-25 Width: 2-6 Height: 3-5
Crevice (cm)	Length: - Width: - Height: -	Length: 25 Width: 1-5 Height: 5	Length: 5-25 Width: 2-6 Height: 3-5	Length: 5-25 Width: 2-6 Height: 3-5
Cavity: (cm)	Length: - Width: - Height: -	Length: 2-7 Width: 1-2 Height: 1-2	Length: 1-6 Width: 1-6 Height: 1-5	Length: 1-7 Width: 1-6 Height: 1-5
Hole (cm)	Diameter: 3 Height: 15	Diameter: 1 Height: 1-3	Diameter: 3-5 Height: 5-25	Diameter: 1-5 Height: 1-5
Surface Texture (cm)	Width: - Height: -	Width: 0.1-0.5 Height: 0.1-0.5	Width: 0.1-0.5 Height: 0.1-0.5	Width: 0.1-0.5 Height: 0.1-0.5

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Table 3.2. Description of hard eco-engineered features tested on rip-rap seawalls and recommended dimensions (range) for armouring units and tidal pools suitable for implementation in Hong Kong intertidal seawalls.

Rip-rap Seawall	Tested features		Recommended for Hong Kong	
Dimensions	**Armouring unit**	**Tidal pool**	**Armouring unit**	**Tidal pool**
Size (cm)	Length: 120 Width: 120 Height: 120	Length: 120 Width: 110 Height: 70	Length: 70-120 Width: 70-120 Height: 70-120	Length: 70-120 Width: 70-120 Height: 70-120
Ledge/extrusion (cm)	Length: >15 Width: 1.5-5.0 Height: 1.0-1.5	Length: >50 Width: 2-3 Height: 1	Length: 5->50 Width: 2-6 Height: 3-10	Length: 5->50 Width: 2-6 Height: 3-5
Crevice (cm)	Length: - Width: - Height: -	Length: >50 Width: 2 Height: 1	Length: 5->50 Width: 2-6 Height: 3-5	Length: 5->50 Width: 2-6 Height: 3-5
Cavity: (cm)	Length: - Width: - Height: -	Length: - Width: 2-6 Height: 1-2	Length: 1-6 Width: 1-6 Height: 1-5	Length: 1-6 Width: 1-6 Height: 1-5
Hole (cm)	Diameter: 3 Height: 10-15	Diameter: 3 Height: 10-15	Diameter: 3-5 Height: 5-25	Diameter: 1-5 Height: 1-5
Surface Texture (cm)	Width: - Height: -	Width: 0.5-1.0 Height: 0.5-1.0	Width: 0.5-1.0 Height: 0.5-1.0	Width: 0.5-1.0 Height: 0.5-1.0

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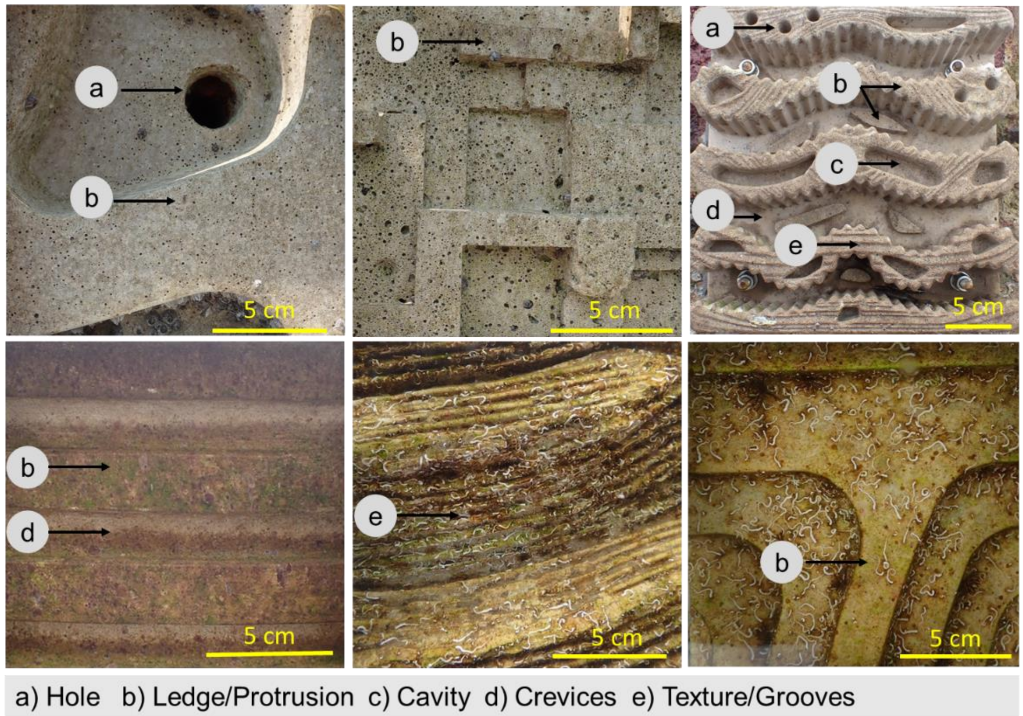

Figure 3.1. Examples of the different designs that may be implemented into hard eco-engineered features.

- <u>Concrete mixture</u>

3.2 It is an option to incorporate waste materials into the concrete mixture to help reduce waste and minimise the use of cement, which will eventually lower the carbon footprint of the eco-engineered features. The impact of waste material must be assessed in a small-scale trial over a period of at least 6 months in order to determine and avoid potential negative effects to the marine environment. The impact of waste material should also be complemented with a desktop review to determine any undesired output that may not be detected in the small-scale trial. The development of the eco-tiles with marine sediment and T-Park ashes in the current trial showed that adding waste materials in the concrete mixture provides comparable material integrity and biodiversity performance as conventional concrete. Specifically, the eco-tiles comprise of an eco-concrete mixture (M1) that integrates milled incineration sewage sludge ash (MISSA) and recycled marine sediment (MS) to partially substitute cement and fine aggregates. The results indicated a good performance from the eco-tiles as they harboured various intertidal organisms and provided an environmentally friendly concrete alternative for implementation in Hong Kong.

3.3 Eco-concrete mixtures must meet the construction standards set in the region.

It is recommended that eco-engineered features installed in Hong Kong should have a minimum concrete compression strength of 30 MPa to meet Hong Kong Standards. Some examples of concrete that may be used for eco-engineered features are the unreinforced eco-concrete (M1) which achieves a compression strength of 39 MPa and the fibreglass reinforced ECOncrete® mixture which has a compression strength that ranges from 30 to 80 MPa (Perkol-Finkell and Sella, 2014; Perkol-Finkell and Sella, 2015).

3.3.1 It is recommended that features that are retrofitted on vertical seawalls or are exposed to tensile forces should be fabricated with reinforced concrete. Concrete without reinforcement may be suitable for deployment in seawalls exposed to compression forces. Therefore, the design and location of the eco-engineered features are important to determine the use of reinforcement.

3.4 The experimental results under this study and other relevant studies show that lowering surface pH (by carbonation or any other means) is unnecessary for Hong Kong's sub-tropical coastal marine environments. The surface pH of all types of concrete eco-tiles, with or without carbonation to reduce surface pH, declined over time naturally, reaching pH values between 8 and 9 after 12 months. More importantly, it was found there were no significant differences in species richness between eco-tiles with normal high pH and low pH.

- Vertical seawall

3.5 Any eco-engineered feature to be retrofitted on a vertical seawall must be engineered to balance between their weight and durability with an ecologically beneficial design. As stated in section 3.3.1 above, eco-engineered features that are retrofitted on a vertical seawall or are exposed to tensile force should be fabricated with reinforced concrete. Glass fibre reinforced plastic (GFRP) may be used to reinforce concrete as long as it meets the standard in the region. Given that the reduction of surface pH is proven to be unnecessary in Hong Kong, concrete mixtures with normal high pH and steel rebars can be adopted in the fabrication of eco-engineered features. The choice of reinforcement should be considered by the project officer following engineering principles and/or standards.

3.6 The vertical seawall eco-engineered features should primarily be designed to increase surface heterogeneity and surface area with a wide variety of microhabitat types such as flat smooth surface, rough surface with grooves, holes of various sizes, cavities, pools, pots, crevices, and shades to elicit the growth of diverse species on multiple features (See Firth et al., 2014 for more details). These microhabitats can support organisms by reducing predation, heat stress and desiccation stress.

3.7 **Table 3.1** and **Appendix** 2 provide some examples and details of the vertical seawall eco-engineered features, which can be used as reference in Hong Kong.

3.8 Eco-engineered designs should be site-specific with due consideration of various important factors such as the orientation to the sun, marine biodiversity present in the nearby natural shores (as a reference of the biodiversity in the area), water quality, water hydrology and hydrography, waterfront usage, and human activities (e.g., vessel traffic, anglers) in the seawall/site of concern. The ecological and environmental assessment of the site should be conducted by ecologist and/or eco-engineering experts to ensure the ecological function and structural integrity of the eco-engineered designs.

3.9 For sites prone to extreme heat stress conditions in tropics and sub-tropics, eco-engineered feature designs should consider using built-in cavities with pools, shade, and the back of the eco-panel (See **Appendix 2**) to serve as habitats for marine organisms. These designs can effectively reduce direct sun exposure, heat stress, and desiccation, enhancing the survival of marine organisms. A sun-shade design could also be implemented, such as cooling facades, but limited to areas without active marine traffic and pier facilities. It is also recommended that the ledge/protrusion depth on eco-panels or eco-tiles should be no less than 5 cm, as small ledges/protrusions would not provide effective shading and cooling.

3.10 The design of retrofitted eco-engineered features should consider managing the contact points (i.e., anchoring points) with the seawall so that the eco-engineered features can be designed to allow for irregular seawall surfaces. If the site allows, the features should be deployed slightly away from the seawall (i.e., will enable a space/ gap) to avoid damaging the existing mature biological communities before the deployment. The space will depend on the thickness of the existing communities on the seawall, the design of the eco-engineered features and the engineering considerations to maintain the structural integrity of the eco-engineered features.

3.11 If feasible, large water retention capacity on the eco-engineered features at the vertical seawalls (e.g., build-in cavity pools, external pots, small water retention areas in panels/tiles) that has the potential to counteract high heat stress conditions, coastal squeeze, and aid in retaining moisture (Morris et al., 2017) should be considered for incorporation into the design whenever feasible.

- Rip-rap seawall

3.12 The design of eco-engineered features for the rip-rap seawalls should be multi-positional for functionality at any face and ease of installation.

3.13 Small thin sections of concrete in the features should be avoided. Any large thin section should be reinforced to reduce structural damage.

3.14 The design of eco-engineered features should consider and incorporate suitable structures for ease of transport and installation.

3.15 The eco-engineered features should have sufficient lifting points for easing their transportation and enabling a smooth installation process. The lifting points (e.g., long channels, lifting sockets or loops) may also later be used as microhabitats by marine organisms.

3.16 The eco-engineered features should be designed to prevent or minimise visual intrusion to the existing rip-rap seawall landscape and, at the same time, fulfil the region’s engineering requirements as a sea defence structure.

3.17 **Table 3.2** and **Appendix 3** provide some examples and details of the rip-rap seawall eco-engineered features, which can be used as a reference in Hong Kong.

- Installation

3.18 Installation of the eco-engineered features should not compromise the engineering function or threaten the structure’s primary function of the marine structures in any way.

3.19 Installation of features at different tidal heights/elevations and different scales (e.g., individual panels onto existing seawalls vs. large scale deployment) would be effective in determining impact, scalability, and management of various projects (Toft et al., 2007). It is essential to focus on a desired target range of elevation to improve and set the project’s goals.

3.20 Durability:

3.20.1 The design of the overall eco-engineered features must be robust enough (could be supported by engineering tests of loading and strength) to be installed with minimal damage (i.e., cracking, chipping, and crumbling) and maintenance. It must facilitate deployment ease for the contractors on site.

3.21 Installation on vertical seawalls:

3.21.1 Lifting and fixing points on vertical seawall eco-engineered features should be prominent and sufficient for retrofitting and movement during deployment.

3.21.2 Fabricators of eco-engineered features should have a clearly outlined protocol to fix the features onto the vertical seawalls (see **Appendix 2** for reference).

3.21.3 Contractors in charge of the installation should work with the fabricators to determine that the proposed installation protocol is suitable for the vertical seawalls.

3.22 Installation on rip-rap seawalls:

3.22.1 Lifting and fixing points of eco-engineered features should be prominent and sufficient for retrofitting and movement during deployment.

3.22.2 Fabricators of eco-engineered features should have a clearly outlined protocol for installing the features into the rip-rap seawalls (see **Appendix 3** for reference).

3.22.3 Contractors responsible for the installation should collaborate with the fabricators to ensure that the proposed installation protocol is suitable for the rip-rap seawalls.

3.22.4 It is advocated to consider the design of the eco-engineered features with interlocking mechanisms for stabilizing them on rip-rap seawalls and/or having the multi-positional aspects for ease of deployment and functionality of the unit.

3.22.5 When necessary, rip-rap boulders could be used to give structural support to the eco-engineered features to prevent dislodgement or substantial movement over time.

3.23 Deployment of the eco-engineered features:

3.23.1 Deployment should be restricted to areas with smaller recreational vessels; project designs should avoid areas used by large marine vessels to reduce strikes and damage to the eco-engineered features.

3.23.2 For reference, installation of eco-engineered features on rip-rap and vertical seawalls should be conducted within a tidal level between 0 m and 1.5 m above Chart Datum (C.D.) as this will allow the most efficient use for marine biodiversity enhancement in subtropical Hong Kong. This tidal range represents the low and middle tidal heights, where most intertidal biodiversity can be found. It is important to note that more positive results on biodiversity enhancement are often seen at lower tidal levels than mid and high tidal levels (Strain et al., 2021).

3.23.3 Site-dependent seasonality should be considered when deploying features in each site so that deployment timing can coincide with a target species' spawning season. Larval supply to the site should also be considered during site selection and design of the eco-engineered features.

3.24 Limitations in deploying eco-engineered features:

3.24.1 Eco-engineered features designed for rip-rap sites may need areas with level ground (e.g., tidal pool and armour unit from ECOncrete®) for proper functionality. Future designs should be multi-positional to avoid this issue, enabling easy deployment and interlocking with existing rip-rap granite boulders.

3.24.2 Replacement or rearrangement of rip-rap during the installation of eco-engineered features may cause structural instability of the seawall, specifically when granite boulders are removed. Therefore, the construction contractor may need to preliminarily assess the rip-rap seawall structural stability. The assessment can determine the number of eco-engineered features that can be retrofitted without jeopardizing the seawall structural stability.

3.24.3 As indicated in section 3.10, vertical seawalls have irregular surfaces that could impact the installation of eco-engineered features. Therefore, when retrofitting eco-engineered features, it is essential to consider managing contact points, or anchoring points, suitable for the irregularity of the seawalls. Considering the two-dimensional configuration of vertical seawalls, there are also limitations regarding increasing surface area and complexity. Eco-engineered feature designs should prioritize double-sided configurations, allowing for the utilization of both the front and back surfaces of the features (e.g., panels or tiles), while preserving the existing community on the seawall. The spacing between the seawall and the back side of the features will depend on the thickness of the existing communities, the eco-engineered feature design, and engineering considerations to maintain structural integrity. Double-sided features for vertical seawalls may require adequate attachment points to support their weight.

- Maintenance

3.25 The eco-engineered features should be designed and fabricated with durable materials to withstand typhoons and tidal surges experienced in sub-tropical Hong Kong. Thus, the use of durable material will reduce the maintenance of the seawall caused by damaged eco-engineered features.

4 Soft eco-engineering considerations

- Soft-engineering feature design specifications

4.1 The design of soft-engineered features should be site specific and determined by ecologists and/or eco-engineering experts and project officer. The specifications of soft eco-engineered features that can be considered into the design of eco-shorelines are provided in **Table 4.1** for reference. The recommended dimensions of steel/metal oyster baskets and oyster bags (e.g., metal wire or biodegradable fibre) are based on on-site observations and results from the eco-engineered features tested in Hong Kong (See **Table 4.1** and **Appendix 4** for reference).

Table 4.1. Description of oyster baskets and bags tested on rip-rap seawalls and recommended dimensions (range) for oyster baskets and oyster bags suitable for implementation in Hong Kong seawalls.

Rip-rap seawall	Tested features		Recommended features	
Dimensions	**Steel oyster basket**	**Oyster bags**	**Metal oyster basket**	**Oyster bags**
Size (cm)	Length: 70 Width: 70 Height: 30 Diameter: -	Length: 30 Width: - Height: - Diameter: 20	Length: 50-100 Width: 50-100 Height: 20-50 Diameter: -	Length: 30-100 Width: - Height: - Diameter: 20-40
Mesh Size (cm)	Length: 3 Width: 3	Length: 3 Width: 3	Length: 3-5 Width: 3-5	Length: 3-5 Width: 3-5

(For reference only)

4.2 Oyster bags and baskets should be made with degradable materials such as

metal wire and/or natural fibre (e.g., hemp or coconut coir). The oyster bags and baskets should be filled and tightly packed to reduce the oyster shells' movement and friction. Oyster shells can also be threaded onto collars (i.e., chains of oyster shells) and deployed in baskets to avoid erosion and displacement.

4.3 Alternatively, oyster shell bags and/or collars could also be deployed within the existing gaps of the rip-rap granite boulders. This method can add habitat complexity to the rip-rap seawalls without modifying the arrangement of the boulders and landscape. The use of oyster baskets, collar or bags may be determined by the scope of the eco-shoreline, intervention level allowed on the seawall and the advice from the ecologists and/or eco-engineering experts.

<u>- Implementation of native oyster baskets/bags:</u>

4.4 Baskets/bags with native live oysters or oyster shells are an ecologically beneficial addition to many eco-shoreline installations as they are cost-effective and easily implemented. Other native bivalves like mussels (*Perna viridis*) and pearl oysters (*Pinctada imbricata fucata*), as well as their shells, can also be adopted. However, shells of the Hong Kong oyster (*Magallana hongkongensis*) are proven efficient in enhancing biodiversity, therefore recommended for Hong Kong. Oyster baskets/bags can be easily installed in combination with hard eco-engineered features, such as armour and tidal pools, in the rip-rap seawalls. For vertical seawalls, oyster baskets/bags can be deployed at the seawall toe, whenever possible, to complement enhanced panels and eco-tiles.

4.5 Based on the experimental results obtained from this study, the performance of biodiversity enhancement was similar between live oysters and oyster shells. Due that mortality of live oysters was high, it is advised to utilise oyster shells. Using oyster shells can facilitate the purchase, transportation and storage for the implementation of the oyster basket/bag. Live oysters can be considered in areas with similar conditions to the source area to reduce mortality and maintenance. The use of live oysters should be advised by ecologists according to the environmental conditions of the site.

4.6 Oyster baskets/bags should be deployed between shallow subtidal and 1 m above C.D. for the most efficient use. Oyster baskets/bags can effectively increase biodiversity at any tidal height below 1.0 m above C.D (including the subtidal section of the seawall). Thus, it is recommended that the top of eco-engineered feature does not exceed 1.0 m above C.D.

4.7 The amount of oysters and shells to be used will depend on the design of the baskets/bags and the size of the oysters and shells available, which is subjected to the determination of the project officer. Installation of oyster baskets/bags in the low intertidal and shallow subtidal zones reduces exposure to strong wave action, reducing the abrasion of the shells.

4.8 Precautions to heed:

4.8.1 Shells of the native oyster *Magallana hongkongensis* should be dried and air-cured for at least six months before deployment to allow the removal of remaining tissues and pathogens. The suggested size range of the shells is approximately 5-15 cm in length (this shell size is available in Hong Kong).

4.8.2 Oyster bags inside the baskets or oyster/shells inside baskets must be packed compactly to reduce their movement, allowing for higher settlement rates of different organisms, and preventing abrasion and fragmentation of the shells.

4.8.3 During deployment, oyster bags or baskets must be secured into the seawalls or seafloor to reduce movement, damage, and/or loss of the feature(s). Oyster baskets can be drilled onto rip-rap boulders or concrete slabs for security as well.

<u>- Mangrove's plantation</u>

4.9 Native mangrove trees species should be selected to ensure ecosystem integrity and minimise the bio-invasion risk as per the advice of ecologists.

4.10 Planting multiple mangrove species can provide more diverse habitats and enhance marine biodiversity in the ecosystem. The plantation of various mangrove species would eventually provide insurance against species-specific mortality events.

4.11 Mangrove plantations should be inspected for the presence and removal of invasive mangrove species as per the advice of ecologists.

4.12 Planting of mangrove species should be conducted in areas with suitable environmental conditions as per the advice of ecologists. The pH of soil used should be within the viable range of the targeted mangrove species as per the advice of ecologists.

4.13 Soil erosion (i.e., sediment loss) should be prevented during the early stage of the mangrove plantation. Hard eco-engineered features at the seaward side of the seawall can be installed to provide a physical barrier to prevent soil erosion.

4.14 Mangrove seedlings tend to have a high mortality rate; thus, initial planting should consider high-density planting (e.g., 1 m distance between plants) as per the advice of ecologists. Subsequently, the mangrove plantation can be thinned as needed.

4.15 The plantation timing should follow the species' natural growth cycle, i.e., seasonality as per the advice of ecologists and or eco-engineered experts.

4.16 The site selection of the mangrove should be considered based on a baseline survey and it should be conducted by an expert in the marine ecology field. The baseline survey will assist to select the most suitable and available native mangrove species for the environmental conditions of the site.

4.16.1 The site selected for mangrove plantation should be sheltered with low wave action and nearby freshwater sources, i.e., regular flowing rivers/streams/drainage where droughts are not impacted.

4.16.2 Stepwise or gentle-slope mangrove habitats are preferred such that intertidal zonation and the subsequent niche partitioning can facilitate the establishment of an intertidal community with high biodiversity.

4.16.3 Plantation should not be higher than 2 m above C.D.. Natural mangrove stands near the mangrove plantation site can be used as reference to determine suitable mangrove species and the environmental conditions needed for such species (e.g., tidal height, sediment composition and intertidal slope).

5 Recommendations

5.1 The benefits associated with eco-shorelines can extend to societal gain as well. The eco-engineered features can be designed to be safely accessible and provide educational means (information boards should be coupled with installation) to locals and tourists; however, this will be site dependent and advice from the ecologists and/or eco-engineering experts shall be sought. In terms of public access to the features, the eco-shoreline must incorporate steps, pathways, and features with anti-slip designs, such as adding more grooves and ledges/extrusions on the outer surfaces.

5.2 Moreover, site selection can greatly influence results; thus, site-specific expectations should be set and managed before design and deployment.

5.3 Site intervention should include proper monitoring to learn from successes and failures, and observe any unintended outcome.

5.4 For a one-year ecological or two-year ecological assessment, monitoring can

be conducted seasonally every six months, instead of quarterly monitoring. Main changes in the communities occur in the dry and wet seasons and therefore biannual monitoring is sufficient to have a short-term evaluation of the eco-engineered features.

6 Concluding remarks

6.1 These eco-engineered features and suggestions are designed to enhance habitat diversity, marine biodiversity, and ecological functions/systems on artificial shorelines. The combination of eco-engineered concrete structures (hard eco-engineering) and natural materials (soft eco-engineering) for enhancement is beneficial to create more heterogeneous habitats for catering for various native marine organisms (**Appendix 5**).

6.2 Conservation of the natural habitat should be prioritized for shoreline development, followed by nature-based solutions for any eco-shoreline practice.

6.3 The eco-engineered features and designs can become future educational tools such as coupling designs with information boards that allow opportunities for locals and tourists to learn about the function of eco-shoreline and local marine biodiversity.

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8 Appendices

Appendix 1. Summary of general guidelines list of hard and soft eco-engineered features.

Hard eco-engineering

1. Concrete should consider to incorporate waste material (e.g. dredged marine sediment, fly ash from incinerator or power plant) to minimise cement use in order to lower the city's carbon footprint.
   - 1.1. Eco-friendly concrete must meet the construction standard set by the region, such that concrete seawall blocks' compression strength should be at a minimum of 30 MPa.
   - 1.2. Development of more durable concrete mixture and eco-friendly structures is encouraged to reduce overall maintenance of the eco-engineered features.

2. Vertical seawall
   - 2.1. Steel rebar and glass fibre can be considered as concrete reinforcement for eco-engineered features when the eco-engineered features are exposed to tensile force.
   - 2.2. Installation should be site specific with due consideration of important factors (orientation to the sun, marine biodiversity in the nearby natural shores (as a reference of the biodiversity in the area), water quality, water hydrology and hydrography, waterfront usage, and human activities (e.g., vessel traffic, anglers) in the seawall/site of concern.
   - 2.3. Microhabitats need to be added into the eco-engineered features to increase surface area and surface heterogeneity; they include flat smooth surface, rough surface with grooves, holes of various sizes, cavities, pools, pots, crevices, and shades to elicit the growth of diverse species on multiple features (Firth et al., 2014).

3. Rip-rap seawall
   - 3.1. Multi-positional designs for eco-engineered features are favourable for ease of installation.
   - 3.2. The design of the features should prevent or minimise visual intrusions to existing rip-rap seawalls.
   - 3.3. Microhabitats need to be added into the features to increase surface area and surface heterogeneity on the seawalls.

4. Installation
    4.1. Eco-engineered features should have sufficient lifting point for easing transportation and enabling smooth installation.
    4.2. Designs of retrofitted eco-engineered features should consider managing contact points with the seawall to prevent damaging (or reduce damaging) existing mature biological communities during the deployment.
    4.3. Sloping seawall features should have interlocking mechanisms to stabilize them on sloping seawalls or have a multi-positional aspect to facilitate the installation.
    4.4. When necessary, rip-rap granite boulders could be used to give structural support to eco-engineered features to prevent dislodgement or movement over time.

Soft eco-engineering

5. Oyster baskets/bags
    5.1. Native live oysters or oyster shells can be used to fill baskets/bags.
    5.2. Oyster shells (or any other bivalve shells) should be air cured for about 6 months before deployment.
    5.3. Oyster bags and baskets should be made with degradable materials such as metal wire and/or natural fibre (e.g., hemp or coconut coir).
    5.4. Oyster baskets/bags can effectively increase biodiversity at any tidal height (or depth) below 1.0 m above C.D (including the subtidal section of the seawall). Thus, it is recommended that the top of the feature does not exceed 1.0 m above C.D.
    5.5. Oyster baskets/bags can be combined with hard eco-engineered features on rip-rap seawalls and vertical seawalls. In vertical seawalls oyster baskets/bags can be deployed on the seawall toe.

6. Mangroves
    6.1. Native mangrove trees species should be selected to ensure ecosystem integrity and minimise the bio-invasion risk.
    6.2. To enrich the habitat complexity, multiple species of native mangrove trees should be planted.
    6.3. The tidal height must be carefully selected for planting each mangrove species since different species have different tolerance to the duration of seawater coverage.
    6.4. Mangrove plantations should be inspected for the presence and removal of invasive mangrove species.

6.5. Mangrove plantation can be combined with hard eco-engineering to prevent soil erosion.

6.6. Measures such as breakwaters and protective geotextiles for retaining sediment on the artificial seawalls will be required.

7. Maintenance

7.1. Prioritise minimal maintenance hence features should utilise durable materials to withstand typhoon.

8. Monitoring

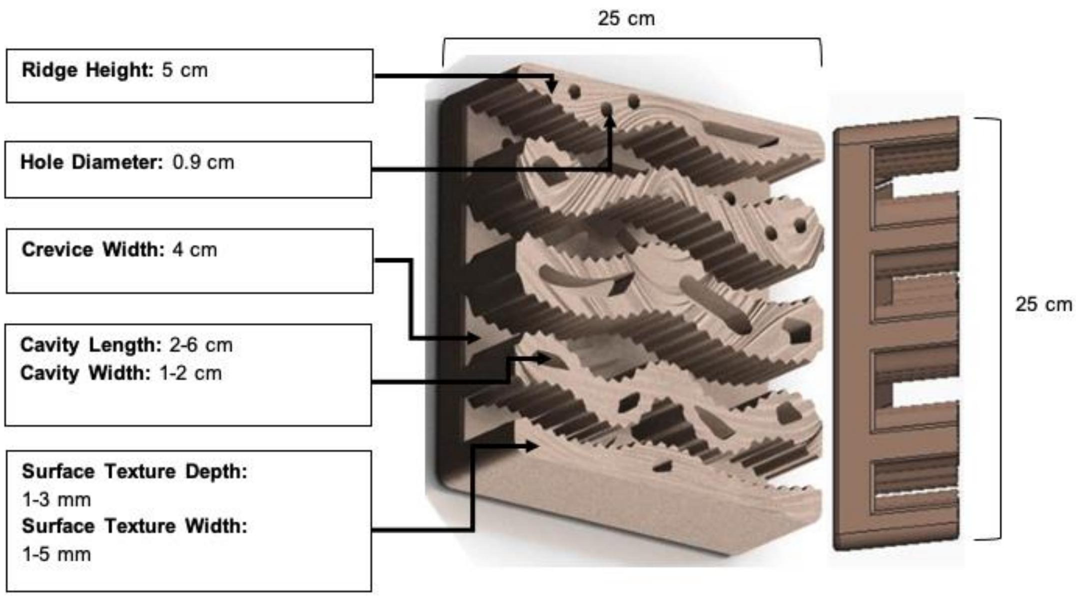
8.1. The two-year initial monitoring of the currently deployed eco-engineered features sufficiently investigated the community growth during periods of low tide, however, some improvements to the monitoring methodology can be made.

8.2. The current two-year monitoring of the eco-shoreline features is considered to be short-term, and the full benefits to the ecosystem may not be realised in this short period. Therefore, biannual or annual monitoring for a five to ten-year period is recommended subjected to funding availability.

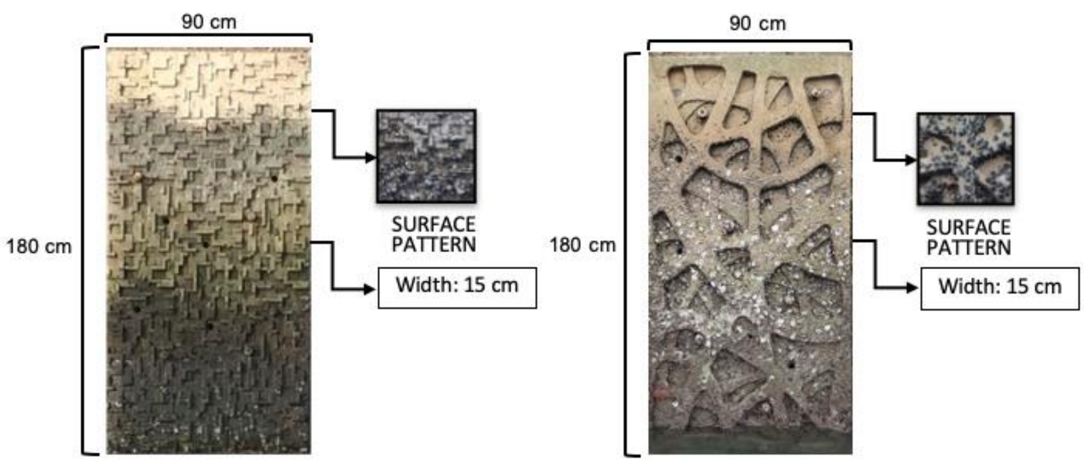
8.3. For a one-year ecological or two-year ecological assessment, monitoring can be conducted seasonally every six months, instead of quarterly monitoring. Main changes in the communities occur in the seasons and therefore biannual monitoring is sufficient to have a short-term evaluation of the eco-shoreline features.

Appendix 2. Vertical seawall eco-engineered features and installation

(Worked Example)

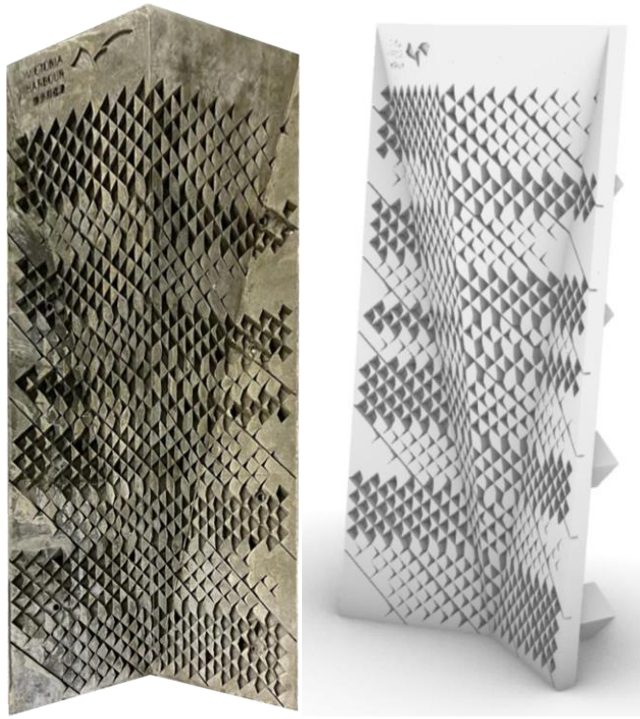


Novel eco-tile design with dimensions.



An example of ECOncrete seawall panel designs with dimensions.

(For reference only)



Example of two-sided vertical seawall panel that could be utilized. This design uses both front and back surfaces for recruitment of epi-biota. The approximate dimensions are 185 cm in high x 95 cm in long x 12 cm wide.

Example of two-sided vertical seawall panel deployed at Tsuen Wan Promenade.

(For reference only)

Reference specification for novel eco-tile design:

- Concrete type: milled incineration sewage sludge ash (MISSA) in replacement (~20%) of Ordinary Portland Cement (OPC)
- Fine Aggregate size/type: 0-5mm, partially substituted with marine sediment.
- Coarse Aggregate size/type: 5-10mm
- Durability: 39 MPa
- Acidity/Alkalinity: pH of approximately 8.3-10.0

Reference specification for ECOncrete seawall panel design:

- Concrete type: standard OPC (0-90%)
- Concrete matrix design: concrete matrix comprises at least one of microsilica/silica fume and Metakaolin and/or Calcium aluminate cements.
- Fine aggregate size/type: at least one aggregate, 4.75mm of fine sand and/or natural/crushed aggregates 0-2mm.
- Durability: 30-80 MPa
- Acidity/Alkalinity: pH of approximately 9-10.5

Reference specification for double-sided seawall panel:

- Concrete type: OPC reinforced with glass fibre reinforced plastic (GFRP) and steel bars.
- Aggregate size/type: 10 mm aggregate. The concrete mixture can alternatively be complemented with recycled aggregates, recycled incineration ash, recycled glass, marine sediment.
- Durability: Compressive Strength: >28 MPa
- Acidity/Alkalinity: pH ~10

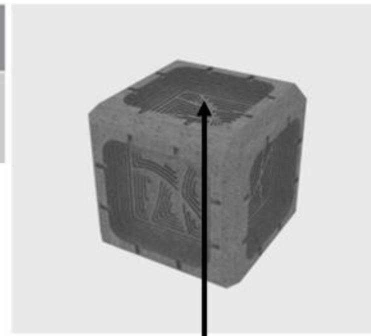
Reference installation methods of the seawall panels and eco-tiles on vertical seawalls

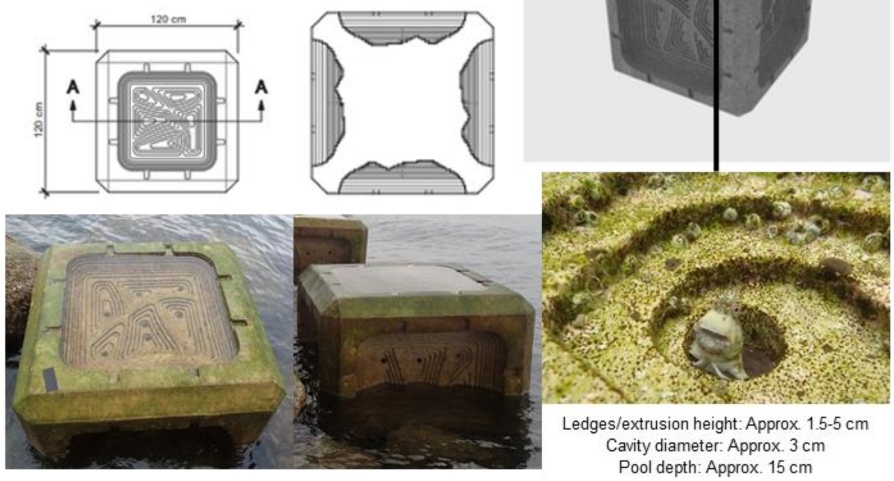
1. The enhanced seawall panels can be bolted on the seawall by stainless-steel bolts.
2. The eco-tiles can be fixed onto the seawall at the four corners using stainless steel dynabolts.

Note: The entire stretch of seawall should not be scraped, scrubbed cleaned or fully sealed with epoxy. Existing biological communities of encrusting organisms and algae should remain protected unless biological surveys are to be conducted.

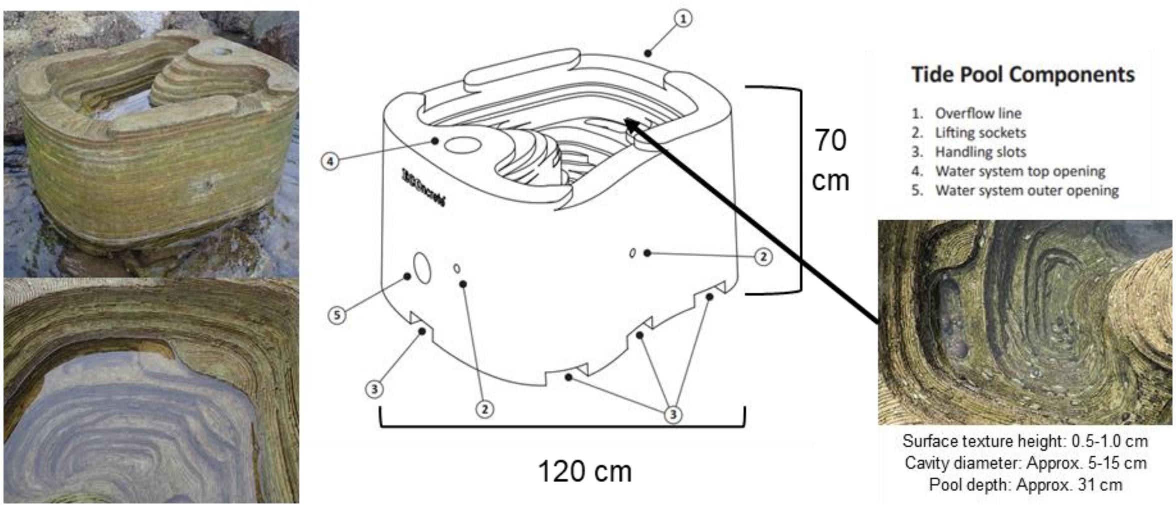
Appendix 3. Rip-rap seawall features and installation (Worked Example)

Unit Length (cm)	Unit Width (cm)	Unit Hight (cm)	Volume (Liters)	Weight (Kg)
120 (47")	120 (47")	120 (47")	1053 (2586 yd³)	2530 (5575 lbs)





ECOncrete's multi-functional armouring unit dimension and components.



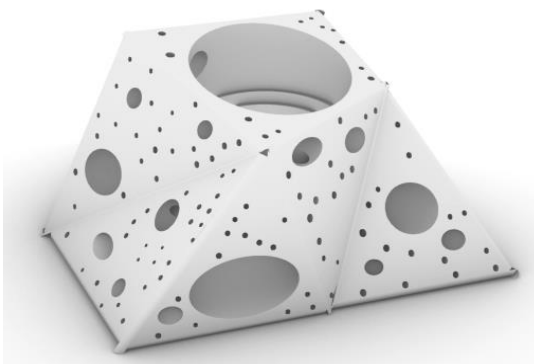
ECOncrete® tidal pool unit dimensions and components.

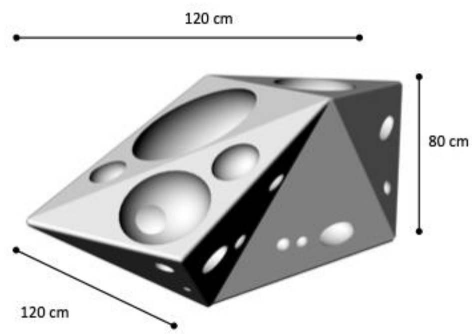
<u>(For reference only)</u>

Reference specification for intertidal units from ECOncrete:

- Concrete type: standard OPC (0-90%)
- Concrete matrix design: concrete matrix comprises at least one of microsilica/silica fume and Metakaolin and/or Calcium aluminate cements
- Fine aggregate size/type: at least one aggregate, 4.75 mm of fine sand and/or natural/crushed aggregates 0-2mm
- Durability: 30-80 MPa
- Acidity/Alkalinity: pH of approximately 9-10.5

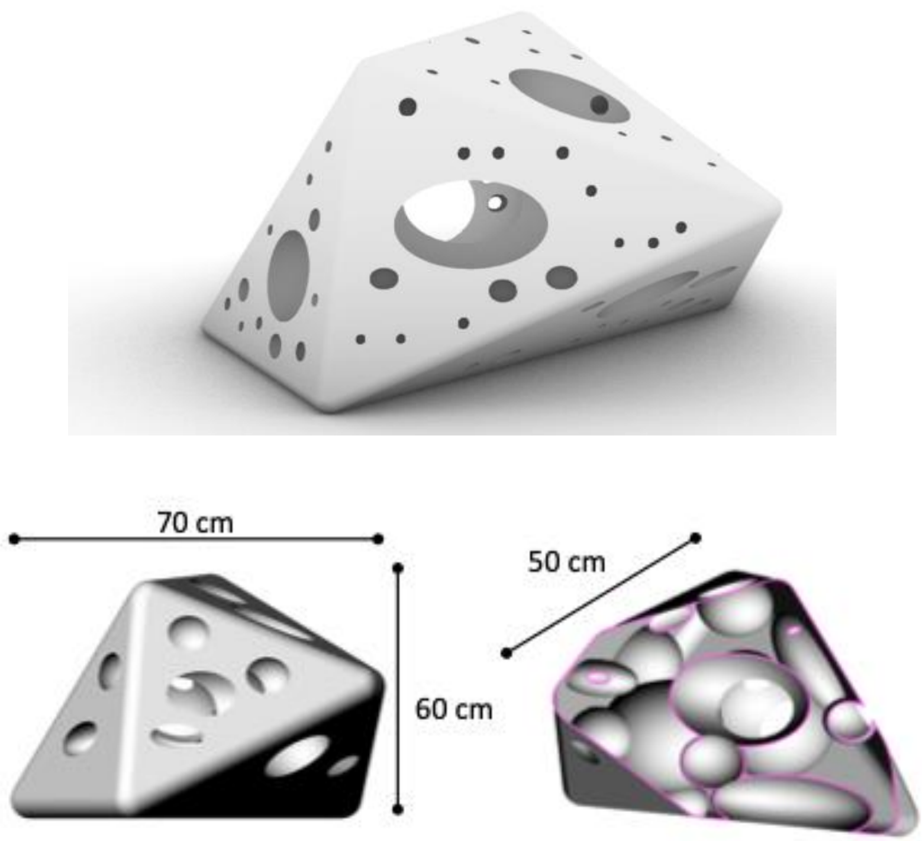
Reference specifications for locally made intertidal multi-positional unit



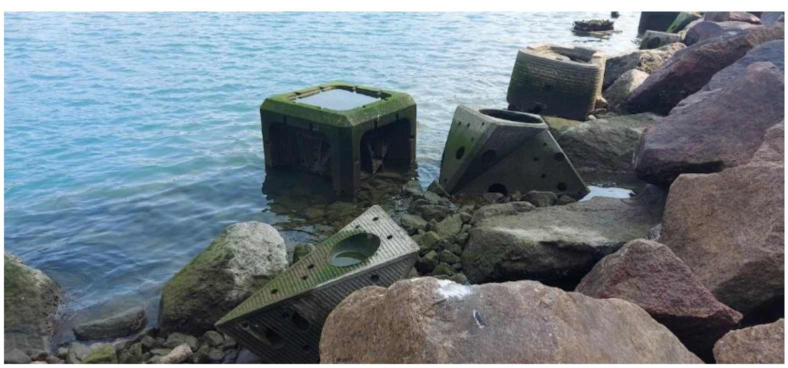


An example of a multi-positional eco-boulder and pool units designed for the project "Pilot Site Trials of Sustainable Measures at Seawalls within Victoria Harbour – Tsuen Wan Promenade" Quotation Ref. PLB(Q)24/2019.

(For reference only)



An example of the of the multi-positional eco-boulder unit designed for Tsuen Wan Promenade.



An example of locally made multi-positional tidal units and ECOncrete's intertidal units deployed at the Tsuen Wan Promenade Seawall.

<u>(For reference only)</u>

Reference specification for locally made intertidal multi-positional units:

- Concrete type: OPC reinforced with glass fibre reinforced plastic (GFRP).
- Aggregate size/type: 10 mm aggregate. The concrete mixture can alternatively be complemented with recycled aggregates, recycled incineration ash, recycled glass, marine sediment.
- Durability: Compressive Strength: ~30 MPa.
- Acidity/Alkalinity: pH ~10.

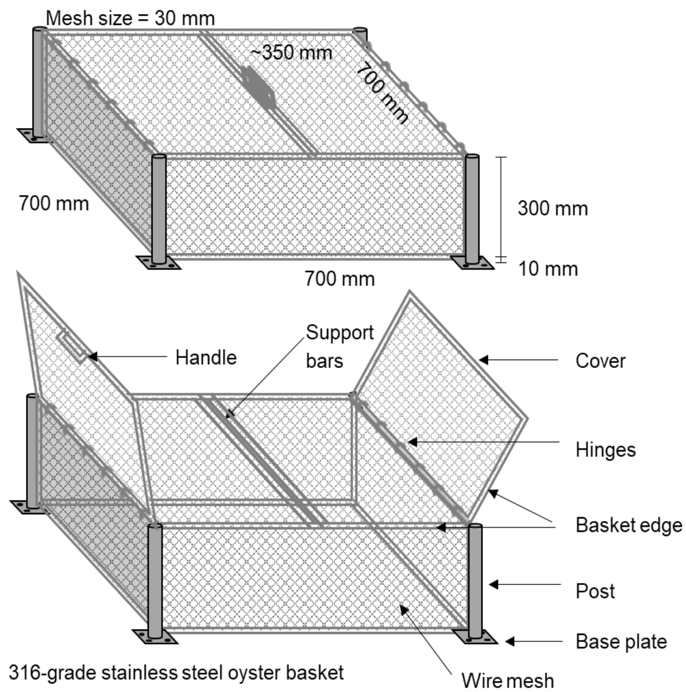
Reference installations instructions for multi-positional eco-boulder unit and tidal pool

Proper placement of the eco-boulder and tidal pool is very important for its biological functioning and should be done with care. The locally made eco-engineered features allow multi-positional installation to fit the arrangement of the local rip-rap seawalls. Eco-boulders can be installed and interlocked within granite boulders, following the installation protocols of the granite boulders. Tidal pools need to be horizontally aligned but their design allow to be interlocked among granite boulders.

1. Find a proper location for the units within the intertidal zone. The units should be placed with the top of the feature at the desire tidal height.
2. Ensure the area allows manoeuvrability to place the units in the correct position, and a proper base to support it in place.
3. For tidal pool, the unit(s) must be lowered with its water system opening facing the open water. Ensure that large and small stones or debris do not block the water system's outer opening, and inner pipe system. The outer wall of tidal pools has a 3 degree inclination thus, leaning stones must be placed to secure the unit.
4. Release straps and pins only after making sure the unit is stable and levelled.
5. The top edges of the unit(s) should ascend about 4" above the surrounding boulders.

Appendix 4. Oyster basket installation in rip-rap seawalls

(Worked Example)



(For reference only)

Reference specifications for oyster baskets:

- All materials are made of 316 stainless-steel
- Wire mesh thickness: 2-3 mm
- Basket edge thickness: 4-5 mm
- Wire mesh size: 30 mm
- Post thickness: 10-15 mm
- Base plate size: 6 x 6 cm
- Base plate thickness: 4-5 mm (each plate has 3 holes to fit 8 mm dynabolts (8 mm x 65 mm).
- Cover hinges: made of steel rings.
- Cover handle: made of 4-5 mm steel
- Support bars: double bar place in the middle to support the covers (4-5 mm stainless steel)

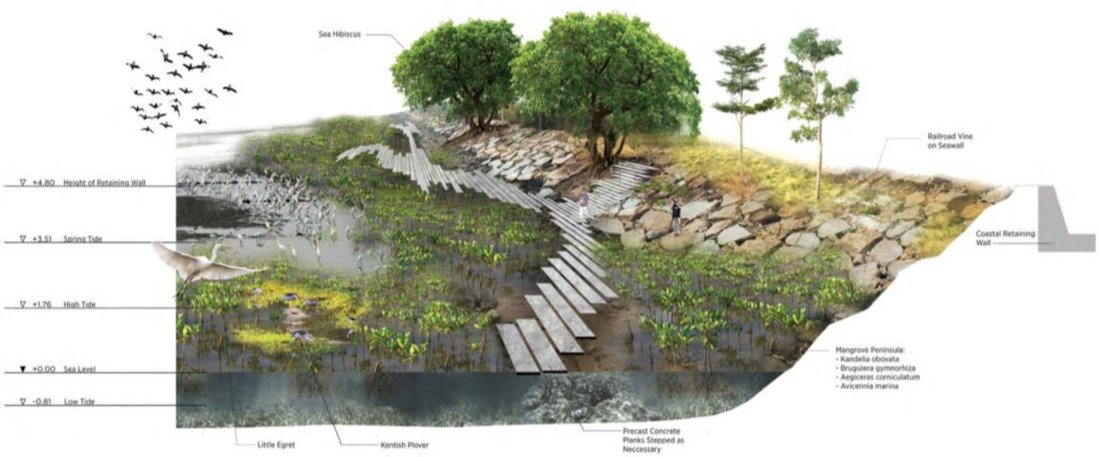
Reference Installation for oyster baskets:

The oyster baskets are designed to be fixed on the top surface of the rip-rap boulder. The boulders must be drilled to fit 8 x 65 mm dynabolts. At least two dynabolts should be placed on each base plate (i.e., corner of the basket).

Appendix 5. Conceptual Site Designs

(Worked Example)

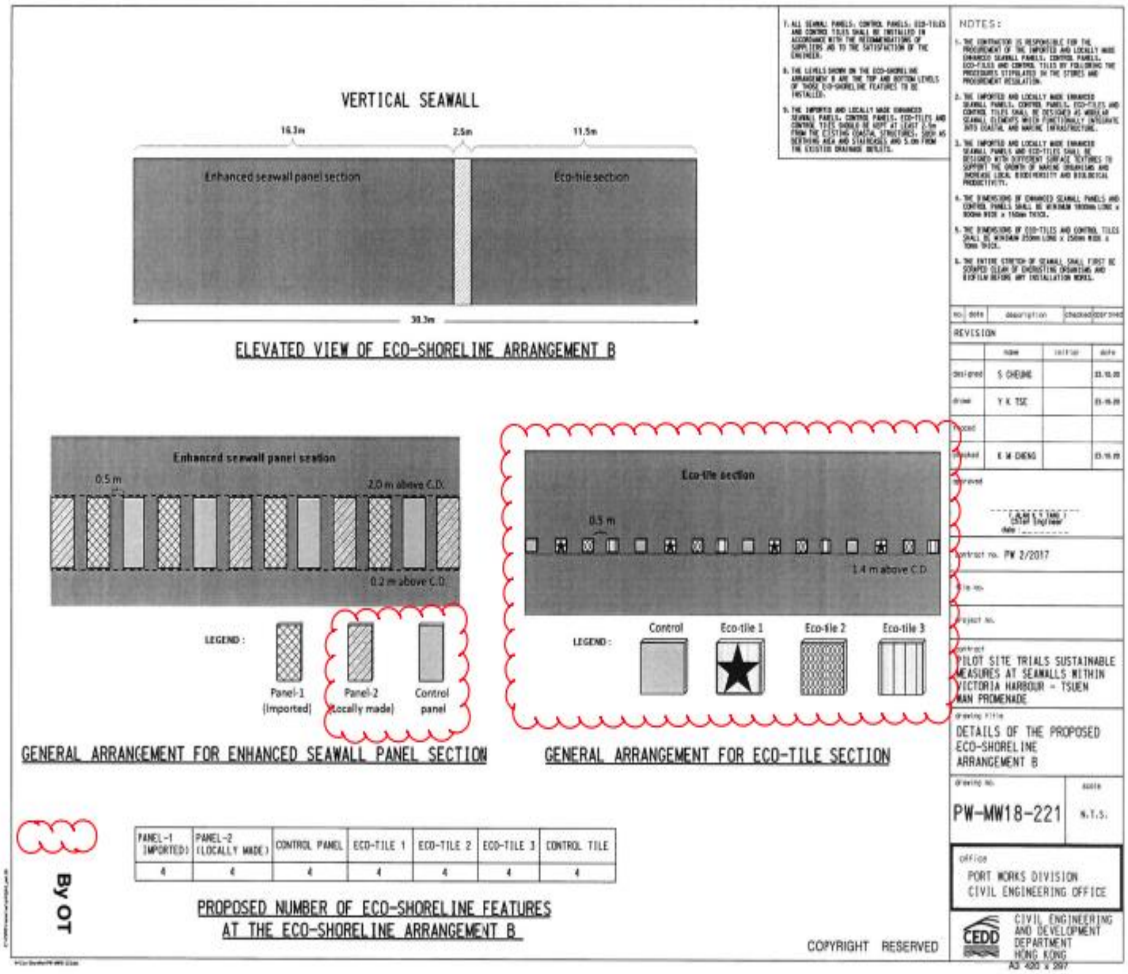
ROCK POOL SITE
Section Perspective



MANGROVE SITE
Section Perspective

(For reference only)

Examples of conceptual designs from the project "Conceptual Scheme for Full-Scale Implementation of Eco-shoreline at Taishan Receptor Site" Quotation reference FM 06/2017.



An example of installation drawings for the project "Pilot Site Trials of Sustainable Measures at Seawalls within Victoria Harbour - Tsuen Wan Promenade" Quotation Ref. PLB(Q)24/2019.

(For reference only)