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Climate change and adaptational impacts in coastal systems: the case of sea defences

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We briefly review how coastal ecosystems are responding to and being impacted by climate change, one of the greatest challenges facing society today. In adapting to rising and stormier seas associated with climate change, coastal defence structures are proliferating and becoming dominant coastal features, particularly in urbanised areas. Whilst the primary function of these structures is to protect coastal property and infrastructure, they inevitably have a significant secondary impact on the local environment and ecosystems. In this review we outline some of the negative and positive effects of these structures on physical processes, impacts on marine species, and the novel engineering approaches that have been employed to improve the ecological value of these structures in recent years. Finally we outline guidelines for an environmentally sensitive approach to design of such structures in the marine environment.

Environmental impact

Artificial coastal defence structures are necessary to protect infrastructure and property. In this review we outline some of the negative and potentially positive effects of these structures on the environment and the novel engineering techniques that have been employed to improve the ecological value of these structures. Finally we outline some steps and suggested guidelines that can be considered for an environmentally sensitive approach to design of such structures in the marine environment. These guidelines will provide decision makers with an immediate understanding of the measures required to ensure that ecologically sensitive artificial coastal defence structures are the norm and not the exception.

1 Impacts of climate change in natural systems

Coastal habitats are subject to increasing environmental pressure from pervasive global climate change interacting with other human impacts at regional and local scales.[1–5] Over the next 100 years global sea surface temperatures are expected to rise between 0.3 and 6.4 °C,[6] with European seas experiencing the most rapid warming.[7] Sea levels are rising with increases of 0.18–0.59 m predicted by 2100.[6,8] Furthermore, global climate change is expected to lead to an increase in the frequency and magnitude of extreme weather events with the past few years ranking among the most extreme weather years on record in the Northern Hemisphere.[9,10] The combination of sea level rise, increased precipitation and frequency of storms will lead to more severe coastal flooding and erosion over the next few decades.[11]

Climate change[12] is affecting the behaviour, performance and phenology of marine and coastal species[13–19] in turn affecting populations and communities.[20,21] Such changes drive general pole-ward shifts in geographic ranges of many marine species.[22–29] The extension in range of some species has been facilitated by the construction of artificial structures in the marine environment. This is discussed in more detail in Sections 3 and 4 below. The rate of change is species-specific, and will therefore alter the diversity and structure of communities, which in turn will affect productivity, nutrient cycling and the structure and functioning of ecosystems.[30–34]

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2 Adaptation to climate change: proliferation of coastal defence structures

The threat of sea level rise, erosion and flooding has led to a growing need for coastal defences such as the use of hard-substrate defence structures (seawalls, breakwaters, groynes and dykes, Fig. 1) which are fast-becoming ubiquitous features of coastal landscapes, particularly in highly urbanised areas.[35–39] For example, more than 60% of the Ventura coastline in

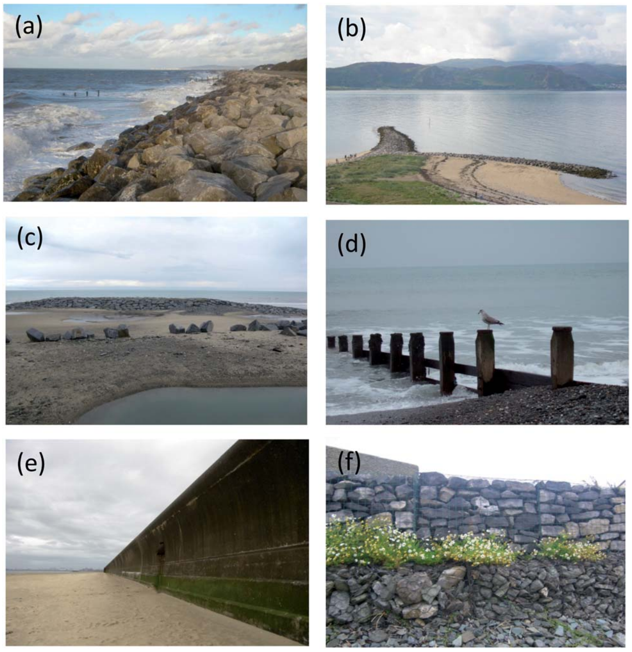

Fig. 1 Photographs of various types of 'hard' artificial coastal defence structures. (a) Rock armour at Llanddulas, North Wales; (b) groynes at Westshore, near Llandudno, North Wales; (c) newly built breakwater at Tywyn, North Wales; (d) wooden groynes in need of repair at Borth, North Wales (e) seawall at New Brighton, Wirral, England; (f) gabions at Porth Dafarch, North Wales.

California is armoured;[40] 50% of Italian coastline on the northern Adriatic Sea is protected by hard defence structures;[41] 50% of Sydney Harbour in Australia is protected by seawalls;[37] and 46% of English coastline is currently protected by artificial beaches or structures.[42] Whilst the primary objectives of coastal defence structures are to modify hydrodynamic and sedimentary regimes to protect vulnerable areas[41] or improve recreational conditions,[43] any structure placed in the sea will become colonised ("fouled") by marine organisms. Sedimentary habitats are reduced in extent and replaced by rocky substrata. Such structures modify sediment dynamics and the grain size of beaches thereby influencing assemblage composition and community structure. Hence extensive loss and modification of habitats is occurring. It is possible, however, within the limits set by the primary necessity of engineering performance of the structure, to modify selected design features. This maximises secondary management endpoints such as enhancing growth of target organisms and reduces the degree of maladaptation arising from construction of artificial structures. It is important to note that perception of desirability or undesirability are value judgments related to societal goals and expectations. In Burcharth *et al.*[43] the following examples of secondary management end points were identified:

Provision of suitable habitats to promote

• living resources for exploitation of food (such as shellfish and fish);

• living resources that are the focus for recreational (such as angling, snorkelling) or educational (such as appreciation of marine life (rock-pooling or ornithology)) activities (Fig. 2);

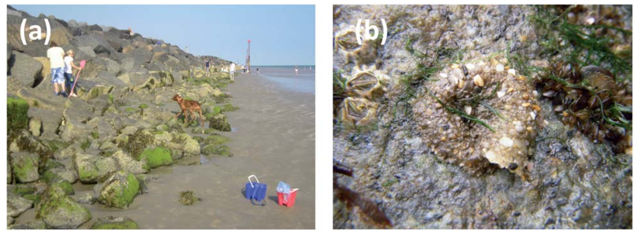

Fig. 2 (a) Children rock pooling in the pools that form in the base of Elmer Breakwater, England. (b) The polychaete worm *Sabellaria alveolata* – an important biodiversity action plan (BAP) species in the UK developing on Tywyn Breakwater, Wales (12 months after construction of the breakwater).

• endangered and rare species or species of conservation importance (Fig. 2);

• rocky substrate assemblages (biodiversity) for conservation or mitigation purposes.

There is now an increasing research effort towards ecological engineering, whereby infrastructure is designed to meet engineering requirements whilst increasing ecological habitat value. In the sections below we outline some of the effects (negative and positive) of these structures on the environment and discuss novel engineering approaches that have been employed to improve the ecological value of these structures.

3 Negative impacts of coastal defence structures

Artificial coastal defence structures are typically built in in soft-sediment environments that are susceptible to erosion and flooding. The creation of new hard-substrate in a location devoid of natural rock features has the potential to provide habitat for organisms that would not otherwise be able to colonise the area and act as stepping stones between areas of natural rock.

Artificial coastal defence structures can also facilitate the range expansion of native species that are undergoing range shifts in response to climate change by functioning as stepping-stones across stretches of unsuitable habitat. The coast of Belgium comprises predominantly sedimentary substrate, and the proliferation of artificial breakwaters along the coastline has facilitated the extension of the range of the periwinkle *Littorina saxatilis* which lacks a planktonic larval stage.[44] Similarly, in the UK, artificial coastal defence structures are becoming increasingly common along south coast of England where Portland Bill, Dorset and St. Catherine's Point on the Isle of Wight represent natural barriers to dispersal.[45] Many southern warm-adapted invertebrate species (*Perforatus perforatus*, *Gibbula umbilicalis*, *Patella ulyssiponensis* and *Melarhaphe neritoides*) have breached these hydrographic barriers reaching natural rocky shores to the east of the Isle of Wight.[23,46–49] Artificial coastal defence structures and marinas are acting as stepping-stones for species, facilitating range extensions by crossing areas of permanently unsuitable natural habitat.[31,50]

Artificial structures are known to be more susceptible to biotic invasion than natural habitats.[41,51–53] By their nature, they are found primarily in areas of frequent disturbances particularly

Fig. 3 The Elmer coastal defence scheme in the UK comprises 8 offshore breakwaters positioned parallel to the shore. This image provides a clear illustration of how a network of artificial structures can provide stepping-stones facilitating the spread of marine species, especially those with poor dispersal capability.

from sand scour or are located in or near areas that are vulnerable to invasion, such as estuaries, harbours and ports.[18,35,53,54] Once invasive non-native species have become established on artificial structures, the population(s) can act as a source for further geographical spread.[55,56] If structures are sufficiently close in proximity to one another they can act as stepping-stones to dispersal of invasive non-native species[57,58] (Fig. 3). Deployment of engineered structures can also cause steepening of the intertidal profile, resulting in coastal squeeze as the spatial extent of habitat available for colonisation is reduced.[59]

4 Potentially positive impacts of coastal defence structures

The primary functions of artificial coastal defence structures are to absorb wave energy, prevent coastal erosion and protect infrastructure. There is no doubt that they modify the natural environment and can have deleterious impacts, with careful management and planning, however, the potential negative effects of these structures can be mitigated to some extent.

The provision of artificial hard substrate in areas of soft sediment can support similar, but usually less diverse assemblages than adjacent comparable natural habitats.[59–63] These structures become colonised by habitat-forming species such as mussels and fucoid algae which provide important secondary biogenic habitat for a range of other species.[64–66] Some coastal defence structures support populations of species of conservation importance. For example, *Sabellaria alveolata* is a reef-forming polychaete worm that inhabits exposed, open coasts with reasonable to substantial water movement and can be found colonising coastal defence structures in high densities.[67] *S. alveolata* is an ecosystem engineer, providing biogenic habitat for colonisation by other species, thus supporting a wide diversity of both epibiotic and infaunal organisms. It is thought that coastal defence structures promote the persistence of this species in some locations as they provide an interface with sedimentary habitats.[67]

Environmental heterogeneity facilitates increased diversity of resources and microhabitats compared to homogenous environments and is therefore an important mechanism in the maintenance of biological diversity at a range of spatial scales.[68,69] On a micro-scale, geology and surface roughness are known to have a significant effect on the structure and functioning of the colonising assemblages.[70–72] Whilst on small to medium scales, crevices, pits and rock pools provide important refuges for many species.[14,72–76]

5 Ecological engineering of artificial coastal defence structures

Ecological engineering is a relatively new concept which integrates ecological, economic and societal needs into the design of man-made ecosystems. The creation of novel habitats can have a positive effect on the biodiversity on artificial coastal defence structures. Borsje *et al.*[36] incorporated modifications (surface roughness, grooves and pits) to concrete blocks at different tidal heights (low, mid, high) on the breakwaters at the entrance to the North Sea Channel at IJmuiden, the Netherlands. Mussels (*Mytilus edulis*) were only found in the sections with grooves and holes, and developed best within the grooves.[36] Both grooves and holes were also used as refugia from adverse environmental conditions by periwinkles (*Littorina littorea*) during low tide. Slabs which were mounted low in the intertidal area showed a more rapid and diverse colonisation, compared to the slabs which were mounted higher in the intertidal zone, most likely because they were immersed for longer periods of time. Thompson *et al.* (unpublished data illustrated in appendix of Witt *et al.*[77]) attached tiles (which had been drilled with holes of differing diameters) to a coastal defence structure in SW England. The addition of habitat complexity to concrete surfaces resulted in significantly increased diversity of intertidal organisms within five months.

Chapman and Blockley[78] demonstrated that creating artificial "rock-pools" into a vertical seawall significantly increased the diversity of species colonising the wall in Sydney, Australia. This was achieved very simply by randomly replacing one of the large building blocks with a sandstone lip, creating a pool that retained water during low tide. Diversity was increased both by the pool environment and the creation of shaded surfaces. Modifications like this are very effective when incorporated at the construction stage, but Chapman and colleagues also came up with a novel solution to enable the incorporation of artificial rock pools into existing seawalls. Browne & Chapman[79] affixed modified flowerpots to seawalls in Sydney Harbour which retained water, mimicking rock pools. The addition of these novel artificial habitats increased species richness by 110%. Importantly, the increased number of mobile species was particularly pronounced with many species (*e.g.* green algae, ascidians, tubeworms and echinoderms) that were not normally able to survive on the vertical faces of seawalls.

Furthermore, the promotion of species of conservation importance can be achieved on these structures through manipulative techniques. Perkol-Finkel *et al.*[39] transplanted the brown alga *Cystoseira barbata* from areas of degraded natural habitat to artificial breakwaters and natural rocky habitats in Italy. Survival of transplanted individuals was greater in the artificial and natural sites than original degraded sites but success was limited on artificial habitats in highly disturbed environments. Similarly, Martins *et al.*[80] examined the influence of pit size on the distribution and survival of the commercially exploited limpet *Patella candei* on seawalls in the Azores. The addition of pits to the otherwise featureless flat-surfaced seawalls increased the number of limpets due to immigration and recruitment.

6 Suggested guidelines

When considering the incorporation of biological enhancement into artificial coastal defence structures, uncontrollable and context-dependent factors (*e.g.* tidal range, wave action and larval recruitment regime) and controllable factors (through careful design and planning *e.g.* vertical position in the intertidal zone, geology of boulders/blocks, surface roughness and habitat heterogeneity (including water-retaining features)) need to be factored into the design stage of the process. Modifications made at this early stage in the construction process can be cheaper and implemented over larger spatial scales than those implemented retrospectively. Here we outline the basic ecological principles underlying the guidelines. A more technical paper[81] aimed at an engineering audience provides comprehensive guidelines to achieve specific secondary management goals. Below is a list of guidelines to consider if the secondary management goal is to *enhance biodiversity on the structure*:

• *Build structure lower in the intertidal zone*. On natural rocky shores low-shore communities are more diverse than high-shore communities.[82] Building a structure lower in the intertidal zone will ensure that it is immersed for longer periods. Greater numbers of species will colonise the lower portions of the structure than the higher portions.[59,76,78]

• *Avoid smooth rock material*. Few organisms will colonise homogeneous surfaces and species colonisation rates will increase with surface roughness. Where possible, use a mixture of hard and soft rock. Soft rock (*e.g.* limestone) will erode quicker than hard rock (*e.g.* granite) which will create surface roughness and habitat for attachment of marine organisms.[50,76]

• *Create rock pools*. Rock pools provide refuges for intertidal organisms and can sometimes support greater diversity than emergent substrata.[14,73,76] If a boulder has a natural depression, it can be placed depression-side up, thus creating a water-retaining feature that will support greater diversity than emergent substrata. Rock pools can be fitted during construction of seawalls by replacing blocks with lips[78] or by manipulating the mortar between blocks to create water-retaining features.[81] Rock pools can be created retrospectively by affixing water-retaining units to seawalls[79] or by drill-coring into the horizontal surfaces of blocks or boulders.[81]

• *Create pits*. Pits and crevices create habitat heterogeneity on natural rocky shores and provide refuges for many organisms.[72,75] Pits can be retrospectively introduced on seawalls and rock armour by drilling directly into the substrata[80,81] or by drilling holes in slabs or tiles that can be affixed to seawalls or breakwaters.[36,77]

• *Deploy precast habitat enhancement units*. Precast habitat enhancement units are likely to become ubiquitous features of artificial marine environments in the near future. An increasing number of habitat enhancement units are being trialled in marine environments worldwide.[79,81,83,84] Depending on artificial environment and the enhancement unit in question, these can be deployed either during construction or retrospectively to effectively increase local biodiversity.

7 Conclusions

With the current predictions of global climate change, the continued proliferation of artificial coastal defence structures is inevitable. Understanding the factors and processes influencing the biodiversity of natural and artificial habitats and assessing the influences of artificial structures on establishment of species (native and non native) is therefore of key importance for prediction and management of future pathways of invasion and range extension in coastal areas and conserve species whose natural habitats are being degraded or removed. Furthermore, the design of artificial structures so as to maximise any potential benefits for marine life[36,37,77–79] is a management option that can increase the ecological value of the structure and will likely also protect the assemblages on these structures from biotic invasion.[85–87]

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