Coastal Engineering 118 (2016) 12–20

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Hidden biodiversity in cryptic habitats provided by porous coastal defence structures

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ARTICLE INFO

Article history:
Received 29 July 2015
Received in revised form 6 August 2016
Accepted 15 August 2016
Available online 12 September 2016

Keywords:
Coastal protection
Porous structures
Coastal management
Habitat provision
Biodiversity
Conservation
Multifunctional role

ABSTRACT

In response to flood risk from rising and stormier seas, increasing amounts of natural coastline worldwide are being replaced by a proliferation of coastal defence structures. While the primary role of defence structures is protecting the coastline, consideration should be given to the biological coastal communities they support. Artificial structures are currently seen as poor habitats for marine organisms. They are constructed in harsh coastal environments, lack structural complexity, and are subjected to episodic disturbance from maintenance, reducing their suitability as habitats for coastal species. Recent work has focused on mitigating the impacts of coastal defence structures, through secondary routes such as enhancing biodiversity by encouraging colonisation of marine biota. Research thus far has focused on enhancements to improve structural complexity on the external surfaces of coastal defences. Many structures are porous with internal compartments. To date no work has been undertaken on the habitat provided by the internal surfaces of the blocks used in building structures.

We investigated the role of porous coastal defence structures in habitat provision. Taking advantage of a groyne reduction from 45 m to 20 m length, we surveyed the internal environment of the structure. We also considered the impacts of maintenance activity on coastal assemblages. Our work shows that the internal environment of artificial structures provides functional habitat space supporting higher species richness and diversity than external surfaces. The more benign environment of internal surfaces protects from desiccation stress and is probably less scoured by mobile sediments, and as such is of unrealised importance to coastal assemblages. External surfaces are also subject to high levels of disturbance from maintenance activities, further limiting the potential ecological contribution this area of the artificial habitat might otherwise develop. These findings reveal the multifunctional role of porous coastal defence structures, acting as engineering protection and habitats for coastal assemblages.

1. Introduction

Coastal areas provide essential economic resources and satisfy a variety of societal needs. Coastal ecosystems account for a substantial proportion of global ecosystem services (Costanza et al., 1999; Martínez et al., 2007), including coastal protection (Bulleri et al., 2005; Chapman and Underwood, 2011; Dugan et al., 2011; Garcia et al., 2004). Faced with the effects of accelerated climate change, coastal regions are susceptible to flooding and loss of land, requiring adaptational actions (Airoldi et al., 2005; Burcharth et al., 2007; Nicholls and Mimura, 1998; Philippart et al., 2011). The development of coastal defence structures (CDS) is fundamental in protecting land, property, infrastructure and other economic and environmental resources. Thus, in many areas worldwide, coastlines are becoming dominated by artificial structures (Airoldi et al., 2005; Bulleri and Airoldi, 2005; Firth et al., 2014; Firth et al., 2013a; Liquete et al., 2013; MAFF, 2000; Moschella et al., 2005) causing significant changes to shores through loss, replacement or fragmentation of natural habitats. This places intense pressure on coastal resources and the environment, and affects the structure and functioning of related marine ecosystems (Airoldi and Beck, 2007;

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http://dx.doi.org/10.1016/j.coastaleng.2016.08.005

Airoldi et al., 2005; Bulleri and Chapman, 2004; Connell and Glasby, 1999).

Infrastructure placed in any natural environment will inevitably become colonised by primary settlers such as epibenthic marine organisms and biofoulers (Evans, 2016). Artificial structures can be viewed as surrogate habitats for natural shores (Burt et al., 2011; Connell and Glasby, 1999; Moschella et al., 2005). With the aid of additional structural modifications to ameliorate habitat heterogeneity, increased colonisation and enhanced biodiversity of marine species on artificial substrates can be encouraged (Evans et al., 2016; Firth et al., 2013a, b, c). Currently, CDS are seen as poor substitutes for natural rocky shores because they support lower species diversity (Bulleri and Airoldi, 2005; Bulleri et al., 2005; Chapman and Blockley, 2009; Moschella et al., 2005). Coastal defence structures are typically built in high-energy environments with stronger wave action than most natural rocky shores (Burt et al., 2011; Evans et al., 2016; Jonsson et al., 2006), providing harsh habitat conditions for common rocky shore organisms, and opportunities for invasive non-native species through new hard substrata (Airoldi and Bulleri, 2011; Firth et al., 2013a). These conditions are made worse by scouring from sand, gravel and cobbles (Bulleri and Chapman, 2010; Moschella et al., 2005). Coastal defence structures are also less topographically complex than natural rocky shores, reducing habitat and microhabitat provision (Hawkins, 2012; Martins et al., 2010). Their extent is often smaller than natural shores (Moschella et al., 2005), inevitably leading to a restricted species pool and altered biological interactions amongst species (Bulleri and Chapman, 2010; Bulleri, 2005; Bulleri et al., 2005; Coombes et al., 2015; Jackson et al., 2008).

In conjunction with factors considered above, there is constant pressure on the structural integrity of CDS due to erosion, scouring, overtopping and undermining (Airoldi and Bulleri, 2011; Firth et al., 2013a; Kamphuis, 2010). Over time this can affect the stability and function of the structure, requiring maintenance (Airoldi, 2003; Dayton, 1971; Moschella et al., 2005; Sousa, 1979). Maintenance, however, can result in severe ecological disturbance. It can remove large areas of the habitat and causes disruption to settled communities by the abstraction and replacement of part or all of the structures (Tsinker, 2004; Airoldi and Bulleri, 2011). Such works can dislodge, crush or expose colonising species, potentially reduce biodiversity and open up space to opportunistic species (Dayton, 1971; Hutchinson and Williams, 2003; Sousa, 1979). Large costs are also incurred in the upkeep of the structures (Roebeling et al., 2011).

Porous rock defence structures are widely used in coastal engineering (Crossman et al., 2003). They serve a practical role in the protection of coastlines by reducing wave transmission, reflecting incident waves from the shores, and dissipating wave energy (Burcharth et al., 2015; Dalrymple et al., 1991; Garcia et al., 2004; Losada et al., 1995). Wave dampening is an important function that many other impermeable defence structures do not provide sufficiently (Garcia et al., 2004). The porous structure allows some of the wave energy to pass through whilst creating flow resistance and some reflection from the structure, resulting in turbulence through the porous medium and dissipation of wave energy (Garcia et al., 2004; Jung et al., 2012; Silva et al., 2000). Consequently, essential protection to the shoreline is provided whilst still allowing the natural process of water run-up on the coast. This imitates many natural shoreline barriers, such as coral reefs, mangroves and rocky shores, which can provide natural protection against waves and storm surges (Fernando et al., 2008; Hu et al., 2014; Lowe, 2005a, 2005b; Monismith, 2007).

Porous defence structures are also seen to be more environmentally friendly than solid CDS because they have a smaller physical footprint creating less disturbance to benthic soft sediment organisms (Koraim and Rageh, 2013), and can be more aesthetically pleasing (Garcia et al., 2004). Considerable recent work has focused on improving secondary functions of CDS, particularly enhancing their colonisation by marine biota. Research into artificial enhancements such as boring holes to create rock pools and drilled grooves to increase heterogeneity have been extensively researched (Borsje et al., 2011; Chapman and Blockley, 2009; Coombes et al., 2015; Evans et al., 2016; Firth et al., 2012, 2014, 2013, 2013b; Moschella et al., 2005; Naylor et al., 2011). Other studies have investigated the use of different materials to encourage settlement on the surface of these structures (Coombes et al., 2011a, 2011b, 2013; Green et al., 2012). Whilst this work has been a successful and an integral step towards working with nature by creating “green” infrastructure, the focus has been solely on the external surfaces of CDS. To date no work has been undertaken on the habitat provided by the internal surfaces of the rock units used in building porous CDS because of logistic constraints. Thus, this study presents the first opportunity to document the internal section of a porous rock armour structure. This is potentially a habitat providing some refuge from the harsh physical conditions of the intertidal zone in general (e.g. desiccation and wave action) and defence structures in particular (e.g. scouring).

The use of porous structures in coastal engineering can be viewed as providing a multifunctional role, protecting vulnerable coastlines and supporting intertidal communities. Our paper compares the community composition, abundance and biodiversity of species of internal versus external surfaces, taking advantage of the reduction of a groyne from 45 m to 20 m extent at Highcliffe on the South coast of the UK as part of reconfiguring an existing coastal defence scheme. More formally we tested the following hypothesis: internal habitats on the porous defence structure will support greater species richness and diversity than external habitats, in particular higher numbers of invertebrate species. In addition, we evaluate the extent of anthropogenic disturbance caused by the removal process, to indicate potential levels of general coastal defence maintenance disturbance and consider their possible impacts on coastal species.

2. Methodology

2.1. Study location

The study took place at Highcliffe in Christchurch Bay on the south coast of England, UK (Fig. 2.1), Christchurch Bay has a steadily eroding coastline of Barton clay beds and cliffs. It experiences a low amplitude double high tide, which is characteristic of the Solent area, meaning it encounters a further four tidal oscillations in addition to the standard semidiurnal UK tides. In spring tides the area experiences fluctuations in mean water levels of approximately 1 m (Nicholls, 1988; Tyhurst, 1986). There is also a complex tidal current system that circulates within the bay and a south-westerly wave pattern causing high-energy beaches to the west and local sediment drift and erosion. The area receives some protection from the Isle of Wight situated to the east and Durlston Head to the West (Tyhurst, 1986). The Highcliffe coastal defence scheme reverted from timber to rock groynes in 1992, and currently comprises eleven rubble mound groynes, consisting of short and long structures (30–45 m) and a bastion, made from Portland Oolitic limestone (Harlow, 2013; Tyhurst, 1986) (Fig. 2.2). The groynes are designed with 1 in 2 side slopes, 1 in 2.5 roundhead slopes and a 4 m crest width (Harlow, 2013). These are situated amongst a mixture of shingle and sand beaches (CBC, 2008), and the structures are estimated to sit approximately 1 m into the substrate. Christchurch Borough Council (CBC) deemed the groyne system at Highcliffe to be over engineered with a number of the groynes not being fully utilised within the coastal defence system. Therefore it was decided that the best approach was to remove and recycle the rock units. Owing to the direct attack from the sea, this area regularly undergoes routine maintenance work that consists of the replacement of rock units, removal/replacement of sand, or in some circumstances the partial reconstruction of a structure (CBC, 2008). The management of this area is essential to retain the current

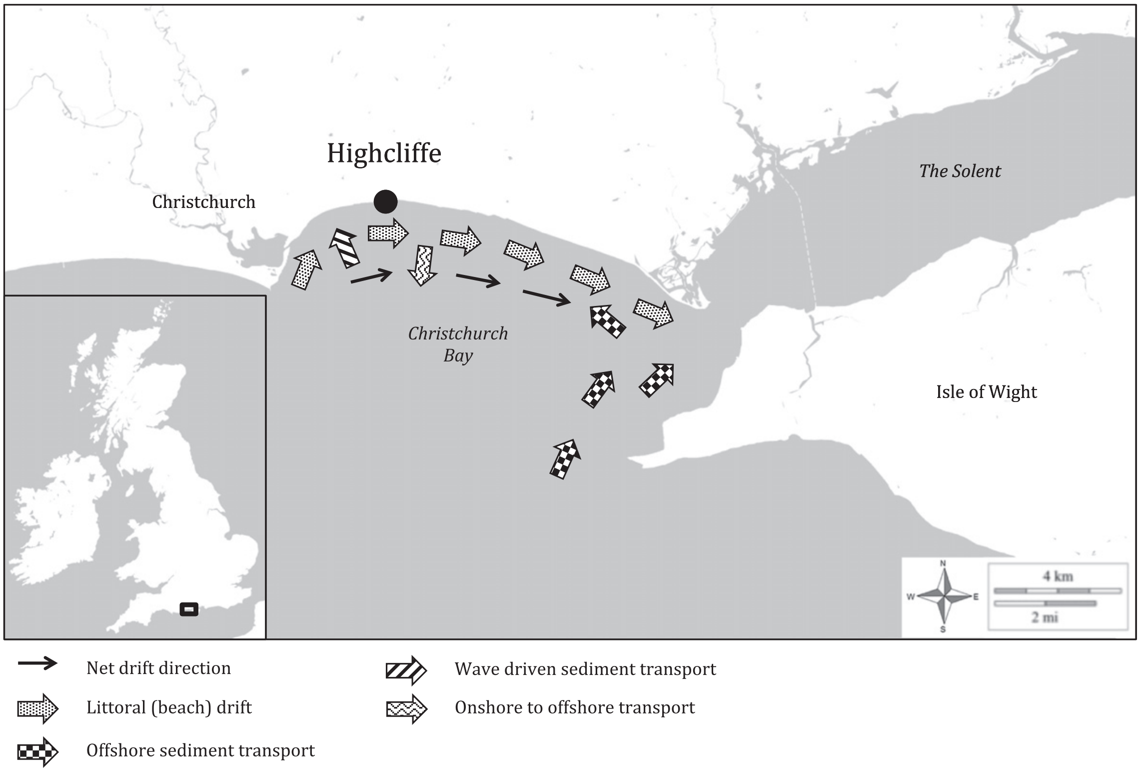

Fig. 2.1. Study area: Highcliffe situated within Christchurch Bay on the South coast of the UK. Map shows the sediment transport activity in the bay. Image adapted from MMIV © SCOPAC Marine Inputs map (http://www.scopac.org.uk/scopac_sedimentdb/chrst/index.htm).

coastline, protect residential properties and maintain the shoreline for tourism and local amenity use.

2.2. Groyne reduction

The groyne reduction took place during the lowest spring tides in June and July 2013 by CBC coastal engineers. The process removed 102 individual rock armour units of varying sizes (1–4 t rock units) roughly rectangular in shape, using a digger with a grab or bucket. The size of the structure was reduced from 45 m to approximately 20 m. Surface rock armour units from the end (nose) of the groyne were the first to be removed, exposing the foundation rocks. This allowed access to larger 4 t rock armour units that had sunk approximately 1 m into the sediment since they were installed. After the seaward nose and initial foundation units had been removed, the top and side layers were extracted followed by the internal (central) units. Owing to the short tidal window available for work, it was essential for the engineering work to be done in the specific removal order detailed above to ensure that structural integrity was retained between removal periods.

2.3. Data sampling

The restricted timeframes meant that ecological sampling was carried out around the engineering works; therefore all information was

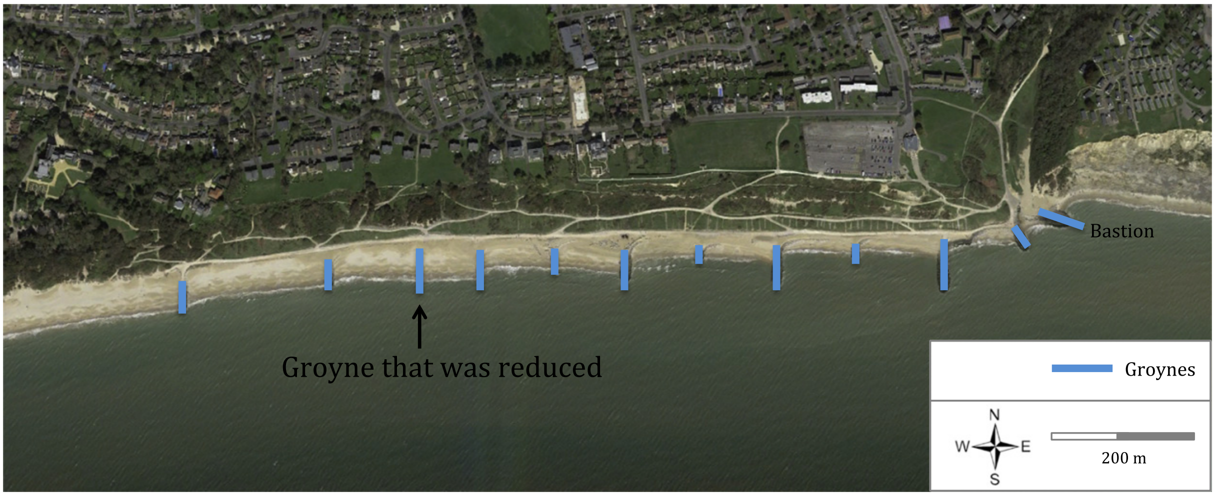

Fig. 2.2. Image of the groyne system constructed at Highcliffe within Christchurch bay. Image shows the eleven rock groynes and a bastion of varying long and short lengths, and highlights the study groyne that was reduced. Image adapted from Imagery ©2016 Google, TerraMetrics, Map data ©2016 Google.

recorded in situ. Photographs and physical details of each unit were recorded, including measurements and calculations of the surface area of each unit face in order to determine the percentage cover species. Each unit face was recorded as an individual sampling point, and categorised by three different factors to determine the position and environmental exposure of each unit face (Fig. 2.3): (1) exposure to environmental conditions (comprising i, external wave exposed – outside unit face towards the seaward, ii, external wave sheltered – outside unit face with landward orientation, iii, internal – unit face located within the groyne, sediment – unit face located within soft sediment due sinking over time); (2) elevation on the shore (foundation – lower shore, middle, top of the shore); (3) placement of unit faces within the structure (nose – end of the structure, internal, side, top). Connections to other rock armour units and the estimated percentage damage to each unit from the removal process were also noted.

Biological sampling was conducted for each unit face by identifying organisms present to species level where possible with counts for mobile fauna and percentage cover for sessile species.

Maintenance disturbance was classified as areas of the unit face where fracturing and/or removal of the surface was visible due to the removal process. The level of maintenance disturbance was estimated by calculating the percentage of the unit face damaged or removed. The number of occurrences per rock armour face and frequency of occurrences out of the total sample were also logged.

2.4. Statistical analysis

To test our hypothesis, statistical analyses were carried out using PRIMER-E ver. 6 and PERMANOVA+ ver. 6 statistical software (Anderson et al., 2008; Clarke, 1993; Clarke et al., 2014) to determine the difference between species richness and percentage abundance of species recorded in relation to exposure levels. Moreover, we conducted supplementary analysis to determine if factors such as placement and elevation affect the data. Data were square-root transformed and a Bray-Curtis similarity matrix (Bray and Curtis, 1957) created for the statistical tests.

Multi-dimensional scaling (MDS) plots using abundance data were created for each factor (exposure, elevation on the shore and placement within the structure) to visualise patterns using rank similarities and hierarchical clustering in the multivariate output (Clarke, 1993; Clarke et al., 2014). Initial Permutational Multivariate Analysis of Variance (PERMANOVA), based on 999 unrestricted random permutations of residuals (Anderson et al., 2008), tested for differences in species richness and assemblages. Factors used in the analysis were: exposure (fixed, 4 levels: external, external sheltered, internal or sediment), elevation on the shore (fixed, 3 levels: foundation, middle or top), and placement within the structure (fixed, 4 levels: nose, internal, side or top unit). Pair-wise comparisons were used to test differences in the species richness and assemblages specifically in response to exposure levels. Similarity Percentage (SIMPER) was then used to identify percentage contributions of individual species providing the dissimilarities between the internal and external exposure levels (Anderson et al., 2008; Clarke, 1993; Clarke et al., 2014). Finally, we used Simpson's Index of Diversity (D) to calculate the species diversity in the internal and external (exposure levels) habitats.

For the maintenance disturbance, we calculated the average disturbance as a percentage of the surface cover, the number of occurrences and the extent of the damage as a percentage of the total number of samples for each factor level, to provide indicative data which may be used to inform methods for reducing disturbance levels.

3. Results

3.1. Ecological sampling

A total of 102 rock units were removed from the groyne structure, and the faces of each unit recorded. Species recorded during the removal process for the internal and external environments and, more

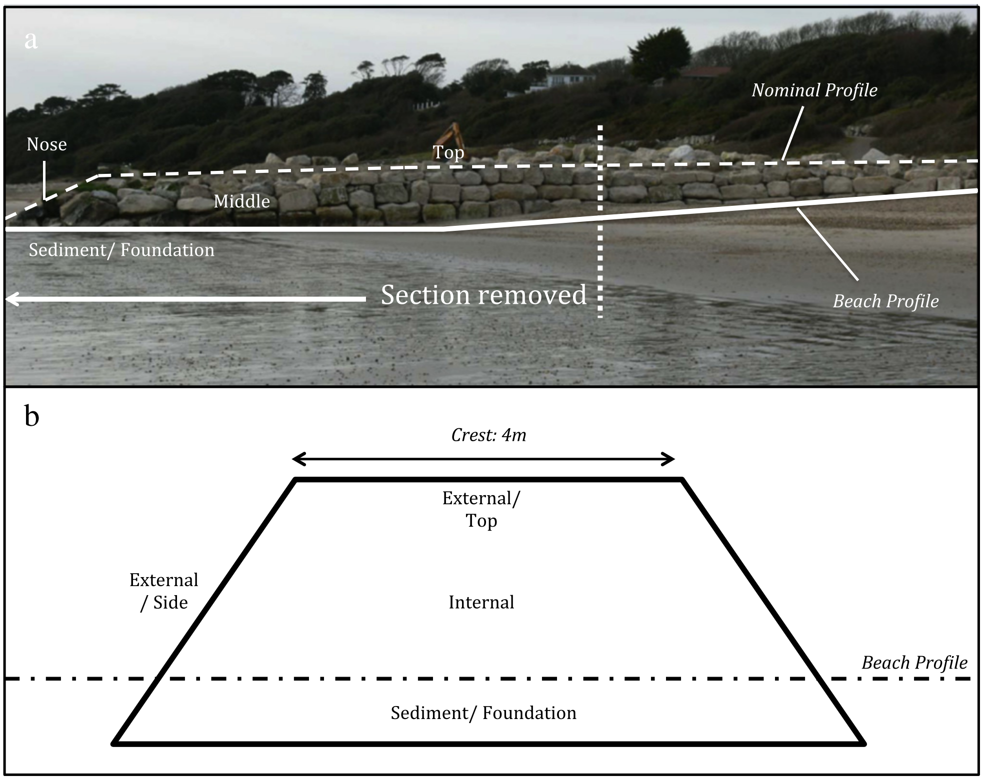

Fig. 2.3. Displays the areas categorised within each factor. (a) Shows a side view of the groyne that was removed, and the location of the categories under each factor that are visible. (b) Illustrates a landward facing cross-sectional representation of the groyne, and the relative locations of the categories under each factor.

Table 3.1
Total numbers of species and their mean percentage covers (sessile species only) in internal and external surfaces. Species diversity (*D*) was calculated using Simpson's Index. Number of unit sampled (n) = 102.

Group	Species	Internal				External			
		No. species	n	Mean % Cover	SD (±)	No. species	n	Mean % Cover	SD (±)
Green seaweeds		1				1			
	Ulva spp.		34	4.82	8.81		60	47.42	31.43
Red Seaweeds		6				2			
	Mastocarpus stellatus		15	0.38	1.12		15	0.30	0.73
	Chondrus crispus		28	7.87	15.89		4	1.33	5.21
	Hildenbrandia spp.		2	0.07	0.56		0	0.00	0.00
	Erythroglossum laciniatum		1	0.06	0.55		0	0.00	0.00
	Porphyra spp.		1	0.01	0.11		0	0.00	0.00
	Polysiphonia spp.		2	0.02	0.15		0	0.00	0.00
Brown Seaweeds		3				2			
	Fucus spiralis		6	0.48	3.32		9	0.66	2.39
	Algaozonia		1	0.24	2.18		0	0.00	0.00
	Dictyota dichotoma		0	0.00	0.00		3	0.13	0.58
	Sargassum muticum		5	1.87	10.26		0	0.00	0.00
Invertebrates		10				5			
	Patella vulgata		27	0.62	1.17		26	0.92	1.74
	Patella depressa		14	0.26	0.64		23	0.50	0.94
	Patella ulyssiponensis		7	0.12	0.45		8	0.22	0.65
	Cirripedia		30	6.88	13.75		12	1.64	5.82
	Actinia equina		19	0.35	0.88		0	0.00	0.00
	Actinia fragacea		1	0.01	0.11		0	0.00	0.00
	Mytilus edulis		35	0.70	1.40		15	0.31	0.75
	Eulalia viridis		3	–	–		0	–	–
	Carcinus maenas (juv)		1	–	–		0	–	–
	Nucella lapillus		4	–	–		0	–	–
Total		20	236	24.76	61.34	10	175	53.43	50.24
Simpson's Index of Diversity (D)		0.90				0.82			

specifically, the presence of species recorded on the rock unit faces and their percentage cover, are displayed in Table 3.1. Internal faces supported a higher number of species, particularly for invertebrate species and red seaweed species, than external unit faces (internal 20 species, external 10 species) (Table 3.1). Mobile fauna such as *Eulalia viridis*, juvenile *Carcinus maenas* and *Nucella lapillus* were all found only on internal faces. There was, however, a higher mean percentage cover of species found on external faces (53% ±50%), than on internal faces (25% ±61%) (Table 3.1). The results in Table 3.1 suggest that this is due to the presence of the alga *Ulva* spp., found in both environments, but more abundant on the external faces. *Ulva* spp. was recorded to cover on average 47% (±31%) of external faces compared to 5% (±9%) of internal faces. Calculations of Simpson's Index of Diversity (*D*) showed overall that internal surfaces had higher species diversity (0.90) than external surfaces (0.82).

An MDS plot (with 25% similarity contours) for exposure factors showed differences with exposure levels (Fig. 3.1*a*), particularly internal and external, where-as external sheltered and sediment levels appeared to be more distributed. Fig. 3.1*b & c* show no patterns with elevation on the shore and placement within the structure.

PERMANOVA analysis (Table 3.2) highlighted significant differences in the species assemblages due to exposure (*Pseudo-F* = 8.80, $P \leq 0.01$). Further analysis of the exposure factor using pair-wise tests showed significant differences between external areas and other exposure levels, particularly internal and external ($t = 5.20$, $P \leq 0.01$), and sediment and external ($t = 2.78$, $P \leq 0.01$). Analysis of the factors elevation and placement also showed significant differences in species assemblages. Additionally, PERMANOVA highlighted interactions between exposure and placement (*Pseudo-F* = 2.14, $P \leq 0.01$), and exposure and elevation (*Pseudo-F* = 2.16, $P \leq 0.01$), but no impact on species assemblages due to placement and elevation, or all factors combined. More specific analysis was not carried out, as this was not the focus of the study.

SIMPER analysis (Table 3.3) confirmed that *Ulva* spp. were the characterising organisms causing observed differences between internal and external faces contributing 42% of the dissimilarity observed. *Ulva* spp. were recorded on every external surface and covered the surface faces, whilst other species occupied smaller areas. *Chondrus crispus* (14%) and barnacles (13%) were contributing factors but were found in higher abundance on internal compared to external surfaces.

3.2. Maintenance disturbance

Table 3.4 shows that damage levels differed amongst locations. External units, alongside those located on the side of the structure and in the middle of the shore (see Fig. 2.3), had the highest incidences of maintenance damage and the highest average percentage cover per unit. External and external sheltered units had the highest number of occurrences as a proportion of the total sample, as well as those units located on the side and nose of the structure. Overall, maintenance disturbance recorded in the external units occurred much more frequently than internal units and caused a higher amount of damage to the surface.

4. Discussion

4.1. Habitat provision

The removal of a porous CDS provided a unique opportunity to gain better insight into the total habitat provision capabilities of artificial structures. It is unusual to come across the decommissioning of CDSs and this rare opportunity provided access to areas of artificial structures that have not previously been investigated or actively considered as a potential suitable habitat for coastal assemblages. By carrying out biological sampling during removal of a porous defence structure, we were able to gain important insights into the coastal species found on artificial structures.

We found significant differences between the biological communities present in internal and external environments (Table 3.1, Fig. 3.1*a*). Internal surfaces supported twice as many species of both

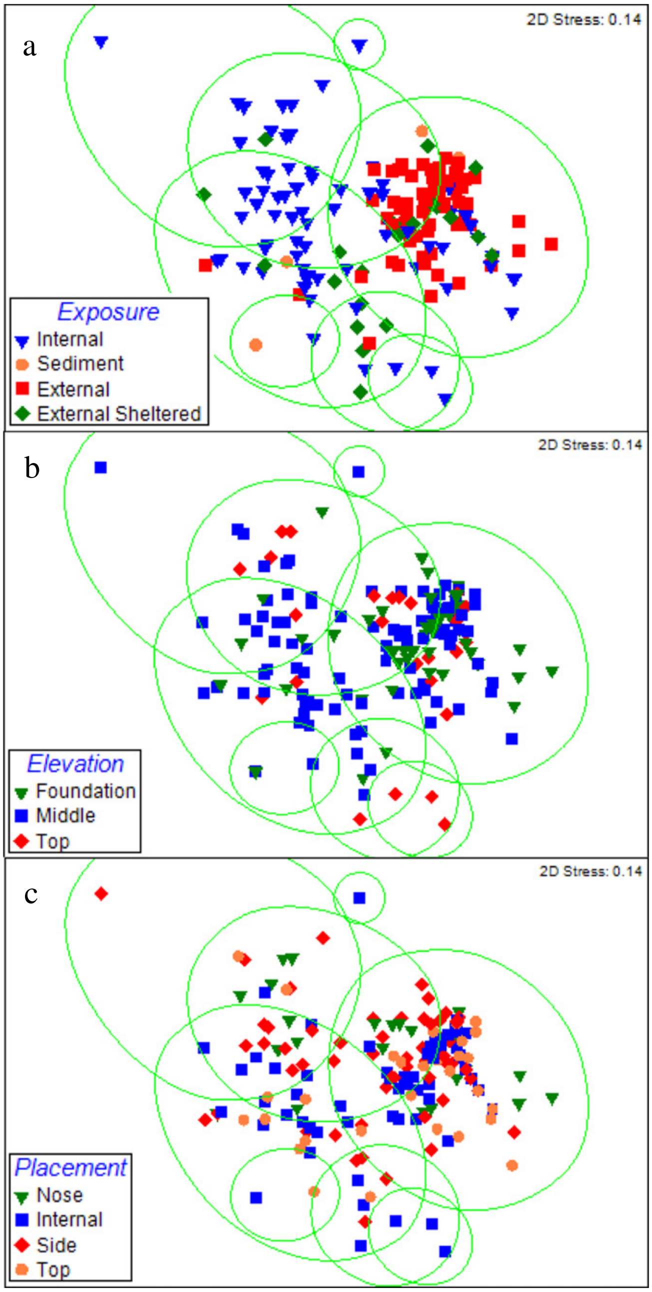

Fig. 3.1. MDS plots of percentage abundance data based on rank similarity for (*a*) exposure (*b*) elevation on the shore (*c*) placement within the structure (Fig. B). Contours of 25% similarity are shown.

Table 3.2
PERMANOVA analysis identifying the impacts of the physical factors that affect community colonisation and species richness (****P(perm)* = 0.001;. ***P(perm)* < 0.01; **P(perm)* < 0.05; NS = *P(perm)* > 0.05). Factors analysed were: exposure (fixed, 4 levels: external, external sheltered, internal or sediment), elevation on the shore (fixed, 3 levels: foundation, middle or top), and placement within the structure (fixed, 4 levels: nose, internal, side or top unit).

Factor	Interactions/ pair-wise test	Pseudo-F	df	t
Exposure		8.80***	2	
	1. Sediment, External			2 78***
	2. Sediment, External sheltered			1.34
	3. Sediment, Internal			1.00
	4. External, External sheltered			1.92*
	5. External, Internal			5.20***
	6. External sheltered, Internal			1.44
Placement		2.43**	3	
Elevation		3.77***	2	
Exp x Place		2.14***	6	
Exp x Elev		2.16**	4	
Place x Elev		1.44	3	
Exp x Place x Elev		1.11	3	

invertebrates and algae as the external environment, particularly mobile species. A clear demonstration of the higher species richness associated with internal habitats on porous defence structures. Moreover, we found a greater species diversity overall on the internal than the external habitats. The results, however, showed higher total percentage cover by all combined species on external than internal habitats. Further analysis (Table 3.3) indicated *Ulva* spp. as the dominant species externally. *Ulva* spp. are green ephemeral opportunistic early successional species and require light to survive. They covered much of the rock unit surfaces in the external environment. This was most likely because of the unfavourable conditions for the majority of invertebrate species, and lack of grazing pressure (Coleman et al., 2006; Hawkins, 1981; Jenkins et al., 2005). The only species not recorded from the internal surface but present on the external exposed surface was *Dictyota dichotoma* (brown fan weed). Invertebrate species were mainly found to colonise the internal areas of the structure in order to seek refuge to allow for foraging, whilst avoiding scour, wave exposure, desiccation and potential predation (Silva et al., 2008).

Despite the lack of visual relationships from the MDS plots, the overall results showed that there was a apparent difference in the species assemblages because of elevation on the shore and placement on the structure. The results also showed combined effects on species assemblages due to exposure and elevation on the shore, and exposure and placement on the structure. These are most likely because most external rock units will inevitably only be located on certain elevation or position areas such as the nose or sides of the groyne, compared to the internal exposure levels which would not be categorised under those locations.

The results of our study support our hypothesis that internal habitats on the porous defence structure will support greater species richness and diversity than external habitats, in particular higher numbers of invertebrate species. Coastal defence structures are constructed in high dynamic environments where there is increased pressure on invertebrate and plant species. *Ulva* spp. are known to colonise marine intertidal habitats (Bunker et al., 2010; Maggs et al., 2007) and dominate exposed surfaces leaving very little surface for other species to attach and colonise, therefore creating inter- and intraspecific competition for space and reducing biodiversity in these areas. *Ulva,* a green algae species, has high light requirements for photosynthesis, therefore colonising external, and non-shaded areas (Bunker et al., 2010; Maggs et al., 2007). *Chondrus crispus* and *Mastocarpus stellatus* successfully colonise the internal areas more than the external environments. Although these species often colonise exposed natural rocky shores, they can tolerate reduced light levels (sciaphilic) (Bunker et al., 2010)

Table 3.3
SIMPER analysis of the percentage (%) contribution of species to assemblage dissimilarities for and between exposure levels on the groyne (internal and external). Only species with contributions higher than 3% in at least one pairwise comparison are reported. Numbers in brackets are average dissimilarities between assemblages.

Species	Int x Ext	Internal	External
	(76.14)	(24.67)	(59.44)
Ulva spp.	42.72	70.39	5.57
Chondrus crispus	13.51	79.86	=
Barnacles	13.3	77.94	=
Patella vulgata	5.43	92.6	=
Mytilus edulis	5.01	88.61	=
Mastocarpus stellatus	3.44	=	=
Patella depressa	3.39	=	=
Actinia equina	3.38	–	–

Table 3.4
Average percentage cover of maintenance disturbance, number of occurrences of damage on internal and external rock armour units, and the frequency of occurrences (%) out of the total number of faces sampled ($n = 280$).

Factor	Level	Average Disturbance (% cover)	Number of occurrences	% of Total sample
Exposure				
	Sediment	0.0	0	0.0
	Internal	1.4 ± 6.0	8	7.3
	External sheltered	2.0 ± 6.2	5	20.8
	External	2.8 ± 8.2	15	14.2
Elevation				
	Foundation	0.5 ± 1.9	5	5.6
	Middle	2.5 ± 8.4	16	11.8
	Top	2.1 ± 6.2	7	12.7
Placement				
	Nose	2.8 ± 6.8	8	21.1
	Internal	0.8 ± 5.4	4	3.3
	Side	3.0 ± 8.4	13	15.5
	Top	1.1 ± 4.0	3	8.3

and are therefore able to colonise shaded, internal areas where there is more protection from waves. They are also later successional species and may be excluded by persistent ephemerals (Sousa, 1979). Invertebrate species were found primarily in the internal areas, with very few (low cover) exceptions. Species distributions on rocky shores are set by the interplay of vertical (tidal elevation) and horizontal (wave action) stress gradients, coupled with biological interactions (Raffaelli and Hawkins, 1996). Refuges are provided by microhabitats created by crevices, cracks and rock pools, which are common features of natural rocky shores (Johnson et al., 2003).

Until now, artificial structures have been perceived as poor surrogates for natural shores because they lack habitat complexity and heterogeneity (Chapman and Blockley, 2009; Firth et al., 2013a, b, c; Firth et al., 2013a; Moschella et al., 2005). Our study shows that porous defence structures do provide valuable habitats for species to colonise formed between rock unit interfaces providing refuge from desiccation stress (Hawkins and Hartnoll, 1983) and disturbance through scouring by cobbles, gravel and sand (Bulleri and Chapman, 2010; Moschella et al., 2005). Not only do porous defence structures effectively dissipate wave energy onto the coastline (Garcia et al., 2004; Jung et al., 2012; Silva et al., 2000), they also provide habitat complexity and protection within their interstices encouraging higher biodiversity than other types of coastal defence designs. They also enable water flow within the structure, providing access to food and submersion for periods, which is essential for many intertidal species. The multifunctionality of porous defence structures is clearly a desirable feature and the benefits conferred are valuable considerations which may usefully inform both engineering and management.

4.2. Maintenance disturbance

There has been little research investigating the effects of maintenance disturbance on coastal assemblages (but see Airoldi and Bulleri, 2011). Our study demonstrates the levels of disturbance that occur during coastal maintenance, particularly to internal and external environments. Anthropogenic disturbance can create openings for opportunistic and invasive non-native species to settle (Dayton, 1971; Hutchinson and Williams, 2003; Sousa, 1979). One key finding is the difference in disturbance levels between internal and external environments. There was nearly double the amount of maintenance disturbance on the external rock unit faces compared to internal ones. Typical coastal maintenance will often involve the replacement of a number of rock units that may become dislodged or moved during intense weather conditions. This will mainly be on external rock units that are more exposed to the extreme conditions and susceptible to movement. Moving units during maintenance work to restore structural integrity after storm damage is an activity that will disrupt those species occupying affected units, as well as species associated with any connecting units. This emphasises the importance of internal environments as suitable habitats to support higher levels of biodiversity on coastal shores. Future work should be carried out to investigate further the effects of disturbance.

5. Concluding comments

Until now, the internal environment of CDS has not been actively considered or explored by ecologists for its potential to provide habitat and enhance biodiversity. Our study highlights the importance of these hidden environments for coastal species, suggesting that porous CDS provide improved habitat heterogeneity and refuges via internal compartments. These features are not present in solid structure designs with no internal compartments. External environments on coastal defence structures are exposed to intense environmental pressures made worse by anthropogenic disturbance from any maintenance work. Therefore they only support a small number of hardy species. Focus must be turned to the internal environment, which can support a higher diversity of species. Porous structures, a common coastal engineering design, are not only effective in engineering; they are also considerably more effective for biodiversity than previously realised. Porous CDS should be considered more widely in future coastal engineering schemes, to encourage settlement of coastal species and to sustain coastal communities, particularly given the growing number of artificial structures and in light of gross environmental change and habitat loss. Finally, further investigations into the impacts of maintenance activity on coastal assemblages should be considered to inform coastal engineers and to provide evidence-based decisions for effective coastal defence management regimes.

Acknowledgements

The authors wish to thank Christchurch Borough Council for their permission to carry out this work during the coastal engineering works, and in particular Steve Woolard for his organisation and assistance throughout the project. We wish to thank Mike Hinton from Neptune Plant Contractor for carrying out the groyne removal process and making the sampling possible. TRWS was funded by an EPSRC studentship. Many thanks also go to OVE Arup & Partners, and Fugro EMU Ltd. for supporting and funding this research. We would also like to thank Dr. Ilse Steyl from the University of Southampton and AHTI Ltd. for her participation in the set up of the research project and funding.

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